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EARTH SCIENCE ISSUES IN THE MISSOURI RIVER BASIN-- MAN'S ADAPTATION TO THE CHANGING LANDSCAPE

by

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Introduction

In a dynamic environmental system such as the Missouri River Basin, geologic, hydrologic, and topographic features play a critical role in guiding cultural, economic, and political development. Land, mineral, and water use decisions at all levels are influenced by their potential for causing environmental change. The earth sciences provide information on resource distribution and availability, and provide planners with an understanding of the limits of the land. Geology's place in the planning process comes from its special capacity to predict how natural processes will affect or have affected specific land uses, to identify potential consequences of land uses on the natural system, and to determine methods to reduce or mitigate the effects of specific land uses on the natural system.

The Missouri River Basin Project is a multidisciplinary effort that focuses on the interactions between human activities and the natural systems in the basin. The State Geological Surveys in the project area and the U.S. Geological Survey have formed the Missouri River Basin Earth Resources Mapping Group to identify important regional earth-science issues within the basin, and to suggest methods and establish priorities to address those issues. It will characterize the cumulative regional environmental effects not apparent on a project-by-project or State-wide basis, and will help avoid conflicts and duplication among different agencies. The Mapping Group is informal and unofficial, its membership is voluntary, and its activities are supported by the agencies that employ its members.

Background

For thousands of years before Meriwether Lewis and William Clark made their historic journey into the territory acquired by the Louisiana Purchase, the Missouri River had served as a framework for human cultures. The river guided the direction of subsequent settlement in the growth of trade and towns, in river navigation, in the provision of water power for industry, and in providing water for irrigation. Today the geologic deposits, rocks, and landforms near the Missouri River, and throughout the Missouri River Basin, provide developable land for buildings, storage for groundwater, disposal sites for both liquid and solid waste, agricultural land, and mineral aggregates. Human-induced changes during the last two hundred years have had a profound effect on the river and the basin. In some areas nature resisted those changes by means of natural disasters such as floods and landslides. In other areas nature responded to human-induced changes in less dramatic, but more persistent, means such as changes in rates and patterns of erosion and sediment deposition. In still other areas nature has adjusted to societal impacts through degradation of the natural system. In order to address these issues, and in order to allow for a planned, environmentally sensitive use of the area, it is necessary to have a sound scientific knowledge of the geologic and related processes in the Missouri River Basin.

Geology Makes a Difference

The Earth's surface is a mosaic of dynamic natural systems in which everything affects everything else. These systems consist of physical components (such as rocks, landforms, soil, climate, water), biological components (such as plants and animals), and societal components (such as land-use, population, economics, and politics). The components operate through complex interrelated physical and biological processes that define a feature of all natural systems commonly referred to as the carrying capacity. Planning and management activities that incorporate standards based on the natural carrying capacity enable man to analyze the consequences of various land-use or resource management options, and help to insure that man's activities are in balance with the natural systems.

As knowledge of the Earth and natural processes increases, the relationships among the physical, biologic, and societal forces become more and more evident. This knowledge can enable humans to predict future phenomena with ever-increasing accuracy, and can make it possible to bring human activities into greater balance with the Earth's natural systems. This knowledge also can enable adaptation of human activities to specific natural processes. For example, if the processes of erosion and deposition, ground failure, earthquakes, and other natural hazards are understood in a specific geographic area, human activities can be located and designed to be compatible with continued operation of the natural processes.

The quality of life in the future depends in part on how well we apply earth science principles in our daily activities. The use of earth science information provides benefit to society in terms of avoiding or minimizing economic losses by reducing the level of geologic risk related to the specific land use. The use of earth science information also benefits society by helping to identify, characterize, and determine the extent of pollution, and to identify measures to remediate these and other earth-science issues associated with existing development.

Two major types of earth-science issues affect the Missouri River Basin; those that have a direct impact on the natural systems and those that are a result of secondary or derivative impacts. Direct impacts commonly result from human activities that are concentrated in a relatively small area (such as urbanization and mining). The impacts occur relatively rapidly, and are quite easy to identify and understand. Direct impacts that frequently occur in the basin include landslides, expansion and collapse of soils, subsidence, earthquakes, and floods.

Derivative impacts have relationships that are less easy to identify or comprehend, and commonly result in more subtle changes to the natural systems. The impacts generally occur slowly over large areas, and may occur a long distance from the sites of human activity. For example, the construction of dams on the main stem of the Missouri River has decreased the transport of sediment by the river, which in turn has affected the sediment balance of the Mississippi Delta. Clearly the distinction between direct and derivative issues is poorly defined. However, it is important to realize that many earth-science issues in the Missouri

River Basin are not readily apparent. Derivative impacts that occur in the basin commonly relate to urbanization, mining, and agriculture, and include soil erosion and sedimentation, contamination of surface or ground water, management of stormwater runoff, and loss of wetlands. Flood control, navigation, and irrigation systems along the Missouri River and its tributaries also have created derivative impacts including major changes in river geomorphology and fluvial processes, and natural habitats.

General Strategy

The Missouri River Basin Project is being conducted in two phases. The first phase is the development phase of the project, during which data are being collected and analyzed to establish the regional perspective and to identify specific areas in the Missouri River Basin for more detailed studies. The second phase of the study will be the implementation phase, during which the more detailed studies will be conducted.

The first phase of the project will focus primarily on collection and analysis of existing data. Regional data (generally at scales of 1:500,000 to 1:2,500,000) are being collected for the Missouri River Basin, and if appropriate, entered into a Geographic Information System (GIS). Information will be analyzed by digital or other techniques, and will provide a regional perspective of the earth-science characteristics of the Missouri River Basin. The map scales utilized for the analysis of data generally will be at a scale of 1:2,000,000.

The regional analysis will provide the basis to identify areas in the Missouri River Basin for more detailed study. The data will be analyzed by the Missouri River Basin Earth Resources Mapping Group and their staff. Identification of areas for more detailed study and priorities will be based on criteria to be established by the Mapping Group, and will include as a minimum, societal significance, environmental significance, and geologic significance, as well as State and local needs and human resource capabilities.

A major part of the implementation phase of the Missouri River Basin Project involves communicating the results to planners and other decisionmakers. Initial contacts during the planning phase will solicit input from planners regarding earth-science information needs. Project information will be made available through State Geological Survey or U.S. Geological Survey reports, or other publications, in open meetings, and as appropriate, in digital format.

INTRODUCTION

For thousands of years before Meriwether Lewis and William Clark made their historic journey into the territory acquired by the Louisiana Purchase, the Missouri River had served as a framework for human cultures, both historic and prehistoric. The river guided the direction of subsequent settlement in the growth of trade and towns, in river navigation, in the provision of water power for industry, and in providing water for irrigation. Today the geologic deposits, rocks, and landforms near the Missouri River, and throughout the Missouri River Basin, provide developable land for buildings, storage for groundwater, disposal sites for both liquid and solid waste, agricultural land, and mineral aggregates. Human-induced changes during the last two hundred years have had a profound effect on the river and the basin. In some areas nature resisted those changes by means of natural disasters such as floods and landslides. In other areas nature responded to human-induced changes in less dramatic, but more persistent, means such as changes in rates and patterns of erosion and sediment deposition. In still other areas nature has adjusted to societal impacts through degradation of the natural system. In order to address these issues, and in order to allow for a planned, environmentally sensitive use of the area, it is necessary to have a sound scientific knowledge of the geologic and related processes in the Missouri River Basin.

This report describes the first phase of a two-phase project designed to determine the geologic and related processes in the Missouri River Basin, and the impact of those processes on society. The objectives of this first phase are to: (1) develop a digital database of regional-scale earth science information; (2) describe the regional setting of the Missouri River Basin; (3) identify geologic and related issues in the basin that merit further study; and (4) prepare a detailed plan to address those issues. The second phase of the project will be to implement the studies designed to address the issues identified in the preliminary planning phase.

The project area includes a variety of physiographic provinces and societal enclaves. The Missouri River Basin Project is a multidisciplinary effort that focuses on the interactions between human activities and natural systems in the basin. The project plans will be based on collaboration and information exchange with State Geological Surveys in the project area. To this end the State Geological Surveys and the U.S. Geological Survey have formed the Missouri River Basin Earth Resources Mapping Group. The Mapping Group is informal and unofficial, and its membership is voluntary. Its activities are supported by the agencies that employ its members. The Mapping Group will identify important regional earth-science issues, and establish priorities based on regional importance. It will identify and assess cumulative regional environmental effects not apparent on a project-by-project basis, and will help avoid conflicts and duplication among different agencies.

The multidisciplinary nature of the project can be further characterized by its open-ended architecture. It is recognized that personnel from numerous Federal, State, and local agencies are working in the basin or have knowledge of the area. A major function of the Mapping Group is to encourage collaboration among the State and Federal personnel who collect, interpret, and use natural resource information in the Missouri River Basin, and to encourage those agencies to contribute to or otherwise participate in data collection and interpretation.

A large amount of important data exist from the Missouri River Basin. However, the earth science information varies widely in availability, detail, and vintage. In order to decrease the level of geologic risk regarding land-use decisions, we need to improve our knowledge of the geologic system in certain critical areas. Currently we have at our disposal many tools for observing and recording the processes of nature. These tools include geologic, hydrologic, and soils maps and reports, remote sensing data, and geophysical data. These tools can provide information necessary to help us better understand nature, including opportunities presented by resources, and risks posed by hazards. This project is designed to provide that knowledge.

GEOLOGY MAKES A DIFFERENCE

In a dynamic environmental system such as the Missouri River Basin, geologic, hydrologic, and topographic features play a critical role in guiding cultural, economic, and political development. Land, mineral, and water use decisions at all levels are influenced by their potential for causing environmental change. The earth sciences provide information on resource distribution and availability, and they provide planners with an understanding of the limits of the land. Geology's place in the planning process comes from its special capacity to predict how natural processes will affect or have affected specific land uses, identify potential consequences of those land uses on the natural system, and determine methods to reduce or mitigate the effects of specific land uses on the natural system.

Beatrice E. Willard (1974) characterized the Earth's surface as a mosaic of dynamic natural systems in which everything affects everything else. These natural systems consist of physical components (such as rocks, landforms, soil, climate, water), biological components (such as plants and animals), and societal components (such as land-use, population, economics, and politics). The systems are characterized by dynamic processes that operate among these three components. For example, landslides, erosion, floods, and sedimentation shape the landscape, and can dramatically affect cultural and economic development. In addition, the processes themselves can be altered by human activities. Patterns and rates of land use can change resource availability, rates and patterns of runoff and recharge, and rates of landscape erosion, sediment transport, and sediment accumulation. Consequently, as the environmental system is modified by natural processes and human activities, the system's capacity to respond to additional perturbations also changes (Bernknopf and others, 1993).

The components of the natural systems function within certain ranges defined by limits such as melting and freezing points, strength limits, nutrient limits, and absorption limits. The relationships between these various parameters describe the operational boundaries and define the characteristics of the natural systems. For example, the transport of sediment by a river requires that the river maintain a certain minimum energy level. That energy level is not maintained in reservoirs, therefore sediment is transported into, rather than carried through, reservoirs. Learning what these parameters are and how they interrelate enables man to plan and analyze the consequences of various land-use or resource management options.

The components of natural systems operate through complex interrelated physical and biological processes. These interrelated processes define a feature of all natural systems commonly referred to as the carrying capacity. For example, a system may have slope, infiltration, and vegetative characteristics that can accommodate the application of a specific amount of waste material without degrading the balance of the system. There is a threshold limit beyond which the application of additional waste will degrade the system. That limit defines the carrying capacity. The plans and analyses that include the determination of carrying capacity can determine methods to avoid the overload characteristics that seriously degrade the natural environment. Development and management activities that incorporate standards based on the carrying capacity will help insure that man's activities are in balance with the natural systems.

Natural systems are dynamic. Although some natural processes, such as soil formation, appear to be static in the time frame of human activities, all natural systems progress through phases of development to a point of dynamic equilibrium. They remain in that state until a major change of one or more parameters changes them to a different stage of development. This can occur precipitously, as by landslide, earthquake, or flood, or gradually, as by weathering or climatic change. Recognition of this principle allows us to view land use and resource management as a dynamic process.

As the knowledge of the Earth and natural processes increases, the relationships among the physical, biologic, and societal components becomes more and more evident. This knowledge can enable humans to predict future phenomena with ever-increasing accuracy, and can make it possible to bring human activities into greater balance with the Earth's natural systems. This knowledge also can enable adaptation of human activities to specific natural processes. For example, if the processes of erosion and deposition, ground failure, earthquakes, and other natural hazards are understood in a specific geographic area, human activities can be located and designed to be compatible with continued operation of the natural processes.

The quality of life in the future depends in part on how well we apply the earth science principles in our daily activities. The use of earth science information provides benefit to society in terms of avoiding or minimizing economic losses by reducing the level of geologic risk related to the specific land use. The use of earth science information also benefits society by helping to identify, characterize, and determine the extent of pollution, and to identify measures to remediate these and other earth science problems associated with existing development.

CHARACTERISTICS OF THE MISSOURI RIVER BASIN

The Missouri River Basin (fig. 1) comprises an area of about 519,000 square miles of the United States and covers about one sixth of the conterminous United States. It includes all of Nebraska, most of the States of Montana, North Dakota, South Dakota, and Wyoming, about half of Kansas and Missouri, and smaller parts of Colorado, Iowa, and Minnesota. (The basin also includes about 9,700 square miles of Canada, although the Canadian section will not be addressed in this study.) Because of its large area, the basin can best be typified as an area of contrasts: contrasts in geology, hydrology, climate, resources, and society.

Geology

The Missouri River Basin includes parts of three major physiographic divisions (fig. 2): the Rocky Mountain System, the Interior Plains, and the Interior Highlands as defined by Fenneman (1946). These three divisions, and their second-order subdivisions - geographic provinces - are used as a means to provide general descriptions of certain aspects of the general physiography (topography and geology) of the basin.

