THE SPOKANE AQUIFER, WASHINGTON:
Its Geologic Origin and Water-Bearing and Water-Quality Characteristics

U.S. Geological Survey Water-Supply Paper 2265

Cover: Aerial view of the Spokane Flood sweeping southwesterly across the study area (outlined in red) and vicinity.

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By Dee Molenaar

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2265

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PREFACE: WHY THIS REPORT WAS WRITTEN

This report was prepared to provide a nontechnical description and understanding of the Spokane aquifer, one of the world's most productive water-bearing formations. Because the aquifer also has a most fascinating geologic origin, a discussion of the geologic story of the Spokane area is presented. This should enhance the reader's appreciation of the natural processes that shape the Earth and provide a description of the nearly unique geohydrologic setting of the Spokane aquifer.

From time to time, the U.S. Geological Survey publishes reports for the express purpose of sharing with the general public the results of its scientific findings in a manner that will appeal to layreader interest. Until now, the Spokane aquifer has been discussed only in technical reports designed primarily for scientists and mostly with the purpose of summarizing and interpreting hydrologic data for the development of policies and decisions by water-management agencies. However, in view of the importance of the Spokane aquifer as the principal source of good-quality water for the people and industries of the Spokane Valley, there have been both an increasing public interest in the aquifer and its physical characteristics and concern about its potential contamination by man's activities. Of special interest is the close connection (hydraulic continuity) between the aquifer and the Spokane River, which is the only year-round, through-flowing stream in the Spokane Valley.

Ground water as an important source of supply has gained considerable public recognition in recent years, as has the term "aquifer." However, how ground water occurs and moves in an aquifer and the great variety of aquifer types are little understood by the general public. For this reason, this report includes a discussion of not only the Spokane aquifer but of aquifers in general. Also discussed are the occurrence of ground water within various aquifer types and its movement into (recharge), through, and from (discharge) an aquifer as part of the hydrologic cycle.

The description of the Spokane aquifer includes the geologic story behind its origin and its part in the Spokane Valley's hydrologic setting. Discussed are the relation among precipitation over the area (mostly in the headwaters of the Spokane River basin), the flow of the Spokane River, and the movement of water to, through, and from the aquifer. Also discussed are the concerns of local citizens and water-management agencies regarding the effects of man's activities on the quality of water in the aquifer and on the Spokane River. This includes a summary of the types of land use and developments on the land surface above the aquifer and an evaluation of water quality in the aquifer and the river. Included is an introduction to the use of ground-water models (mathematical or digital) as a water-management tool to aid in describing existing hydrologic and water-quality conditions in an aquifer and for predicting future changes in the aquifer when subjected to changes in man's activities and "stresses" on the system. The location of further information is summarized (Appendix A). Also summarized are the statutes and requirements of the State of Washington relative to the management and protection of the surface- and ground-water resources (Appendix B) and the well- and location-numbering system (Appendix C).

The information presented in this report is based primarily on previously published technical reports of the U.S. Geological Survey and other selected reports and maps. A list of these references is given at the end of the report. We hope that the reader will gain from the information provided in this report and from the manner of presentation—with nontechnical terms and attractive, easily understood illustrations. The report should enhance the reader's understanding of the geologic and hydrologic processes that provide man with the resources necessary for his existence on the planet Earth.

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THE SPOKANE AQUIFER, WASHINGTON: ITS GEOLOGIC ORIGIN AND WATER-BEARING AND WATER-QUALITY CHARACTERISTICS

By Dee Molenaar

ABSTRACT

The Spokane aquifer is an unconfined aquifer consisting of coarse sand, gravel, cobbles, and boulders deposited during several catastrophic glacial outburst floods—known as the Spokane Floods—of Pleistocene time. The aquifer is one of the most productive in the United States, and, as the only significant source of good-quality water supply in the Spokane Valley, it has been designated as a "Sole Source Aquifer" by the U.S. Environmental Protection Agency.

The Spokane aquifer underlies an area of about 135 square miles in the Spokane Valley and varies in saturated thickness from a few feet to 500 feet or more. The aquifer is recharged by ground-water underflow from the Rathdrum Prairie aquifer in Idaho on the east, by ground-water underflow and surface-water seepage from small drainage areas along the Spokane Valley margins, and by percolation from various sources—from rainfall and snowmelt, from some reaches of the Spokane and Little Spokane Rivers, and from septic-tank drain fields, cesspools, and irrigation water. Discharge from the aquifer occurs by ground-water underflow from the lowermost end of the valley, by leakage to the Spokane and the Little Spokane Rivers, by evapotranspiration, and by ground-water withdrawal by pumping. The transmissivity of the aquifer ranges from less than 0.05 to 70 feet squared per second, and its specific yield ranges from less than 5 to 20 percent of the aquifer volume. Seasonal water-level fluctuations in wells tapping the aquifer are generally less than 10 feet. The annual pumpage from the aquifer in 1977 was about 164,000 acre-feet, of which about 70 percent was for municipal supplies, which included some industrial and commercial supplies.

Land use over the aquifer includes predominantly agricultural activities in the eastern one-third of the valley and urban and residential developments in most of the remaining area. Potential sources of contamination of the aquifer include percolation from cesspools, septic-tank drain fields, and municipal and industrial waste-disposal sites. In general, the high rate of ground-water movement through the highly permeable aquifer materials has resulted in the ground-water quality being little affected by the overlying land use activities. Some local degradation of water quality has occurred due to industrial waste-disposal practices, however. During the water-quality study period of May 1977 to May 1978, average specific conductance of the ground water ranged from less than 100 to about 500 micromhos per centimeter at 25 degrees Celsius, average chloride concentration ranged from less than 2 to about 12 milligrams per liter (equivalent to parts per million), and average nitrate nitrogen concentrations ranged from less than 1 to about 8 milligrams per liter.

The streamflow and water quality of the Spokane River, which are related to the flow and quality of water in the Spokane aquifer, indicate that, during the period 1913 to 1978 inclusive, the river at Post Falls, Idaho, had an average annual discharge of 6,307 cubic feet per second, a maximum discharge of 50,100 cubic feet per second, and a minimum discharge of 65 cubic feet per second. The quality of the river water along its course through the study area is affected to some extent by inflows of industrial wastewater and treated municipal sewered water. In the 30-mile reach between the State line and Riverside State Park, during the 1975 to 1978 water years inclusive, concentrations of nearly all the constituents analyzed increased, and concentrations of dissolved oxygen correspondingly decreased from 1968 to 1977 inclusive; coliform bacteria also showed notable increases in the downstream direction.

ABOUT THIS BOOK: ACKNOWLEDGMENTS OF HELP IN ITS PREPARATION

This book is a byproduct of several studies of the geology and water resources of the Spokane area generally and of the Spokane

aquifer specifically. The earliest studies involved fieldwork and mapping of