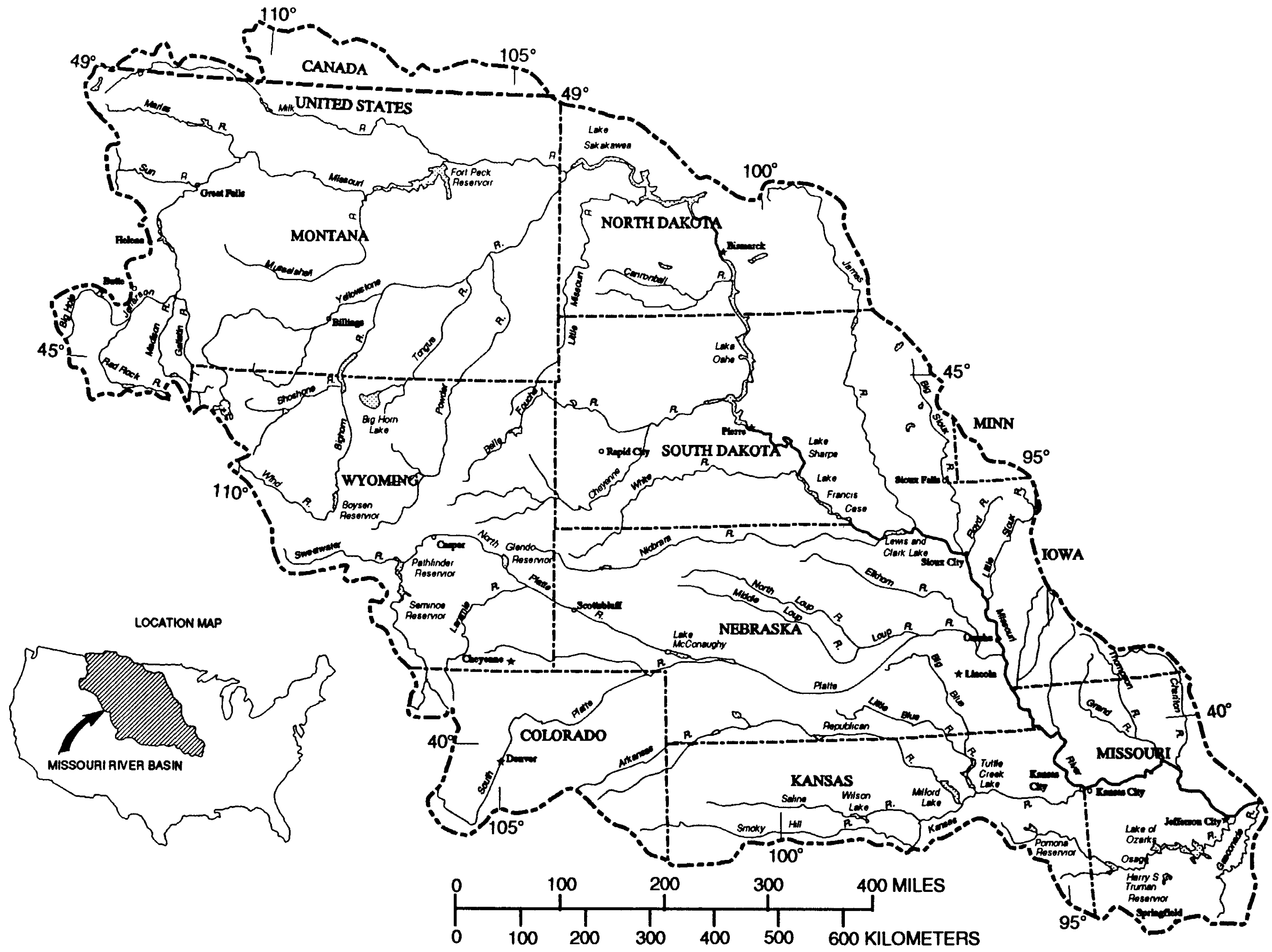

Figure 1.--Surface drainage features of the Missouri River Basin.

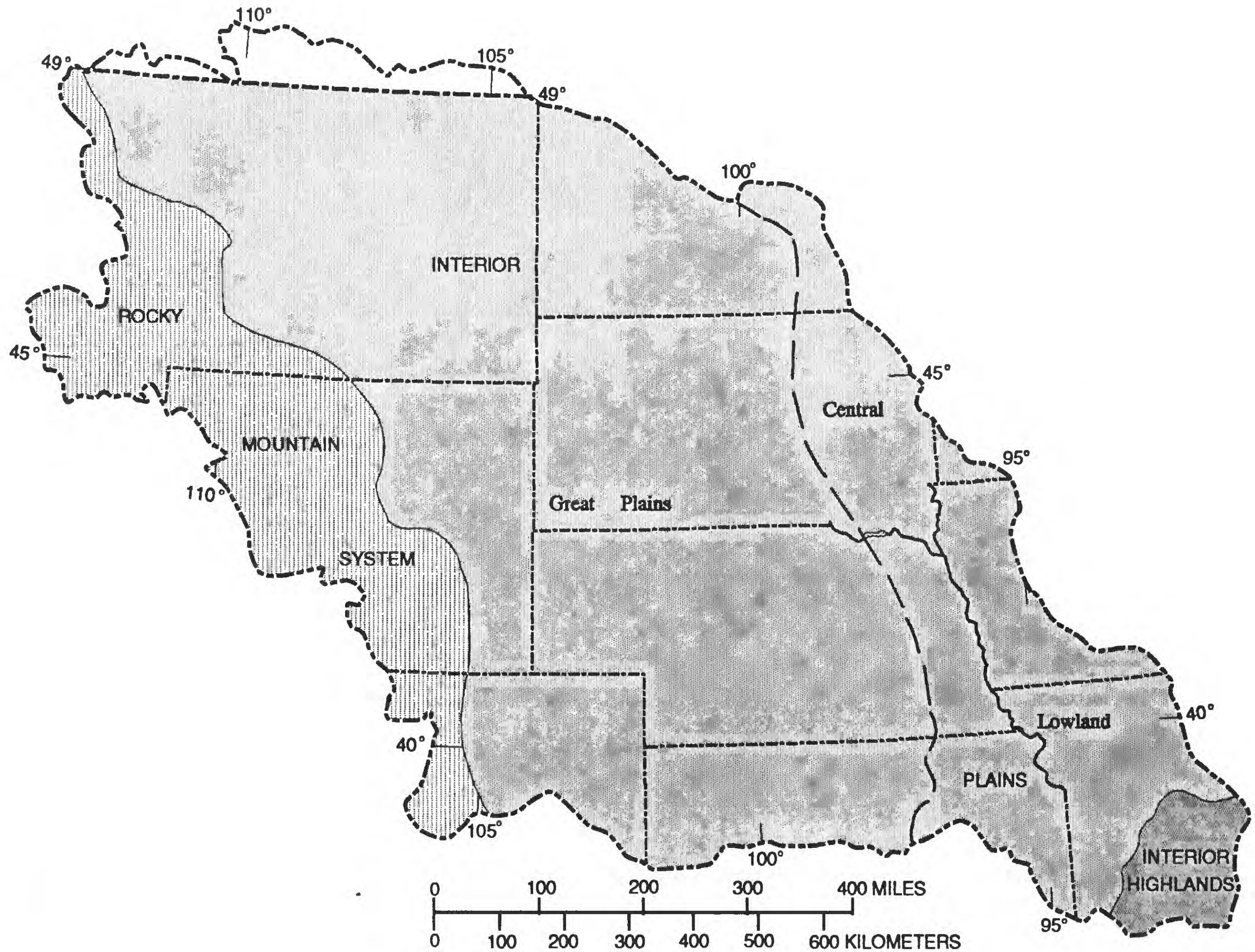

Figure 2.--Physiographic divisions and provinces of the Missouri River Basin (from Fenneman, 1946).

Physiography

The Rocky Mountain System, in the western part of the Missouri River Basin, occupies about 11 percent of the basin area. The area consists of tall, massive mountains alternating with intervening valleys. In the northern part of the basin the mountains crest around 10,000 feet. In general, mountain slopes are mostly rock, and the valley basins are deep and filled with clastic rocks and volcanic ash. In the southern part of the basin the summits of some mountains are higher than 14,000 feet in altitude, and are separated by relatively narrow, steep-sided valleys. Notable peaks include Pikes Peak, Mount Evans, and Long's Peak. Most of the mountain ranges have been uplifted to such an extent that erosion, controlled by the structure of the rocks, has exposed the Precambrian granitic and metamorphic core rocks (fig. 3). The summits and steep slopes of the mountains consist of bare or thinly covered bedrock. Debris cover is thicker along the bases of the slopes. The sedimentary rocks that covered the area prior to uplift now flank the mountains or occur in downfaulted or downfolded intermontane basins. The smaller, narrow valleys are floored by relatively thin, coarse, bouldery alluvium. Volcanic rocks are scattered widely throughout the Rocky Mountain System, and they are present in great quantities in the Yellowstone area.

The Interior Plains constitutes about 87 percent of the Missouri River Basin, and in the basin, includes of parts of two provinces; the Great Plains Province and Central Lowland Province. The Great Plains Province consists of a large area between the Rocky Mountain System on the west and the Central Lowland Province on the east. The boundary between the Great Plains Province and the Central Lowland Province has a poor topographic expression, but occurs at about the 1500-foot contour.

The Great Plains Province occupies more than 70 percent of the Missouri River Basin. The Great Plains landscape was formed by erosion of a fluvial plain that extended eastward from the Rocky Mountains. The surface of the plain is generally flat with low relief, descending from altitudes of about 6000 feet on the west to about 1500 feet on the east. Areas of moderate relief occur in badlands areas, along major entrenched streams, near high areas such as the Black Hills, in dunal areas such as the Sand Hills in north-central Nebraska, and in the areas north and east of the Missouri River that are covered by glacial drift. Isolated mountains formed by dome uplifts, such as the Black Hills, occur within the Great Plains.

Rocks exposed at the surface of the Great Plains Province are dominantly Mesozoic and Cenozoic in age. Rocks of Cretaceous and Tertiary age occur at the surface in much of the Great Plains Province. The Tertiary formations range in age from Paleocene to Pliocene. The most prevalent formations in the basin are the Ft. Union, White River, Brule, Arikaree, and Ogallala.

The Central Lowland Province constitutes about 17 percent of the Missouri River Basin. It is a large province, only a small part of which occurs within the basin. There is no clear topographic demarcation with the Great Plains Province on the west. The eastern divide of the Missouri River Basin separates that part of the Central Lowland Province that occurs within the basin from the bulk of the province to the east. The rocks of the Central Lowland Province primarily are Paleozoic and Cretaceous in age. Within the basin, most of the Central Lowland Province in North Dakota and South Dakota, Minnesota, and part of Iowa is underlain with Cretaceous

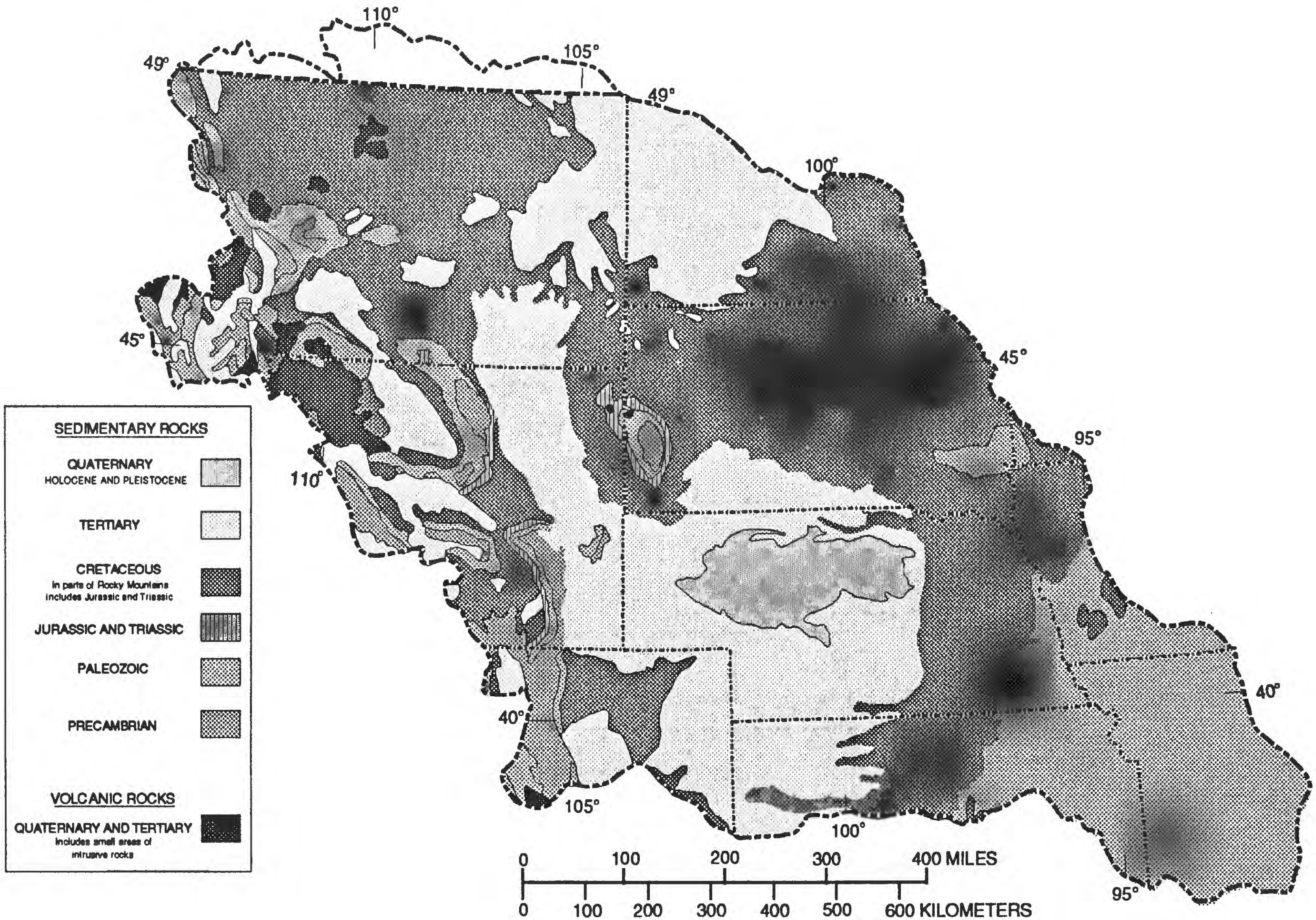

Figure 3.--Generalized geology of the Missouri River Basin (modified from Kinney, 1966).

rocks. In addition, much of North Dakota and South Dakota is covered by glacial drift, whereas much of the area farther south is covered with loess.

A small part of the Ozark Plateau Province of the Interior Highlands System occurs in the southeastern part (about 2 percent) of the basin. The topography is generally hilly, and was formed by erosion of the Ozark uplift. Local relief is generally rather low, but relief adjacent to the Gasconade River may be as great as 500 feet. Most of the area is underlain by Ordovician and older sedimentary rocks, primarily limestone and dolomite.

Geologic History

The following discussions on geologic history is largely from Ruppel (1993), Trimble (1980), and Trimble and others (1984). The geologic history of the Missouri River Basin relates primarily to the history of the Interior Plains and the Rocky Mountain System. The most significant aspects of that history start about 570 million years ago (beginning of the Cambrian). From that time until about 70 million years ago (during the Cretaceous), the interior of our continent was covered at times by shallow seas, into which a thick sequence of layered sediments (between 5,000 and 10,000 feet) was deposited. These sediments subsequently were consolidated into rock. About 70 million years ago the area underwent slow uplift. At most places in the area, the sedimentary rocks underwent only minor deformation and tectonic forces caused gentle undulations of the Earth's crust. Local exceptions occurred where mountains like the Black Hills were uplifted, warped, and locally broken by igneous intrusions.

While the flat-lying areas of the Interior Plains were being gently warped, the area of the present Rocky Mountains was being uplifted at a greater rate by thrust faulting and other geologic mechanisms. Sediment stripped from the rising mountains by erosion was transported to, and deposited on, alluvial plains to form Cretaceous rocks. Volcanic eruptions occurred intermittently during this time, and spread ash layers throughout much of the area. Vegetation thrived on the alluvial plains, and thick accumulations of peaty and woody debris were buried ultimately to become coal.

Beginning about 45 million years ago (in Eocene time), there was a period of relative stability, lasting approximately 10 million years, during which a widespread and strongly developed soil formed over much of the Great Plains. Renewed uplift and volcanism ended this period of stability, and great quantities of sediment and volcanic ash were once again carried out to, and deposited over the Great Plains to form rocks of the White River Group and the Arikaree and Ogallala Formations.

Sometime between 5 and 10 million years ago, the western part of the continent began to uplift, causing streams that previously had been depositing sediment on the plains, to erode into and excavate the sediment they had formerly deposited. One of the river systems that eroded headward into the northern Great Plains was the predecessor of the Missouri River and its tributaries. That river system carried huge volumes of sediment from the Great Plains northeast to the Hudson lowland. As uplift continued, the streams eroded deeper into the sediments and developed tributary systems that excavated broad areas. High divides left between streams formed broad plateaus such as the escarpment-rimmed plateau that is the High Plains. Much of the northern High Plains are covered with sand dunes (as typified by the Nebraska Sand Hills) and windblown silt deposits (loess) that mantle the Ogallala Formation.

By 2 million years ago, alpine glaciers had formed in the Rocky Mountains and continental ice sheets had expanded southward from Canada into the United States. The continental ice sheets formed, and were dissipated several times during the past two million years. The advancing ice front blocked one after another of the northeastward- and northward-flowing streams, diverting them southeastward along the ice front. River channels which had previously been firmly established, were forced to adopt new courses along the margin of the ice. Among these rivers was the Missouri River, which before expansion of the continental ice sheets, had flowed northeastward into Canada and to the Hudson lowland. Much of the present course of the Missouri River from Great Falls, Montana to Kansas City, Mo., was established by ice-marginal drainage.

The glaciated area of the Great Plains Province within the basin is characterized by two suites of landforms. Much of northern Montana is a plain of little relief that is characterized by a nearly continuous cover of thin glacial deposits. In much of North Dakota southwest of the Missouri River, glacial deposits are thin, widely scattered, and discontinuous (Clayton and others, 1980). The glacial deposits commonly are poorly- to non-sorted silt, sand, clay, and stones (till). Because of the thinness of the glacial cover, much of the topography is slightly modified preglacial topography. In North Dakota, northeast of the present course of the Missouri River, the area is covered by thick glacial deposits. The landscape is characterized by a rolling, hummocky, or hilly surface, with water-filled closed depressions between the hills and hummocks. The area is also marked by morainal ridges of till. Within the basin, the glaciated area of the Central Lowland Province is covered by till. The landscape is characterized by hummocky topography with very low relief (Mickelson and others, 1983).

During deglaciation, melting ice provided large volumes of meltwater. In some areas that meltwater collected in front of the ice in glacial lakes. In other areas meltwater flowed across the till-mantled surface in front of the ice. The meltwater transported sediment, and as it was transported, the sediment was rounded and sorted into sand and gravel. That material subsequently was deposited as kames, kame terraces, outwash plains, and eskers.

Hydrology

The Missouri River is the longest river in the United States. It is formed by the junction of the Jefferson, Gallatin, and Madison Rivers at Three Forks, Montana, and flows 2,315 miles to its confluence with the Mississippi River about 15 miles above St. Louis, Missouri. Major tributaries to the Missouri River in downstream order include the Milk, Yellowstone, Little Missouri, Cheyenne, Niobrara, James, Big Sioux, Platte, Kansas, Grand, Chariton, Osage, and Gasconade Rivers.

Surface Water

Much of the flow in the Missouri River system is controlled by man-made structures. Before these structures were built, the Missouri River was a typical Great Plains river. It meandered widely within a broad floodplain, and had a braided channel that followed a tangled network of branching and reuniting channels. The river was choked with sediment which created constantly shifting channels throughout most of the year. Except during periods of flood, the Missouri River was rather slow-flowing (fig. 4). This is because surface runoff in the region is approximately proportional to precipitation and drainage area, and the area the river drains, for the most part, is arid

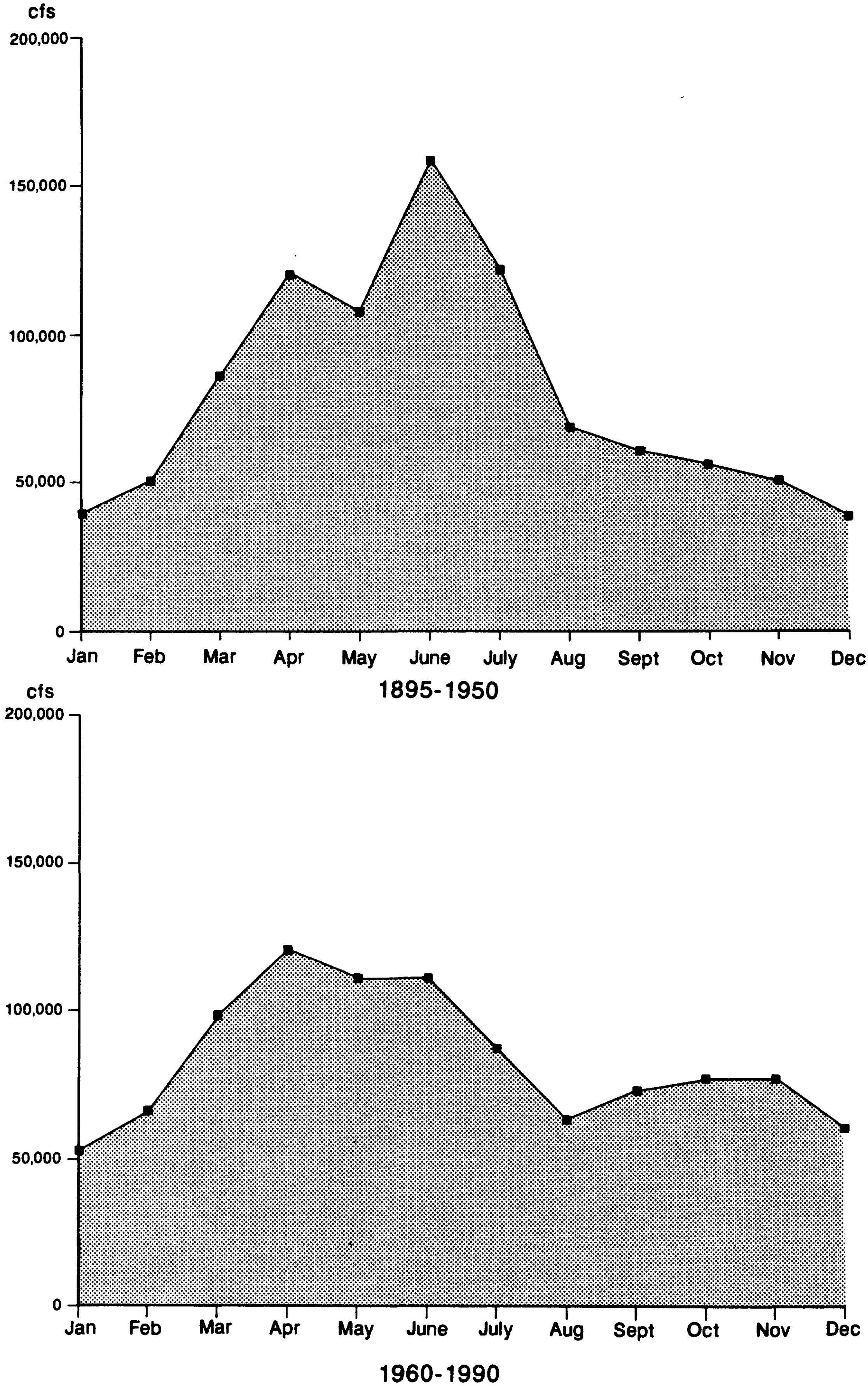

Figure 4.--Hydrographs showing monthly mean discharge, in cubic feet per second (cfs) at the Missouri River at Hermann, Mo., for the periods 1898-1950 and 1960-1990.

to semi-arid. At the same time the Missouri River Basin seasonally receives large volumes of runoff. The majority of the river's yearly flow comes during two periods; the early spring when snow on the plains of the Dakotas, Montana, and Wyoming thaws, and late spring or early summer when the melting of the deep snowpack in the Rocky Mountains combines with spring rainfall on the plains.

Today, river flow in much of the Missouri River system is controlled by reservoirs, dikes, levees, channels, or other structures. Sixty-seven percent of the Missouri River is either impounded or channelized (Hesse, 1987). Surface reservoirs (their associated dams, and the date the dam was closed) constructed for various and multiple purposes are numerous in the region, and along the trunk stream include Fort Peck Reservoir (Ft. Peck Dam, 1937) in northeastern Montana; Lake Sakakawea (Garrison Dam, 1953) in western North Dakota; Lake Oahe (Oahe Dam, 1958), Lake Sharpe (Big Bend Dam, 1963), Lake Francis Case (Ft. Randall Dam, 1952) in southern South Dakota, and Lewis and Clark Lake (Gavins Point Dam, 1955) in southern South Dakota and northern Nebraska.

The man-made changes to the river have greatly affected the flow characteristics of the river. They have eliminated most of the seasonal peak flows, and have evened out the rates of annual flow. However, no average flow estimate for the Missouri River can give a meaningful picture of the river's overall behavior. The Missouri River and its tributaries generally carry comparatively little water in terms of total average annual flow. At Hermann, Missouri, near the mouth of the river, the Missouri River has a mean discharge of approximately 80,050 cubic feet per second (ft^3/s). On a National scale the mean discharge of the Missouri River is small. Shorter rivers with smaller drainage areas have larger mean discharges than the Missouri River (e.g., Columbia River, 193,500 ft^3/s; St. Lawrence River, 243,300 ft^3/s) (Saboe, 1991). Maximum unregulated flow at Hermann, Missouri was 892,000 ft^3/s during 1844. The maximum regulated discharge of 750,000 ft^3/s occurred during 1993 (Parrett and others, 1993). In contrast, for much of the year flow is well below average flow, and during a period of extreme drought in 1940, the river reached a low flow of 4,200 ft^3/s as was recorded at Hermann (Saboe, 1991).

The river is below flood stages during most of each year. The ability of the river's banks, levees, dikes, and other structures to contain high flows from its tributaries depends on the timing of rainfall and other factors. Simultaneous or rapidly successive heavy downpours in several parts of the basin (such as those during 1993) commonly cause floods. In contrast to floods, low-flow conditions result from droughts that may occur within one year or over several consecutive years. For example, during the prolonged drought of 1976 to 1977, runoff at a number of gaging stations with long-term records reached new lows, and storage at most reservoirs was well below normal (Rogers and Armbruster, 1990).

Ground Water

Aquifers are numerous and widespread in the Missouri River Basin, and they include alluvial deposits of sand and gravel, glacial deposits, dune-sand deposits, basin-fill deposits of sand and gravel (fig. 5); and formations of sandstone, siltstone, fractured sandy clay, limestone, and dolomite. The alluvium aquifers are of Pleistocene and Holocene Age, and generally are located in and adjacent to present stream valleys. An exception is in central Nebraska, where areally extensive Pleistocene alluvium occurs. Aquifers in glacial deposits of Pleistocene age in the region generally are confined to the region north and east of the Missouri River,

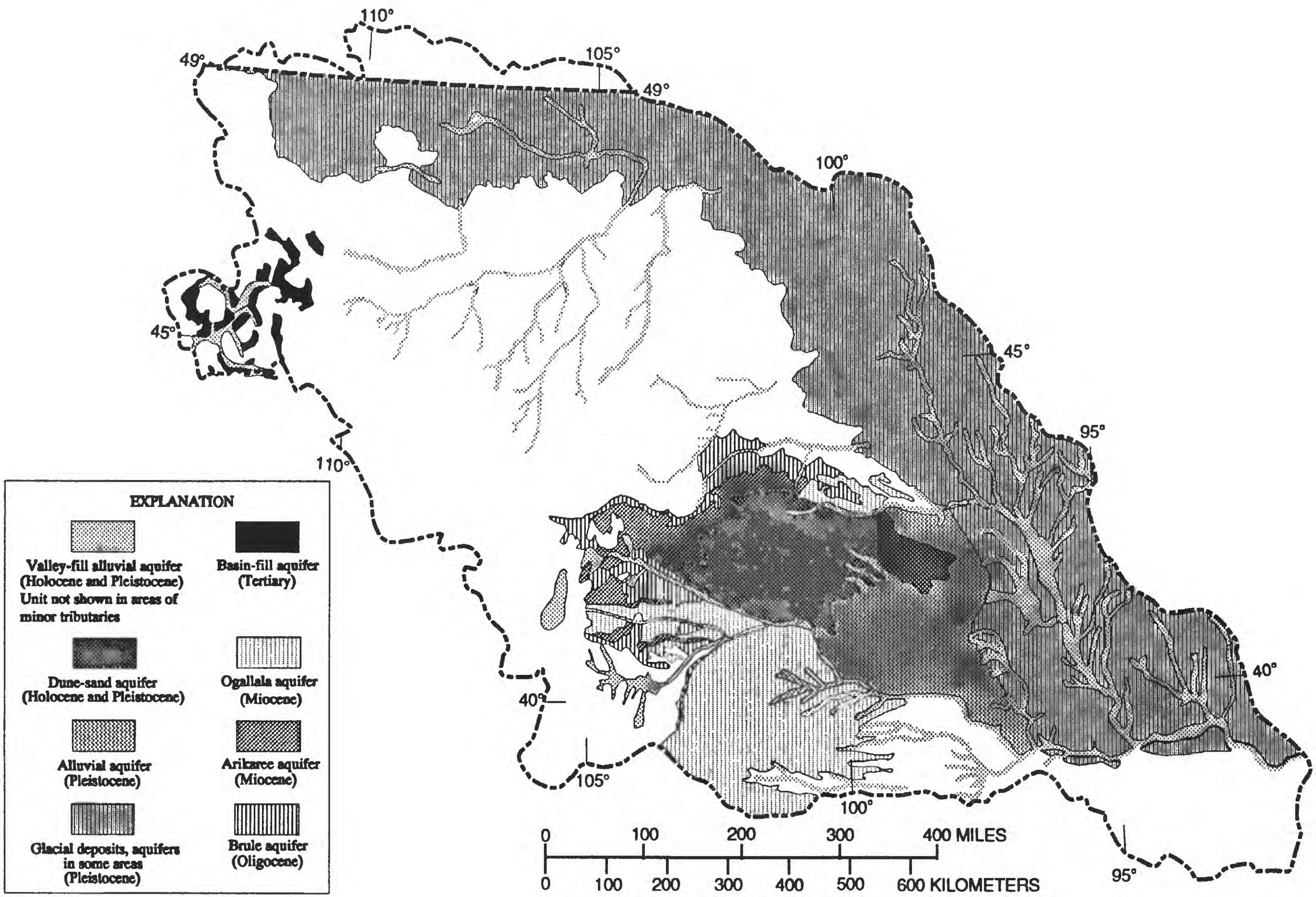

Figure 5.--Surface extent of principal unconsolidated and semiconsolidated aquifers in the Missouri River Basin (from Taylor, 1978).

although aquifers formed in meltwater channels south and west of the Missouri River are important local sources of groundwater. A major dune-sand aquifer occurs in north-central Nebraska. Two Miocene aquifers, the Ogallala aquifer, which consists of poorly-consolidated gravel, sand, silt, and clay, and the Arikaree aquifer, which consists of semiconsolidated sand, silt, and clay, occur in the south-central part of the basin. The Brule aquifer, composed of siltstone and fractured clay of Oligocene age, underlies parts of Wyoming, South Dakota, Colorado, and Nebraska. Sandstone aquifers ranging in age from Cambrian to Cretaceous lie near the land surface and at various depths in the basin. The Madison Limestone aquifer of Early Mississippian age lies at depth in much of the western part of the basin. Limestone and dolomite aquifers of Permian and Pennsylvanian age occur at various depths in Nebraska, Iowa, Kansas, and Missouri. In addition, the region may contain undiscovered aquifers capable of yielding large water supplies. The aquifers are recharged from precipitation, irrigation water, leaky reservoirs, losing streams, and leakage from other aquifers. The aquifers discharge to streams, springs, phreatophytes, wells, and to other aquifers (Taylor, 1978).

Climate

In the Missouri River Basin, the climate strongly influences natural factors such as runoff and river flow, water quality, soil type, vegetation, and slope stability. Climate also influences how people live and their socioeconomic structure. Primarily because of its mid-continent location, great fluctuations and extremes in weather occur in the basin. Average climatological values are misleading because average weather conditions seldom actually occur. Instead, weather tends to fluctuate widely around the annual averages, with the occurrence and degree of fluctuation being difficult to predict. The climate of the basin is determined largely by four extensive air masses: warm moist air from the Gulf of Mexico; cool, moist air from the northern Pacific Ocean; cold, dry air from the northern polar regions; and hot, dry air from the plateaus in north-central Mexico. When these extremely different air masses collide, their interactions create weather changes that are sudden and severe. In addition, before they reach the basin, the air masses cross wide land areas. In doing so, much of their available precipitation is lost, and their temperatures are changed considerably by radiation from the land surface (Missouri River Basin Commission, 1977).

Precipitation

In the Missouri River Basin, the zone between the 97th and 100th meridians is a subhumid belt dividing the midwestern humid lands from the western semiarid and arid lands. Average annual precipitation (fig. 6) east of the 97th meridian ranges from 25 to 40 inches per year, and generally is adequate for crops. Although that region can experience periods of drought, commonly it does not suffer from water shortages. West of the 100th meridian average annual precipitation ranges from 3 to 40 inches, and generally is less than 20 inches. However, average precipitation values commonly do not reflect actual precipitation. During any one year, annual precipitation commonly ranges from less than half to more than double the average annual precipitation. Furthermore, seasonal precipitation is more variable than annual precipitation. Precipitation trends also vary throughout the basin, with below- and above-normal precipitation occurring concurrently in different parts of the region (Ridgeway, 1955; Taylor, 1978). About 70 percent of the precipitation in the basin occurs in the form of rainfall during the growing season. Precipitation from November through March generally is in the form of snow. Thunderstorms are prevalent in July and August and often are localized, with high-intensity rainfall or hail. Prolonged

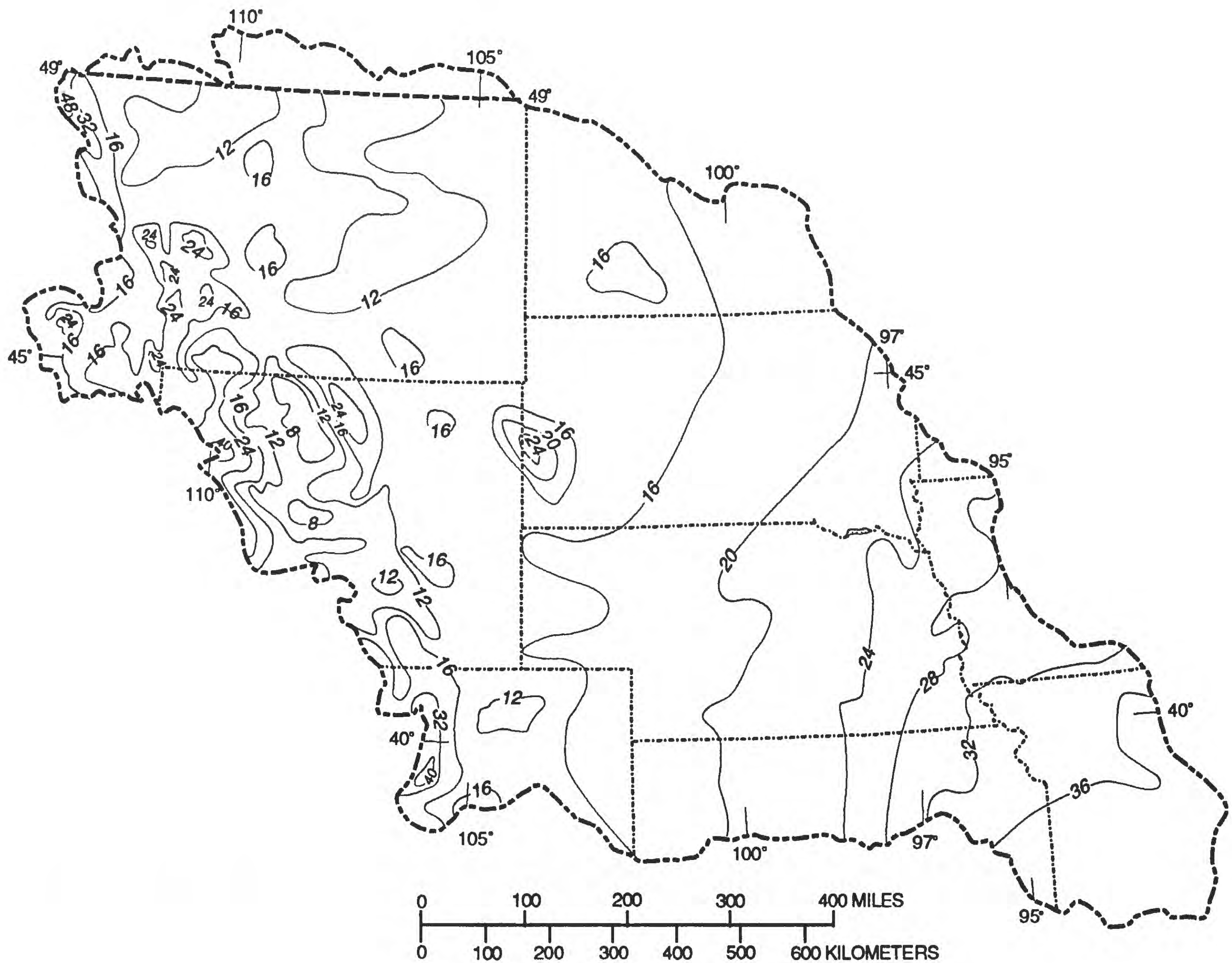

Figure 6.--Average annual precipitation in the Missouri River Basin (from Taylor, 1978).

droughts and lesser periods of deficient moisture may be interspersed with periods of abundant precipitation (Missouri Basin Inter-agency Committee, 1971).

Evaporation

The aridity of parts of the basin is due to both low precipitation and high evaporation. Evaporation is greatest during periods of intense solar radiation, low relative humidity, and rapid wind. Annual evaporation ranges from about 28 inches in western Montana and northern Wyoming to about 62 inches in western Kansas. Over most of the region annual open-water evaporation exceeds annual precipitation, and reaches a maximum deficit of precipitation versus evaporation of more than 23 inches in the central part of the basin (Wolman and Riggs, 1990).

Temperature

Temperatures in the basin are as variable as precipitation. Winters are relatively long and cold; lows of - 40° F have been recorded. Summers are fair and hot; temperatures over 110° F are not uncommon. Spring is cool, moist, and windy, and autumn is cool, dry, and windy. The length of the frost-free period in the basin is about 30 days at higher elevations in the Rocky Mountains, about 140 days in the Great Plains, and about 180 days in the Ozark Highlands (Missouri Basin Inter-agency Committee, 1971).

Mineral Resources

There is a variety of mineral resources in the Missouri River Basin. Gold and silver occur in significant quantities in the mountainous areas of Montana, Wyoming, and Colorado, and in the Black Hills of South Dakota (Ashley, 1991). Copper and molybdenum deposits occur in the western part of the basin (Tooker, 1991). Nickel, cobalt, chromium, and platinum group metals occur in some areas in the western part of the basin, such as in the Stillwater Complex in Montana (Foose, 1991). Ferroalloys and other minor metals such as tungsten, vanadium, beryllium, and lithium have been produced from localized ore deposits (Gluskoter and others, 1991). Nonmetallic minerals including sand and gravel, crushed stone, dimension stone, gypsum, and clay, fertilizer minerals, and minerals for chemical and other uses including bentonite, fluorspar, lime, feldspar, mica and salt, all occur in the basin. Nearly every county in each State has reported production of industrial minerals, primarily to meet construction industry needs.

Energy resources in the Missouri River Basin include coal (fig. 7), oil, gas, and uranium. The Rocky Mountains and western Great Plains Regions of the Missouri River Basin contain more than half the Nation's total recoverable coal reserves. These resources include bituminous to sub-bituminous grade Upper Cretaceous coal, and sub-bituminous to lignite grade lower Tertiary coal. Cretaceous coal also occurs in eastern Nebraska and Kansas (Flores and Cross, 1991). Pennsylvanian age coals occur in the Western Interior Basin in Iowa, Kansas, and Missouri (Donaldson and Eble, 1991). The Williston, Bighorn, Powder River, Wind River, and Denver Basins, as well as other smaller basins, have had significant production of oil and gas. Other significant oil and gas fields occur in Kansas and Missouri (Gluskoter and others, 1991). Several significant uranium districts have been developed in areas underlain by Eocene rocks in the Wyoming basins. Other uranium deposits occur elsewhere in Wyoming, as well as in Colorado, Montana, Nebraska, North Dakota, and South Dakota (Shawe and others, 1991).

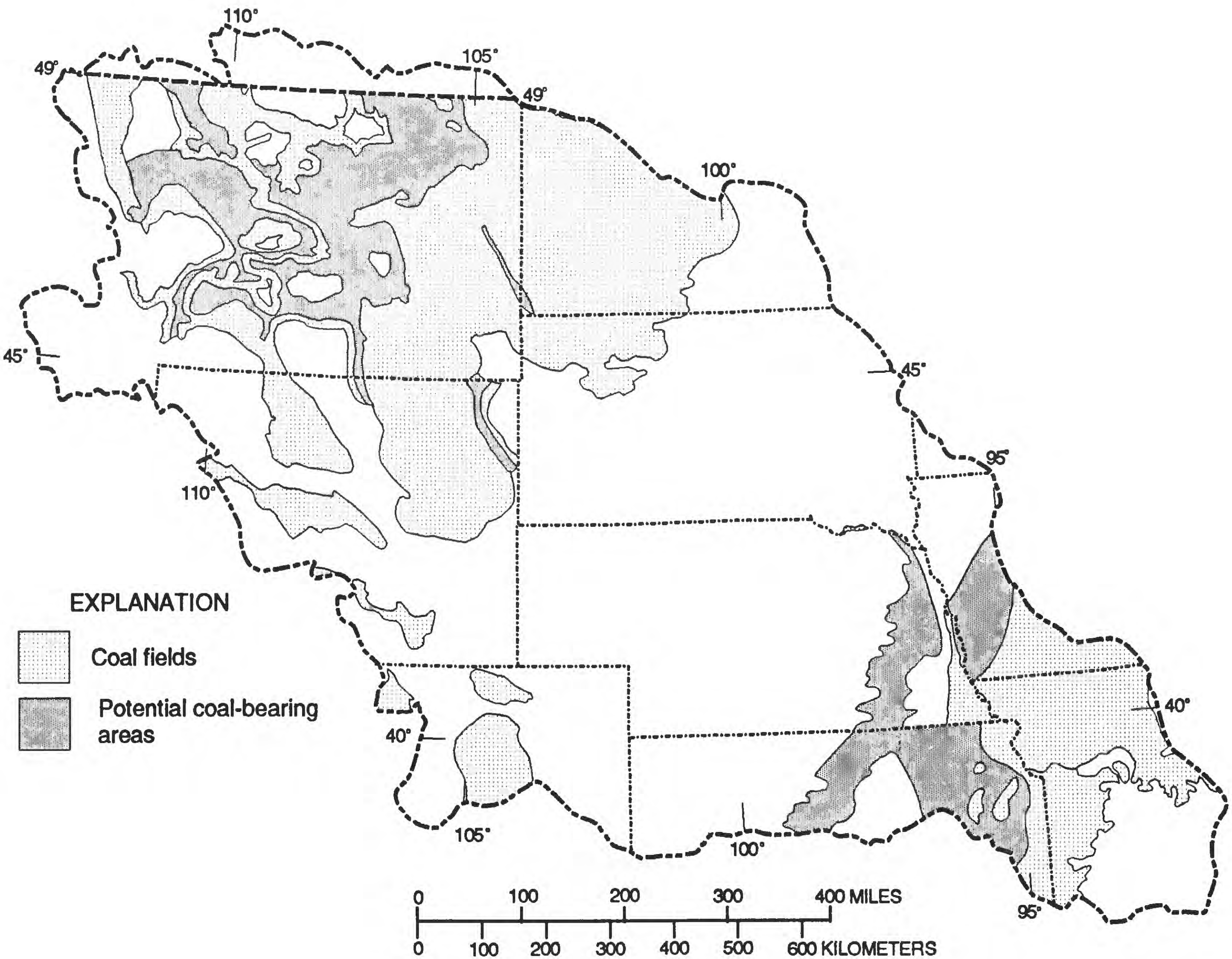

Figure 7.--Coal occurrences in the Missouri River Basin (modified from Wood and Bour, 1988).

Other Natural Resources

One of the most valuable resources in the Missouri River Basin are the National, State, and local forests, (including wilderness areas and primitive areas), parks or monuments, battlefields, recreation areas, grasslands, wild and scenic rivers, and wildlife refuges. These are areas of land and water that are of exceptional scenic, historic, or recreational value. Some of the more frequently visited National areas are Glacier, Grand Teton, Theodore Roosevelt, Yellowstone, and Rocky Mountain National Parks, and Badlands, Devil's Tower, Mt. Rushmore, and Homestead National Monuments. The National areas make up a substantial portion of the northwestern part of the basin, and although the majority are in the states of Montana, Wyoming, North Dakota, and South Dakota, all 10 states in the basin have at least one of these National resource areas.

In addition to the National, State, and local forests and parks, etc., the Missouri River Basin includes many other areas of natural, aesthetic, and cultural resources that include scenic badlands, high mountain ranges, mountain streams and canyons, alpine lakes, coniferous forests, lakes and marshes, sandhill prairies, and unique landmarks and geological formations. The designation of wilderness areas within the national forests and national refuges demonstrates the uniqueness of many natural areas with the basin. Spectacular parks provide abundant outdoor recreation opportunities. Natural lakes and streams in the basin provide habitat for diverse fish, macroinvertebrates, waterfowl, and other aquatic-dependent animal species like the river otter. Wetlands of national significance exist in Montana, North and South Dakota and in the Nebraska Sand Hills. Recreational activities such as scenic drives, wilderness travel, picnicking, fishing, camping, hiking, skiing, swimming, boating, white-water rafting, and hunting serve as the primary industry in some areas. Archaeological, paleontological, cultural, and historic resources are abundant in the basin.

Prior to intense alteration by man, ecosystems of the Missouri River Basin were dominated by grasslands in the prairies and plains region, and by forests, shrublands, mountain grasslands, and alpine tundra in the mountain regions. Forests with great biotic diversity developed along the major rivers and streams in the middle and lower parts of the Missouri River Basin. Grasslands supported a host of terrestrial biota, including herbs, shrubs, trees, insects, birds, and mammals. The shrublands, forests and woodlands of the high plains and mountains also provided suitable habitats for biota.

Socioeconomic

The social and political attitudes of the people living in the Missouri River Basin are as varied as the area through which the river flows. Environmental impacts associated with development and geologic constraints on development tend to be most critical in areas of dense population. These impacts also tend to vary, depending on the nature of the economic activities that support the area. Urban, agricultural, mining, industrial, and recreational activities all have characteristic impacts. In addition, the basin hosts large populations of minorities. Consequently, it is important to recognize and incorporate multicultural aspects of society when making environmental decisions within the basin.

Population

In the Missouri River Basin population has grown from 9 million in 1975 (Missouri River Basin Commission, 1977) to more than 10 million in 1990 (World Almanac, 1993). However, during the last five decades, its population, as a proportion of the total U.S. population, has decreased. Within the basin, population change has mimicked the Nation's growth patterns by shifting from rural areas to urban and suburban areas. More than half the basin's population is now concentrated in four Metropolitan Statistical Areas (MSA)[1], (World Almanac, 1993). These metropolitan areas include Denver-Boulder-Greeley, Colo.; St. Louis, Mo.-Ill.; Kansas City, Mo.-Kans.; and Omaha, Nebr.-Iowa. Only the Omaha MSA has a population less than 1.5 million. Although St. Louis lies just outside of the basin (a few miles south of the confluence of the Missouri and Mississippi Rivers), its proximity to the basin and strong economic influence on the basin warrants its inclusion in these statistics.

In 1980, about 6.2 million people resided in the four Metropolitan Statistical Areas. By 1990, the population was nearly 6.7 million, an increase of about 8 percent (World Almanac, 1993). Although all these areas are experiencing population increases, the growth rates are modest compared to growth rates of more than 20 percent in many metropolitan areas located in southwestern United States (World Almanac, 1993). Even though there has been an overall growth rate of the MSA's in the basin, the core cities of Denver, Kansas City, and St. Louis, have undergone population losses of 5.1, 7.0, and 12.4 percent, respectively (World Almanac, 1993). These figures reflect the national trend (since 1950) of migration from central cities to suburban or nonmetropolitan (rural) areas.

Economic Structure

The social and economic structure of the rural areas of the basin, like the rest of rural America, steadily is becoming more diverse and is now one of the Nation's most economically diverse areas (Hady and Ross, 1990). Although agriculture has historically dominated the basin's economy, during the period from 1979 to 1986 the number of nonmetropolitan farming, manufacturing, and mining counties declined, and the number of specialized government counties and unclassified counties increased (Hady and Ross, 1990).[2] The decline in farming had a tremendous impact in many counties in the basin, because half the counties dependent on farming are in the North-Central region, especially in the Great Plains (Bender and others, 1985).

Although agricultural activities have declined in the basin, it continues to be the dominant economic activity in the basin. The basin is an important producer of the Nation's, as well as the World's, food supply (Missouri River Basin Commission, 1977), and provides approximately 25 percent of the Nation's food and fiber. In

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1 Defined by the Office of Management and Budget as areas with populations over 400,000.

2 Hady and Ross (1990) utilized the following criteria to classify the county types. Farming-dependent counties contributed a weighted annual average of 20 percent or more of total labor and proprietor income in 1981, 1982, 1984, 1985, and 1986. The year 1983, an extremely aberrant year for farm income, was dropped. Manufacturing-dependent counties are counties where manufacturing contributed 30 percent or more of total labor and proprietor income in 1986. Mining-dependent counties were defined as counties in which mining contributed 20 percent or more to total labor and proprietor income in 1986, and specialized government counties are those where where government activities contributed 25 percent or more to total labor and proprietor income in 1986. Unclassified counties include counties which fell in none of the other categories.

addition to livestock and poultry, a large share of the Nation's wheat, soybeans, sorghum, hay, and corn crops are grown in the region. Differences in types of agriculture within the basin reflect the differences between climatic regimes and differences in soils between the northwestern and the southeastern parts of the basin. Corn, soybeans, winter wheat, oats, and pigs are primarily produced in the southeastern part of the basin. Wheat and barley crops are primarily grown in the northern part of the basin in Montana, Wyoming, and North Dakota. Grazing land and rangelands occur throughout the basin; most agricultural activity in the arid, northwestern part of the basin is grazing and rangeland (National Geographic Atlas of the World, 1992).

Manufacturing activities occur in towns and cities throughout the basin, but most are in the southern part of the basin. The number of manufacturing counties in the basin has declined between 1979 and 1986 (Hady and Ross, 1990). Much of the manufacturing activity relates to agriculture (agribusiness), such as food processing and production of agriculture machinery. Electronics, automobile assembly, light industrial activity, paper and lumber production, and chemical and petroleum production also are important activities in the basin.

The mining and timber industries also are very important to the region's economy. Metallic minerals such as gold, silver, copper, lead, zinc, taconite, uranium, and molybdenum, as well as large quantities of industrial minerals such as fluorspar, feldspar, phosphate, lime, mica, bentonite, and construction aggregate are produced in the basin. Energy fuels constitute a major share of all non-renewable resources produced in the basin (Missouri River Basin Commission, 1977). Timber products are obtained primarily from the Rocky Mountains, the Black Hills, and the Ozark Plateau. All these industries will play an important part in the basin's future economy.

The forested areas, reservoirs, and many other scenic attractions in the basin have created a growing recreation-tourism industry which is fundamental to the economic growth of the area.

EARTH-SCIENCE ISSUES AFFECTING THE MISSOURI RIVER BASIN

State and federal planners and managers have recognized the need for land-use management in the Missouri River Basin for many years. However, many of the earth science issues affecting the Missouri River Basin appear to be problems only when they interface with human activities. Communities of all sizes encounter geologic constraints on their use of the land. The larger the community and the more technologically advanced the society, the larger and more complex the encounter is likely to be. Nevertheless, even in remote areas and areas of low population densities, natural geologic processes and human activity can induce changes in the natural system, such as alteration of existing aquatic and terrestrial habitats.

Two major types of earth-science issues affect the Missouri River Basin; those that have a direct impact on the natural systems and those that are a result of secondary or derivative impacts. Direct impacts commonly result from human activities that are concentrated in a relatively small area (such as urbanization and mining). The impacts occur relatively rapidly, and are quite easy to identify and understand. Direct impacts that frequently occur in the basin include landslides, expansion and collapse of soils, subsidence, earthquakes, and floods.

Derivative impacts have relationships that are less easy to identify or comprehend, and commonly result in more subtle changes to the natural systems. The impacts generally occur slowly over large areas, and may occur a long distance from the sites of human activity. For example, the construction of dams on the main stem of the Missouri River has decreased the transport of sediment by the river, which in turn has affected the sediment balance of the Mississippi Delta. Clearly the distinction between direct and derivative issues is poorly defined. However, it is important to realize that many earth-science issues in the Missouri River Basin are not readily apparent. Derivative impacts that occur in the basin commonly relate to urbanization, mining, and agriculture, and include soil erosion and sedimentation, contamination of surface or ground water, management of stormwater runoff, and loss of wetlands. Flood control, navigation, and irrigation systems along the Missouri River and its tributaries also have created derivative impacts including major changes in river geomorphology and fluvial processes, and natural habitats. Earth-science issues, either direct or derivative, that have occurred and have been recognized in the Missouri River Basin are discussed below.

Earth-science Issues Associated with Urbanization

Activities associated with urbanization have had serious, and sometimes far-reaching, effects on the natural systems and natural resources of the Missouri River Basin. Conversely, the natural systems greatly affect urbanization. Depending on the location within the basin, one or more of the hazards associated with floods, ground failure, earthquakes, and faulting (discussed below) are likely to present geologic constraints on land use in the urban environment. Other major problems associated with urbanization include contamination of surface or ground water, management of stormwater runoff, and extraction of construction materials.

Daily operations in urban environments routinely generate a variety of wastes including sewage, solid waste, and industrial wastes. All of these wastes, if improperly handled or disposed, can be potential sources of pollutants that can degrade surface water or groundwater supplies (fig. 8). Petroleum or other chemicals contained in leaky underground storage tanks, and toxic chemicals improperly stored or disposed of at industrial sites can also be potential sources of pollutants. Any of these types of potential pollutants can become mobile and travel long distances from the original source.

When an area is developed, natural drainage commonly is replaced with gutters, storm sewers, and confined drainageways, and large areas that previously were vegetated are paved. These artificial drainage conveyances cause storm runoff to peak sooner and more intensely than under natural conditions. Where storm drainage can contain local flooding, the problem commonly is passed on to downstream areas. In addition, stormwater runoff generated in urban environments commonly is contaminated by oil, grease, pesticides, fertilizers, fecal droppings, street dirt, and other pollutants, and in some instances, may be as much a pollutant as domestic sewage discharge. Urbanization also increases erosion, and sediment yield commonly is double, and may be as much as ten times, that from undeveloped areas (Hansen and others, 1975).

Nearly all residential, commercial, and industrial building construction, as well as most public works projects such as roads, highways, bridges, railroad beds, dams, airports, tunnels, and water and sewer treatment facilities use construction aggregate (crushed stone and sand and gravel). Although construction aggregate is widely

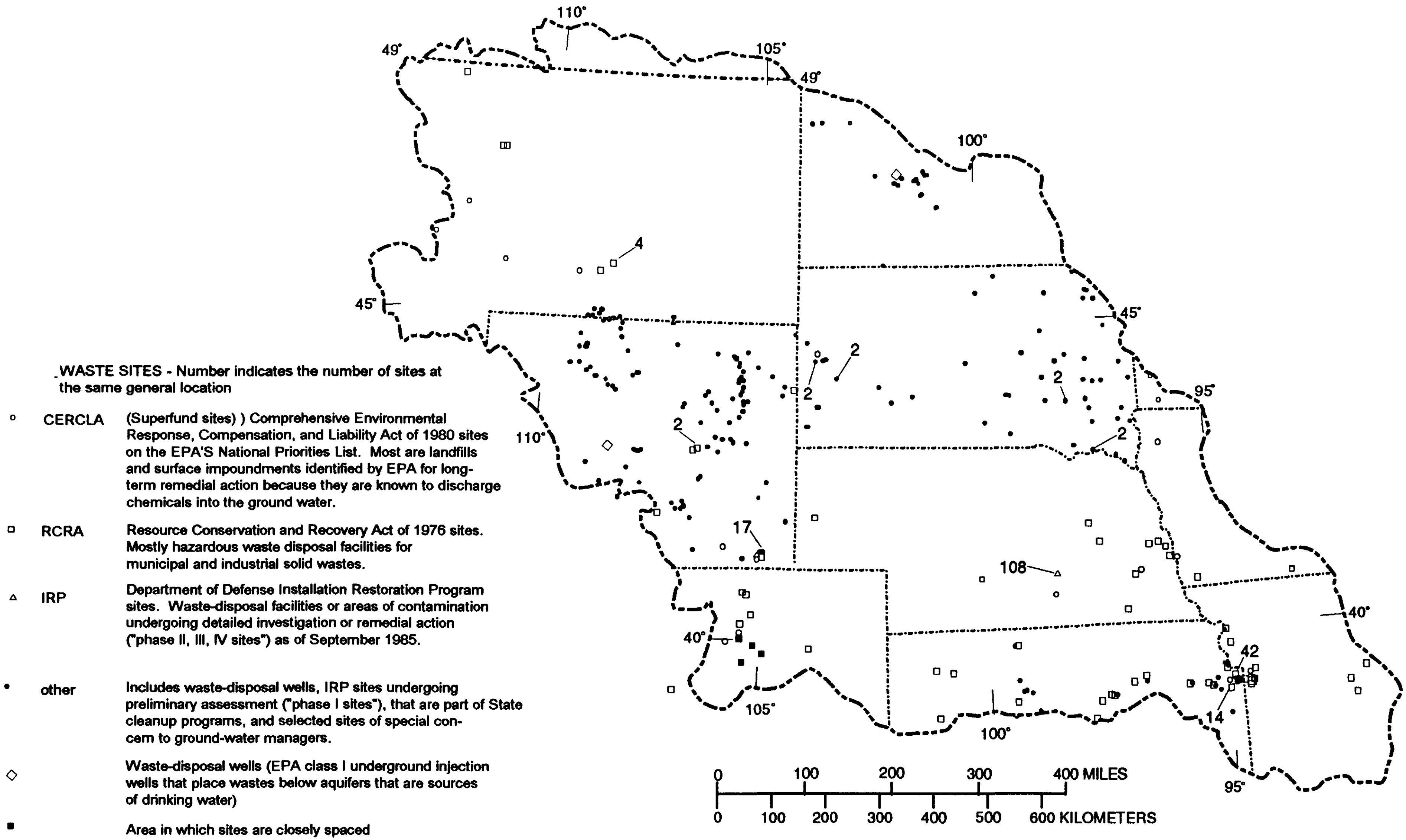

Figure 8.--Waste sites in the Missouri River Basin as of 1986 (from Moody and others, 1986).

distributed throughout the Missouri River Basin, it is not always available near the site of use, or the aggregate may not meet the physical and chemical standards for its intended use. Aggregate also is an inexpensive, heavy, bulky commodity, that is expensive to ship. Therefore, in order for aggregate to be economically developable, it must be near the point of use. However, citizens and regulatory agencies in residential communities commonly desire that mining be conducted far from their boundaries. Therefore, zoning, regulations, or competing land use may preclude the development of aggregate. Nevertheless, urbanization creates an annual per capita demand of approximately 9 tons. Mining operators, public officials, consumers, and community residents, all should work together to ensure adequate supplies of low-cost aggregate while simultaneously protecting the community and environment from the hazards and nuisances of mining (Langer and Glanzman, 1993).

Earth-science Issues Associated with Mineral and Energy Development

A number of potential geologic or hydrologic problems can result from mineral or energy development. Four of these, landslides, erosion, sedimentation, and subsidence, are discussed in separate sections below. Energy and mineral development have specific water requirements that depend on techniques, cost, and efficiency. Water requirements could affect either groundwater or surface water supplies or both. In addition, mineral or energy development could affect water supplies and could cause contamination problems such as mine drainage and leaching of waste materials.

Some coal deposits in the Missouri River Basin are aquifers. Improper mining and reclamation techniques could impact the function of those aquifers. Most of the private wells that tap coal aquifers in the basin are located in the northern Great Plains, particularly in Colorado, Wyoming, Montana, and North Dakota. In those areas the well yields commonly are small and water quality is considered acceptable, although the amounts of dissolved solids commonly exceed desirable health limits. This region has a relatively low population density, so, although the supply of water commonly is small, so is the demand. However, the lignite deposits of North Dakota are an important source of domestic water (Kilpatrick, 1979).

Much of the coal in the Missouri River Basin is suitable for the production of synfuels. Although synfuels production in the Missouri River Basin currently is low, the potential for major impacts exists should the level of production increase. The conversion of coal to synfuels commonly result in the generation of waste residue. The residues contain leachable organic and inorganic substances that potentially can seriously degrade the quality of surface or groundwater resources. Some of the leachable substances are carcinogenic. Others, where present in sufficiently high concentrations, are toxic to aquatic organisms and to animals that ingest the water. To develop specific waste-management plans, local geohydrologic and climatic conditions must be evaluated carefully (Robertson, 1979).

In coal mining areas of Pennsylvanian age coals (Iowa, Kansas, and Missouri), there is a potential for problems associated with acid mine drainage. Mine drainage is metal-ion-rich water that forms from reactions between water and rocks containing sulfide minerals. This water commonly is acidic (low pH) and frequently is formed in areas where ore- or coal-mining activities have exposed rocks rich in pyrite. Metal-rich drainage also can occur naturally in mineralized areas. The problems most commonly associated with mine drainage include contaminated surface or ground water and disrupted growth and reproduction of aquatic organisms. To stop the formation of acid mine drainage, air and water must be kept away from the exposed rock (Gough, 1993).

There are protective measures that can be applied to limit the formation of mine drainage or contain its flow.

Earth-science Issues Associated with Agriculture

Agricultural activities have had major impacts on natural systems and natural resources in the Missouri River Basin. Major issues in the basin associated with agricultural activities cover large areas, and relate to ground- and surface-water consumption, application of agricultural chemicals, soil erosion and runoff, and wetland losses. Geologic information can be used to help mitigate those impacts, as well as help agribusiness adjust to regulatory requirements.

Consumption of Surface and Ground Water

The availability and quality of the surface- and ground-water resources are critical to agricultural productivity in the Missouri River Basin. During 1990, 66 percent of the total water withdrawals from the basin was used for irrigation; approximately 17,600 million gallons per day (Mgal/d) from surface water and approximately 7,200 Mgal/d from ground water (Solley and others, 1993). The use of ground water for irrigation in the basin has been increasing, primarily because of increases in use of sprinkler irrigation. Although aquifers that contain large supplies of water underlie large portions of the basin, the increased use of ground water for agricultural purposes continues to deplete ground water resources. Water tables in the basin States have declined due to overdrawing, with parts of Kansas, Colorado, Wyoming, Nebraska, and Missouri having experienced significant declines. In many parts of Kansas, Colorado, and Nebraska, the increased withdrawal of ground water has resulted in significantly reduced base flow in the interrelated surface streams (Missouri River Basin Commission, 1977). Continued depletion of the water supplies will have significant effects on this indispensable resource, which, in turn could have a significant effect on the basin's economy. This issue poses a major problem for States in the basin.

Application of Agricultural Chemicals

Chemical herbicides, pesticides, and fertilizers routinely are applied to agricultural land in the Missouri Basin to increase crop productivity. Many of those chemicals are partly soluble in water and are washed out of the soil into the rivers and streams or ground-water systems. The use of chemicals in the basin has risen sharply in the last few decades (National Geographic Atlas of the World, 1992), and has raised pollution levels in soils and in surface and subsurface waters. Many streams in the basin contain measurable concentrations of herbicides. Concentrations generally are highest during several weeks to several months after initial application (Goolsby and Battaglin, 1993). Flooding can increase the transport of agricultural pollutants. For example, flooding in the Mississippi River Basin in 1993 increased pollution levels of agricultural chemical in surface waters above normal levels largely because of the intensity of spring and summer rainfall and because the heavy rains began soon after application of the chemicals (Goolsby and others, 1993). Herbicides also can contaminate ground water. Unconsolidated aquifers are more susceptible to contamination by herbicides than are bedrock aquifers, and shallow aquifers are more susceptible than deep aquifers (Kolpin and others, 1993). Many of the fertilizers used in the basin contain nitrates. Nitrate concentrations generally are highest in late fall, winter, and spring. Furthermore, nitrate is transported by both surface runoff and groundwater discharge, whereas herbicides are transported primarily by runoff (Goolsby and Battaglin, 1993).

Soil Erosion

Agricultural losses due to soil erosion are of considerable importance on land used for cultivated cropland and for grazing. Problems associated with erosion have been recognized for many years, and were documented sixty years ago in a reconnaissance survey made by the Soil Erosion Service (now the Soil Conservation Service). In some parts of the basin, formerly-productive farmland has become so damaged by soil erosion that their use for crops or grazing is economically unfeasible. Elsewhere, soil erosion has resulted in greatly reduced crop yields and has caused a decline in the quality and quantity of vegetation on pasture and rangeland.

In addition to the direct losses to agricultural productivity caused by soil erosion, there are many indirect effects. Soils which have been damaged by soil erosion frequently require additional fertilizer and soil amendments to maintain productivity. Increased runoff from eroded land has led to increased flooding which destroys crops and property and can bury productive soils under several feet of sediment. Sediment deposited in drainage ditches and irrigation canals has resulted in increased maintenance costs. Sediment in surface water supplies has destroyed aquatic organisms, eliminated the nesting and spawning areas of many kinds of fish, reduced the capacity of lakes and reservoirs, and increased the cost of treating water for domestic use.

Water and wind are the two main agents of soil erosion. Water erosion is dependent on the amount and velocity of surface flow, nature of the soil, ground cover, slope, and many other factors. Falling raindrops or flowing water initiate the erosion process by detaching soil particles from the surface. Raindrops tend to loosen particles from the land surface through splash erosion (dislodging soil particles through raindrop impact) or sheet erosion (combined action of raindrop splash and sheet flow of water). Flowing water tends to erode by scouring the land surface. Material that has been eroded commonly is transported downslope by water, either by sheet flow (a shallow sheet of water that has no perceptible channels) or by collecting in rills, gullies, or valley channels. At some point downslope, the water is no longer able to transport the material, and the material will be deposited. The first materials to be deposited are those of lowest transportability (generally the heaviest). The materials of highest transportability will be deposited farthest downstream.

The erosion of soil by the wind (deflation) is a complex process influenced by a number of factors including the nature of the eroding surface, vegetation, and moisture content of the soil, as well as wind conditions. Commonly wind erosion is most active in arid to semi-arid regions where vegetation is sparse or absent. In order for soil to be eroded it must first be loosened from the surface. It may then be lifted, slid, or bounced along the surface. Eroded material may be carried to great heights and long distances, and thus can be considered a loss to the eroding area. After transport, the soil may be deposited on farmland where it can be used, or it may be deposited on other land where no use can be made of it, or where it creates problems of removal.

Based on data collected by the Soil Conservation Service for the 1982 National Resources Inventory (USDA, 1987), approximately 10 percent of the cropland acreage in the 10 States that make up the Missouri River Basin had moderate water erosion problems (annual soil loss between 5 and 10 tons per acre). Another 9 percent of the cropland acreage had severe water erosion problems. The States with the most severe water erosion problems were Iowa and Missouri, primarily because of the higher rainfall and the large acreage of deep loess soils that occur in these States.

Wind erosion was a problem on a slightly greater percentage of the cropland acres in these basin States with 13 percent of the acres having moderate wind erosion problems and 10 percent having severe wind erosion problems. The States with the most severe wind erosion problems were Colorado and Montana, primarily due to the arid climate.

Many studies demonstrate the relationship of rates of erosion to land use, and have determined that rates of erosion and soil loss have been accelerated by man's use of the land. Agricultural land in the basin is particularly susceptible to wind and water erosion. Soil erosion is accelerated on agricultural land, through tilling, the removal of permanent vegetation, and irrigation all of which cause sheet and rill erosion (Jenny, 1980). In many areas the rate of soil erosion exceeds the rate of soil formation by at least 10 times. Sheet and rill erosion occurs in all the States in the basin. Erosion rates during 1977 were very high in Iowa, northern Missouri, eastern Nebraska and Kansas, where cropland was eroded at an average rate of 10-12 tons per acre (U.S. Congressional Board, 1982).

Wetland Losses

One of the most dramatic effects that man has had on the ecosystem relates to the draining of wetland areas for agricultural purposes, resulting in substantial wetland losses throughout the United States (Lee and Tobin, 1982). In the 18th century the conterminous United States contained an estimated 221 million acres of wetlands (Dahl, 1990). During the period from 1780 to 1990 more than 117 million acres (53 percent) of those wetlands were modified for other use. According to Dahl (1990), some of the basin States incurred even higher losses during the same period (Iowa 89 percent, Missouri 87 percent, and Wyoming, 62 percent) (fig. 9). Percent losses for Colorado (50 percent), North Dakota (49 percent), and Kansas (48 percent) approach the national average, whereas Nebraska, South Dakota, and Montana each sustained wetland losses of more than 25 percent.

In addition to incurring great loss in acreage, the distribution of wetlands in the Missouri River Basin has changed considerably in the last 200 years. Remaining wetland areas in the basin occur principally along the Missouri River and it's major and minor tributaries. Other wetland areas typified by a high density of small wetlands intermixed with uplands occur in a large areas of Nebraska, South Dakota and North Dakota, and smaller areas occur in north central Iowa, central Kansas, northeastern Colorado, western Wyoming, and northern and southern Montana (Dahl, 1991).

Hazards Associated with Ground Failure

A variety of natural and human-induced processes result in ground failure. Specific types of ground failure that occur in the Missouri River Basin include landslides, expansive soils, collapsible soils, and subsidence.

Landslides

Landslides occur when the force of gravity exceeds the strength of the soil or rock involved. Prolonged rainfall can affect landsliding by adding weight to a

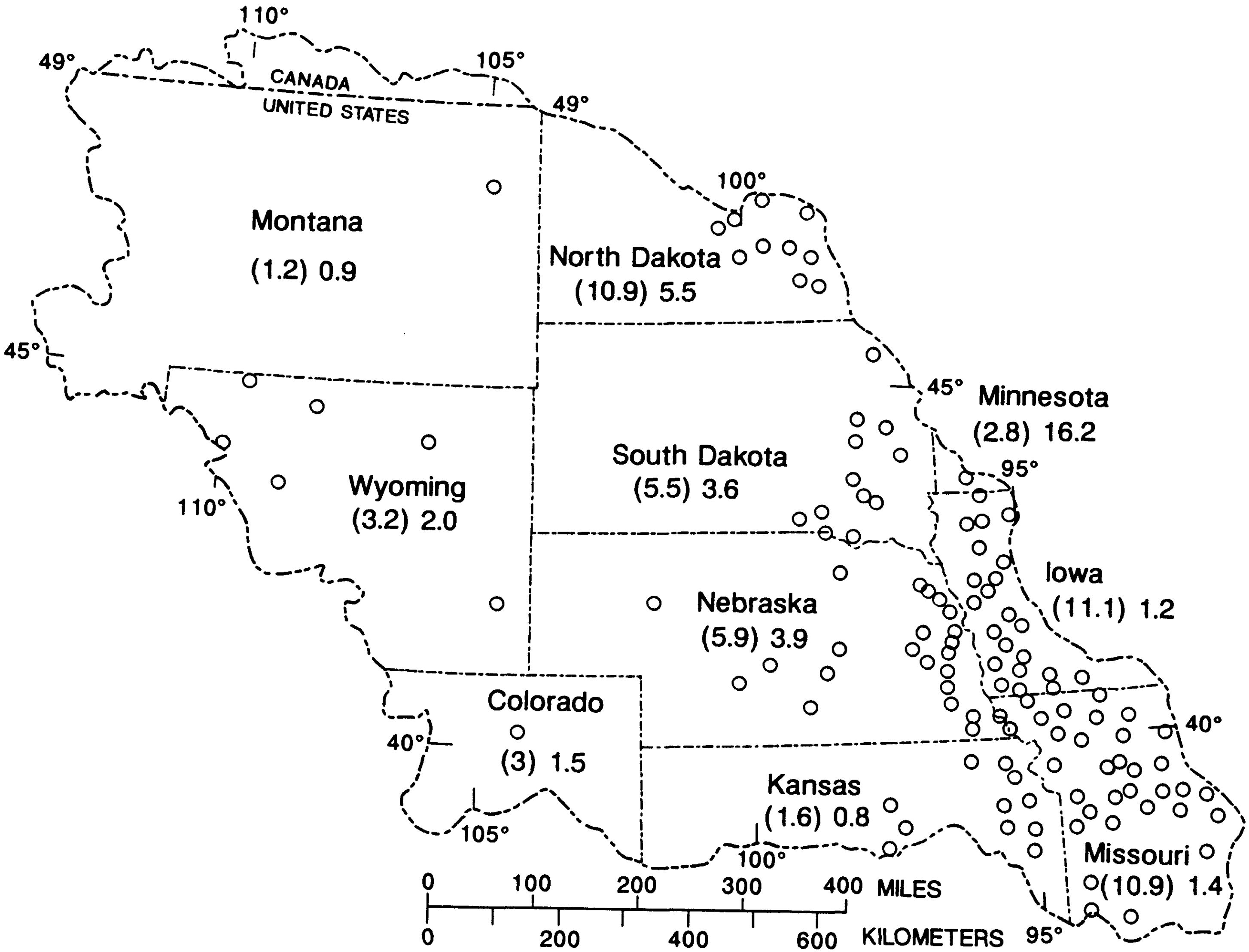

Figure 9.--Areas (denoted by circles) in the Missouri River Basin where 20,000 acres of wetlands have been drained for agricultural purposes (modified from Dahl, 1990). Percent of wetland acreage in 1780 (in parentheses) and 1980 for the entire State (modified from Dahl, 1990).

potentially unstable slope and by reducing the strength of soil or rock by increasing pore-water pressure. Landslides also may be triggered by vibrations, such as those produced by an earthquake. In developed areas, landslides commonly are induced by improper construction techniques. Damage from landslides can occur as direct or indirect costs. Direct costs relate to actual damages to installations or property. Indirect costs include loss of tax revenues on properties devalued as a result of landslides, reduced real estate values in areas threatened by landslides, loss of productivity of agricultural or forest lands affected by landslides, and loss of industrial productivity because of interruption of transportation systems by landslides. Landslides in the basin commonly do not result in major loss of life. The Madison Canyon landslide that occurred in the Missouri River Basin in 1959 is a notable exception. That landslide was a major landslide triggered by the Hebgen, Montana earthquake. The landslide had a volume of about 37 million cubic yards and buried 19 people who were camped along the Madison River (Radbruch-Hall and others, 1976; Schuster and others, 1981).

Landslides may occur in many parts of the Missouri River Basin (fig. 10). Many areas in the Rocky Mountains have severe landslide problems. In the Great Plains of North Dakota, South Dakota, and northern Nebraska, large areas are underlain by relatively weak shale. Landslides occur along much of the Missouri River and its major tributaries. In addition, landsliding, in the form of shoreline erosion, is a major problem in main stem reservoirs. Areas in western Iowa and northern Missouri are underlain with materials that are subject to landsliding. In both those areas, small landslides are abundant on moderate to steep slopes and, where the materials are weak, large man-made excavations commonly cause development of landslides.

Expansive Soils

Expansive soils are unconsolidated surficial material or soft bedrock that increase in volume as they are wetted, and shrink as they are dried. All clayey materials swell or shrink to some degree when subjected to moisture change. Clays of the smectite group, the best known of which is montmorillonite, undergo greater volume changes than most other clays. Smectites and other swelling clays are regionally abundant in geologic formations throughout the Great Plains part of the Missouri River Basin (fig. 11). Swelling soils are one of the Nation's most prevalent causes of damage to structures, and are estimated to cost $6 - $11 billion annually (Ross and Skinner, 1994). Expansion can cause damage to homes, commercial buildings, highways and streets, buried utilities, and other structures. Improper building, design, and maintenance practices can aggravate an otherwise manageable situation. However, the problems associated with swelling soils commonly can be avoided or minimized, provided the swelling soils are recognized and appropriate mitigation measures are taken (Patrick and Snethen, 1976; Schuster, 1981).

Collapsing Soils

Collapsing soils are relatively low-density unconsolidated materials, primarily loess or wind-blown silt, that decrease in volume when they become wet or are subject to heavy loads. Loess is widespread over large parts of the Missouri River Basin. Most loess is weakly bonded by thin films of clay or by loose calcareous cement. When it is dry it is relatively incompressible under light loads, but, it can collapse under moderate loads. When it is wet it is subject to rapid collapse and volume can be reduced by 10 to 15 percent, even under no load. Ground displacement of several feet can result from collapse (Hansen and others, 1975; Shelton and Prouty, 1979).

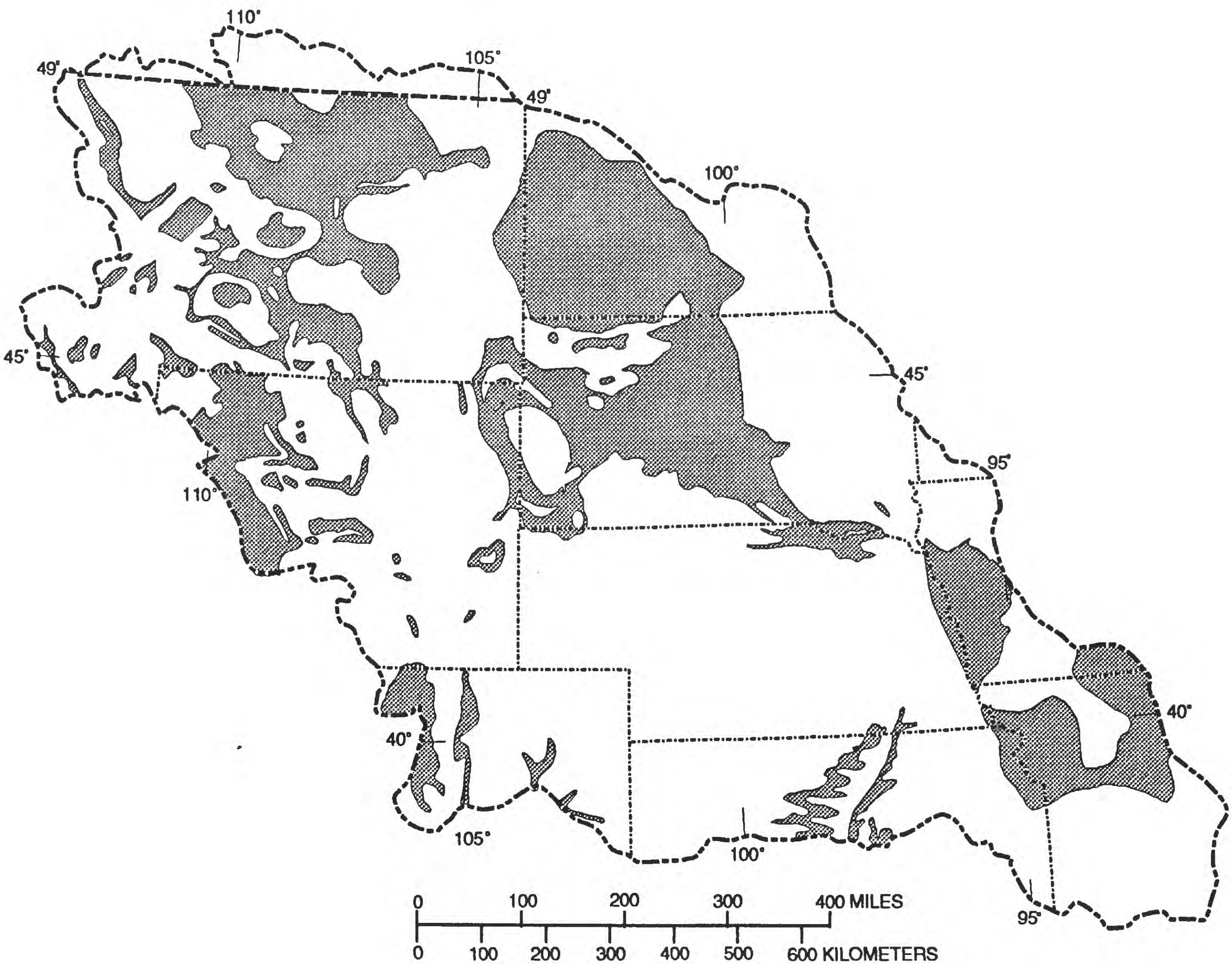

Figure 10.--Major areas susceptible to landslides in the Missouri River Basin (modified from Radbruch-Hall and others, 1987).

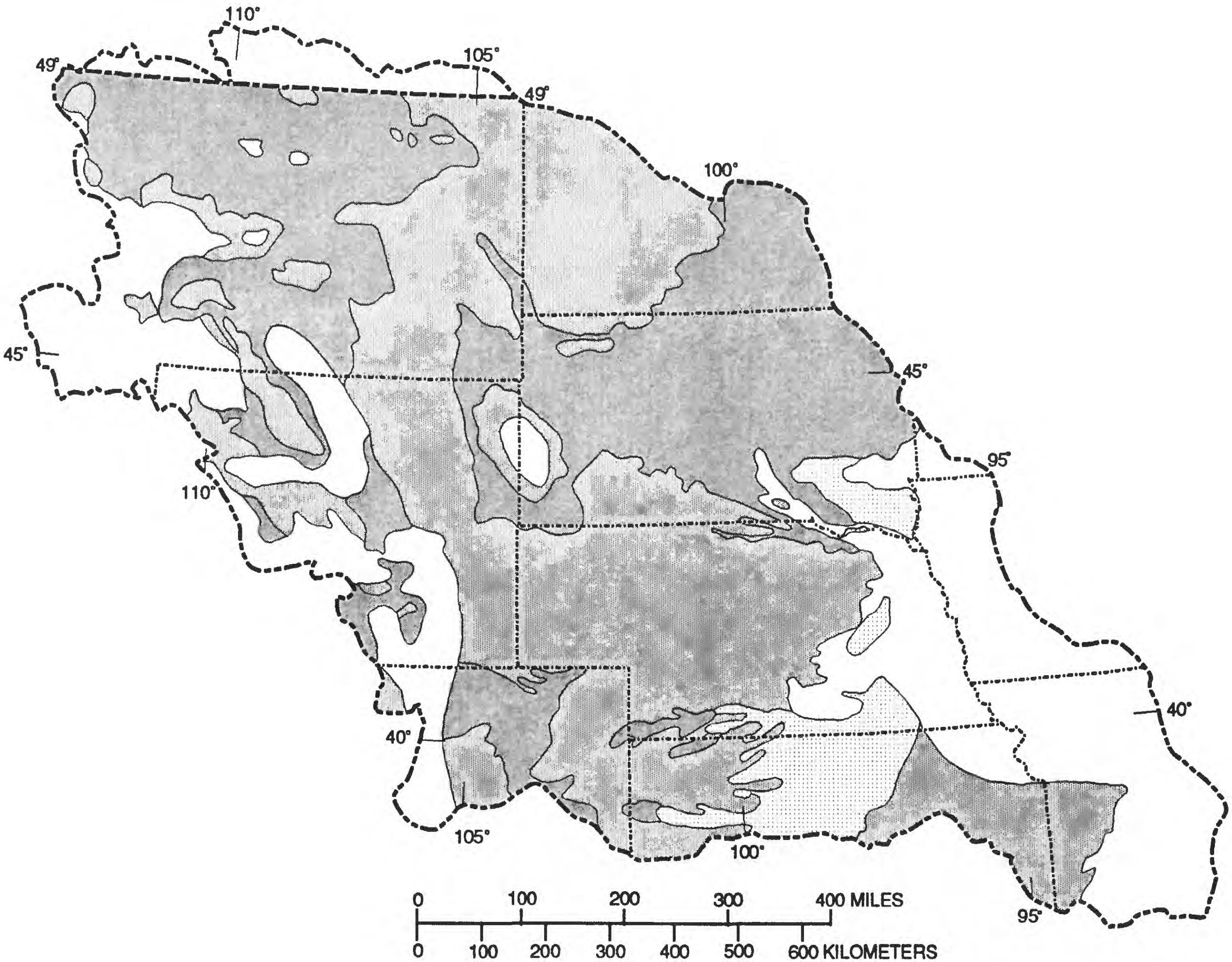

Figure 11.--Expansive soils in the Missouri River Basin (from Schuster, 1981). Soils are most abundant in darker shaded areas and decrease in abundance as shades lighten. Areas which may contain expansive soils on a scale too small to be shown are not shaded.

Subsidence

Subsidence is lowering or collapse of the land surface, either locally or regionally. Subsidence is caused by a number of natural and human-induced activities. Natural subsidence occurs when the ground collapses into underground cavities as a result of solution of limestone, salt, and other soluble materials by groundwater. Natural subsidence is not common in the Missouri River Basin, although it does occur in the western and southeastern parts of the basin (Davies, 1970; Lee and Nichols, 1981). Most current subsidence in the basin is man induced, and is related to underground mining, especially shallow mining of Cretaceous and Tertiary coal, and in a few places, the dissolution of salt. The rocks above coal mine workings may not have adequate support and can collapse from their own weight, either during mining or long after mining is completed. Subsidence in areas of underground coal mining has caused hazardous conditions in Colorado, North Dakota, and Wyoming. The crystalline rocks from which most metals are mined have greater strength and are less likely to collapse (Rickert and others, 1979; Lee and Nichols, 1981).

Hazards Associated with Earthquakes

Although earthquakes normally are not associated with the Missouri River Basin, that perception is incorrect. The Hebgen earthquake that triggered the Madison Canyon landslide mentioned above had a magnitude of 7.5, and caused damage as far away as Helena, Montana (Robinson and Spieker, 1978). Algermissen and Perkins (1976) show large areas of ground-shaking hazard in the western part of the basin, in the four-State area of Iowa, Kansas, Missouri, and Nebraska, and in eastern Missouri. Small earthquakes are recorded regularly throughout the basin. Consequently, ground shaking is a potential hazard in the western part of the basin, along parts of the Missouri River, in the St. Louis area, and elsewhere in the Missouri River Basin (Algermissen and Perkins, 1976; Goter and others, 1982) (fig. 12).

Hazards Associated with Fault Displacement

A fault is a fracture or a set of fractures along which there has been displacement of the sides relative to one another parallel to the fracture. Surface faulting occurs when the fault displacement intersects the land's surface. Although surface displacement can be caused by landslides and other shallow crustal processes, surface faulting as used here applies to differential movement caused by deep-seated forces in the Earth. It is unlikely that death or injuries will be incurred directly from faulting, but casualties can occur indirectly as a result of fault damage to structures. Nearly all historic surface faulting has taken place on faults that have geologically young displacements. Therefore, future faulting is expected to take place on geologically young faults, and prediction is based on identification of those faults. Young surface faults have been mapped in many areas. Those maps typically show two general fault categories: faults that have been displaced during the last 10,000 years and those that have been displaced within the last 2 million years. Although these time periods are long by human standards, faults can be dormant for thousands of years between short periods of vigorous activity. In the Missouri River Basin, young surface faults that have been mapped generally are in the western part of the basin, and generally they are near the Rocky Mountains in Colorado, Montana, and Wyoming (Howard and others, 1978; and Bonilla, 1981). However, other young faults that have not yet been recognized or documented may occur elsewhere in the basin.

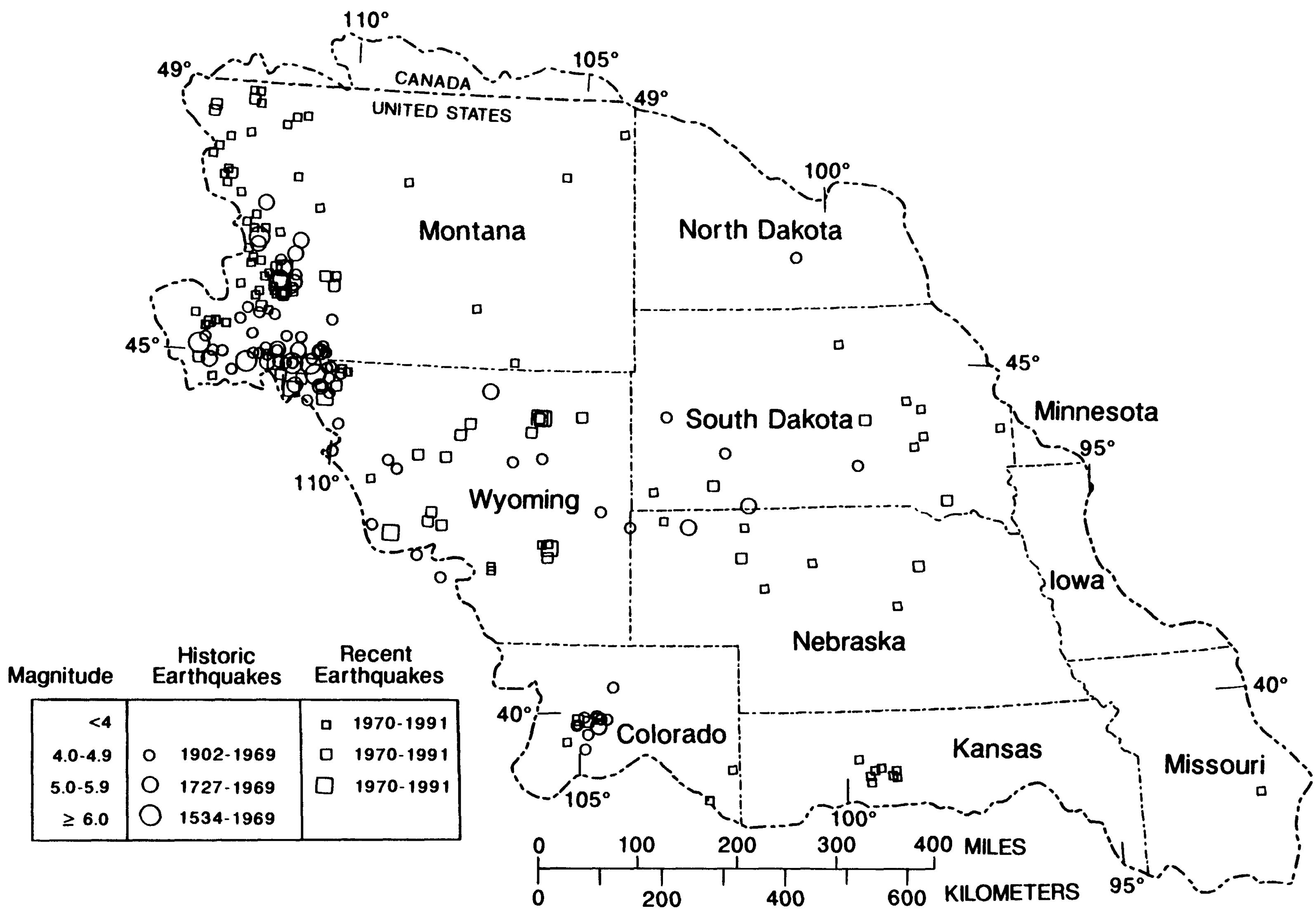

Figure 12.--Earthquake epicenters in the Missouri River Basin (modified from Goter and others, 1992). In the Rocky Mountains, not all recent earthquakes with magnitudes <4 are shown. Historic (1962-1969) earthquakes with magnitudes <4 and recent (1970-1991) earthquakes with magnitudes ≥ 6.0 do not occur in the Missouri River Basin.

Hazards from Floods

Flooding is a natural and recurrent characteristic of rivers, and it occurs when flow overtops the natural or artificial banks of a stream or river. When the channel is filled, the water overtops the stream banks and spreads over the flood plain. When man competes for the use of flood plains, floods become a hazard by causing social and economic disruption and damage to crops and structures. The damage associated with floods is caused by the force of the water itself, the inundation of land, structures, and crops, the erosion by the water, and the deposition of mud and debris (Edelen, 1981). Average costs from floods in the United States are $3 billion to $4 billion annually (Ross and Skinner, 1994). The cost of a single flood can greatly exceed that. For example, unofficial damage estimates related to the Great Midwestern Flood of 1993 exceed $12 billion (World Almanac, 1993).

Most large cities in the Missouri River Basin are adjacent to waterways and in part are on flood plains. Large areas of agriculture are on land reclaimed from flood plains. Nevertheless, in spite of expenditures for flood control, nearly all flood plains are subject to flooding and damages from floods can be severe. There have been a number of major riverine floods along the Missouri River as well as along major tributaries to the river.

Flash floods are local floods of great volume and velocity and relatively short duration that generally result from a torrential rain or a "cloudburst" on a relatively small geographic area. Most small and steep-gradient watersheds in the mountainous part of the basin, as well as areas where the land is hilly with deep ravines, are subject to flash floods. The tremendous destructive power and short notice of flash floods can enable them to destroy essentially all works of man, and can result in large loss of life. Notable flash floods in the Missouri River Basin occurred on the Big Thompson River, Colorado (July 1976), and in the Black Hills, South Dakota (June 1972).

Changes to the Natural River System

Much of the flow of the Missouri River is controlled by reservoirs, channels, and other structures. These construction projects have direct effects on the river by shortening its length (due to straightening), and by reducing its surface area (Hawker, 1992). In addition, man-made changes throughout the basin have indirect but dramatic affects on other aspects of the geomorphology of the river and its tributaries. The flood-control reservoirs in the river basin have an active storage of 1.9 times the mean flow of the rivers in the basin (Hirsch and others, 1990). Altering the normal river flow by storing flood waters in these reservoirs and then slowly releasing the waters has greatly changed channel morphology. One of the best documented cases of changing the characteristics of channel as related to dam construction is the North Platte River. Along the controlled sections of the river, the width of a typical cross section has decreased from an average of approximately 2600 ft. in 1865 to an average of approximately 300 ft. during 1965-1969 (Hirsch and others, 1990). There also have been dramatic changes in vegetation along the North Platte River. Prior to development, the large floods that occurred limited the growth of trees on the active floodplain. Trees were uncommon on and along the river banks, although some trees grew on islands in the braided river. After the construction of flood control structures, the channel narrowed and a succession of vegetation including sedges and grasses, followed by willows and other trees, occupied a large part of what previously had been the original channel (Hirsch and others, 1990).

A study conducted by Iowa State University has documented the cost of channelization of several tributaries to the Missouri River the deep loess region of western Iowa and eastern Nebraska. Several streams and rivers in this region have experienced severe degradation and streambank erosion as a result of channelization and changes in land use that have occurred within the region. Damages estimated at $190,000,000 have resulted from lost agricultural land and damage to highway and railroad bridges, rural water and natural gas pipelines, and fiber optic and coaxial telephone lines (Golden Hills RC&D, 1994).

The Missouri River channel and floodway also has undergone a slow but continual loss of carrying capacity. This loss has been attributed to bank stabilization and navigation structures, accretion of land in and along the channel, construction of levees within the floodway, and construction of public, commercial, and industrial facilities in the floodway. Of these, the bank stabilization project has had the most impact on the loss of floodway conveyance capacity. Lateral dikes constructed to stabilize the banks narrowed the flow width of the channel, and induced increased hydraulic resistance along the banks. The channel areas landward of the protruding dikes have been progressively filled, creating new accretion land. Consequently, the overall channel has been progressively narrowed. Secondary channels (chutes) have either been filled with silt or closed off by fluvial processes, and have become wetlands or forests. Much of the accreted land is converted to crop land, the majority of which is protected by levees (Missouri Basin States Association, 1983).

The dams and reservoirs that have been built along the Missouri River and its tributaries have had a major impact on the transport of sediment by the river. The reservoirs that form behind the dams are slack water areas that interrupt the down-river flow of sediment. Historically, the Missouri River has been the principal supplier of sediment to the Mississippi River. The two other large components of the Mississippi River system, the upper Mississippi and Ohio Rivers, supply large volumes of water but relatively small volumes of sediment. Following the closure of the Gavins Point Dam in 1953, downstream sediment loads were diminished and effects of the closure were observed all the way to the mouth of the Mississippi River. Partly because of the construction of these and other Missouri River Basin reservoirs, the Mississippi River discharge of sediment to the Gulf of Mexico is less than half of that before 1953 (Meade and others, 1990).

Changes to Natural Habitat

Human activity in the basin strongly influenced ecosystems, sometimes with far reaching results to terrestrial and aquatic biota. One of the largest impacts that human activity has had on the ecosystem of the Missouri River Basin is the impact on wetlands and associated habitats. Channelization of the Missouri River in the reach from Sioux City, Iowa, to its confluence with the Mississippi directly eliminated 374,300 acres of wetland and terrestrial habitat, and 100,300 acres of aquatic habitat. In addition, channelization, along with other flood control efforts, has allowed agricultural, urban, and industrial development to expand onto 95 percent (1.8 million acres) of the floodplain. This encroachment has dramatically altered the natural plant communities that formerly occupied the floodplain, and has disrupted vital life habitat for nearly all of the native resident and migratory fauna that depended on habitat along the Missouri River corridor (Hesse and others, 1989). The impact of agriculture similarly has changed wetlands in other areas of the basin. These effects are described above in the section on earth-science issues associated with agriculture.

USE OF EARTH-SCIENCE INFORMATION FOR URBAN AND SUBURBAN DEVELOPMENT

Communities of all sizes encounter geologic constraints on their use of the land. The constraints commonly are more severe and complex in larger communities and in rapidly growing communities. In addition, the issues confronting the communities, and the ability to address the issues, are quite different between the established urban areas and the fringe area that surrounds them.

In established urban areas, the existing buildings and infrastructure commonly limit the ability to implement major changes in land use. In addition, past practices in urban areas sometimes allowed activities such as construction and waste disposal to take place with little or no regard for geologic hazards or constrains. Therefore, many geologic issues addressed directly in the urban areas relate to the identification and mitigation of geologic hazards, and to the remediation or prevention of pollution.

The continued operation and maintenance of established urban areas creates a large demand for natural resources. Those demands commonly include suitable building sites for residential, commercial, and industrial growth, suitable sites for liquid and solid waste disposal (toxic and non-toxic wastes), water supplies, mineral resources (particularly construction-related materials), and land for recreation, conservation, and preservation. Natural resource requirements commonly cannot be met in urban areas where available land is at premium. Consequently, many of the earth-science issues created by the cities are transferred from the cities to the fringe area that surrounds the urban areas.

In meeting the needs of their urban neighbors, planners and decisionmakers in the fringe areas commonly have the opportunity to influence future land use. The knowledge, information, and activities that are implemented during land-use planning and development are summarized in figure 13. This flow chart is equally applicable to urban, suburban, and rural activities, and the benefits derived from the use of geologic data in urban, suburban, and rural areas are qualitatively the same. The places where geologic information impinges on the system are indicated by circled numbers.

Geology overlaps other physical sciences and, in the urban settings, several of the social sciences. Geologic information is used in the planning process to predict how natural processes will affect specific land uses, and the potential consequences of those land uses on the natural system. Specifically, geologic information is needed to make rational decisions concerning land-use (fig. 13, no. 1). Necessary geologic information includes identification of land characterized by potential hazards such as floods, erosion, landslides, subsidence, and earthquake hazards, and identification of land characterized by environmental hazards such as that underlain by rock or deposits with high radon levels, that with soluble, naturally-occurring toxic elements or minerals (e.g., selenium), and land contaminated by human activity. Areas in which hazards don't exist, or in which they can be accommodated by engineering practices can be identified as land potentially suitable for development (fig. 13, no. 2).

In addition to accommodating development, responsible planning includes provisions to minimize the impact of society on nature. Geologic information contributes to the identification of land suitable for uses other than development (fig. 13, no. 3), such as critical or irreplaceable land with specific geologic attributes such as wetlands, floodways, sensitive ecosystems, parks or recreation areas, or other sites of

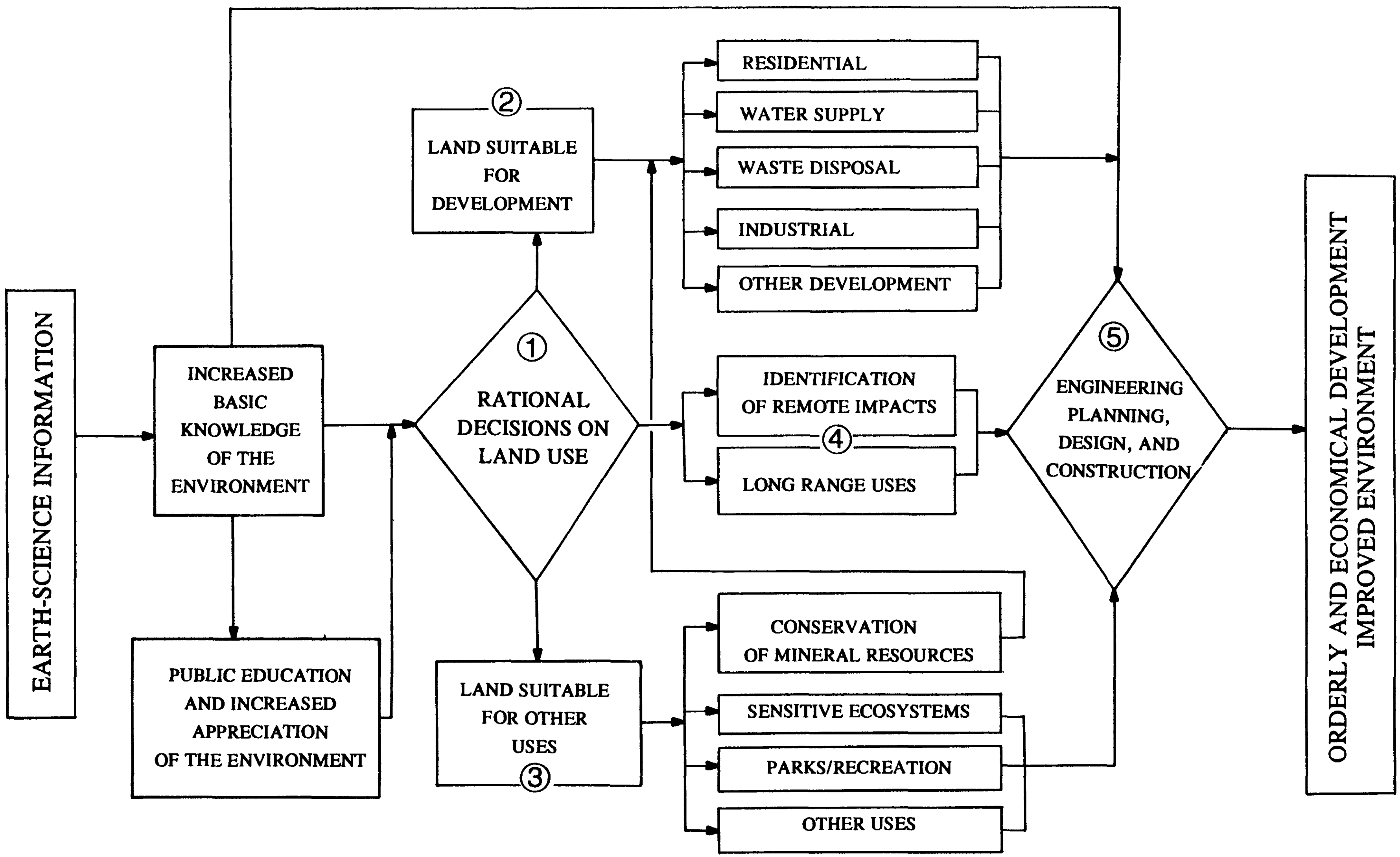

Figure 13.--Impact of geologic information on land use decision making.

unusual importance. Geologic information can be used to identify and protect potential mineral resources such as construction materials (sand, gravel, clay, crushed stone) needed to replace buildings and an aging infrastructure in and near urban centers.

Not all consequences of urban growth are restricted to the urban centers or their fringe areas. Some requirements for urban growth, such as water and energy, must be met in locations remote from the urban centers. Earth-science information is necessary to identify and assess the remote impacts (fig. 13, no. 4), and is necessary for long range plans designed to help avoid future land-use conflicts.

As the planning process proceeds to engineering design and construction (fig. 13, no. 5), knowledge of geologic conditions helps to reduce initial planning and construction costs. In addition, by properly assessing and planning for potential geologic hazards, foundation conditions, and environmental considerations, society can avoid costs for maintenance and repair that would be necessary if construction had taken place without considering geologic conditions.

STRATEGY FOR REGIONAL CHARACTERIZATION AND ASSESSMENT

General Strategy

This project is being conducted in two phases. The first phase is the development phase of the project during which data are being collected and analyzed in order to establish the regional perspective and to identify specific areas in and the Missouri River Basin for more detailed studies. The second phase of the study will be the implementation phase, during which the more detailed studies will be conducted.

During the first phase, regional data (generally at scales of 1:500,000 to 1:2,500,000) are being collected for the Missouri River Basin. If appropriate, those data will be entered into a Geographic Information System (GIS). This phase will focus primarily on collection and analysis of existing data. The map scales utilized for the analysis of data will be dictated by the reliability of existing data; however the basin overview analysis generally will be at a scale of 1:2,000,000. In addition, larger-scale compilations depicting the geologic, hydrologic, and geomorphic processes in specific areas may be conducted to demonstrate feasibility and to help design future studies. Information will be processed and produced by digital or other techniques, and will provide a regional perspective of the earth-science characteristics of the Missouri River Basin.

The regional perspective will provide the basis to identify areas in the Missouri River Basin for more detailed study. Identification of study areas will be based on criteria to be established by the Mapping Group, and will include as a minimum, societal significance, environmental significance, and geologic significance. The data will be analyzed by the Missouri River Basin Earth Resources Mapping Group, and their staff. Studies will be prioritized based on criteria yet to be established, but will include as a minimum criteria listed above, as well as State and local needs and interests, and human resource capabilities.

A major part of the implementation phase of the Missouri River Basin Project will relate to communicating the results to planners and other decisionmakers. Initial contacts during the planning phase will solicit input from planners regarding earth-science information needs. Project information will be made available through State Geological Survey or U.S. Geological Survey reports, or other publications.

Data Management Plan

Most of the digital files pertinent to the Missouri River Basin Project will be maintained in a geographic information system. We have selected Arc/Info as the GIS for this project. The system will run under the UNIX operating system on various hardware platforms. This software is accessible, provides formats for data exchange, and handles both raster and vector data that are needed for analysis.

Users will be able to display earth-science data on a monitor or in a map format by using a plotting device, and will be able to access and overlay different types (layers) of data to study spatial relationships and conduct analyses to prepare derivative maps. In addition, the GIS will provide capabilities to format the data at a common scale and projection. For the initial phase of the study, data will be analyzed at the 1:2,000,000 scale where information can be viewed in a regional context. Various layers of information will be available at uniform, consistent, comparable coverage that will allow users to compare and contrast different parts of the region, as well as identify critical cultural and environmental questions.

The map scale for the regional assessment strongly influences the sources and types of data that will be collected and used. As stated above, map information for the regional analysis will generally be at a scale of 1:500,000 or smaller. There is insufficient data available at appropriate resolutions to support producing a larger-scale map series within the time frame of the project. Types of regional data to be considered include:

Base Information
- Political boundaries
- Population & census data (Census Tiger data)
- Land use and land cover
- Hydrography
- Topography
- Digital elevation data
- Transportation network
- National & state parks and forests
- Wild & scenic rivers
- CERCLA sites (Comprehensive Environmental Response, Compensation, and Liability Act)
- Geologic (and other) index maps

Geologic Data
- Bedrock geology
- Glacial geology
- Surficial materials
- Non-fuels mineral resources
- Energy resources

Climate
- Precipitation
- Temperature
- Evaporation
- Wind

Hydrology
- Surface flow
- Flood data
- Water quality
- Water table
- Aquifers

Geophysical and Remotely Sensed Data
- Aeroradioactivity
- LANDSAT
- HCMM
- AVHRR
- GOES

Geologic Hazards	Other Natural Resource Data
Landslides	STATSGO (soils)
Expansive soils	Slope
Earthquakes	Physiographic provinces
Ground motion	Agriculture
Young faults	Ecosystems

We have started to identify, inventory, and acquire datasets of earth-science information within the Missouri River Basin. This information will provide an opportunity to study and visualize the distribution of various types of information throughout the basin. An important component of this visualization process is to begin to identify questions that may be answered with analysis and production of derivative maps.

After identifying critical environmental problems, we will conduct and prepare the data for analysis. Derivative and interpretive maps will be prepared by combining or contrasting data from the different datasets. For example, maps describing the distribution of surficial materials commonly contain, among other things, information regarding the physical properties of those surficial materials. The specific information regarding physical properties can be compiled, and interpretive maps showing physical properties of surficial materials can be prepared. Following analysis, original and derivative maps can be combined for a final synthesis map. For example, identifying regional areas of potential landslides would require combining information about physical properties of surficial materials with data related to regional slope characteristics. Furthermore, the map produced from this study could be combined with county information to produce a landslide potential map that identifies the counties most likely to experience landslides.

The identification and collection of existing, pertinent digital data will be a priority activity. For many data categories there is no uniform digital coverage over the entire basin. Selected critical data sets that are not in digital format may be digitized. However, all data used in basin analysis will not be in digital format. For example, analog map data, tabular data, and incomplete data sets may be analyzed using conventional cartographic techniques. Digital files, including derivative products, will be made available as a Missouri River Basin Spatial and Attribute Database.

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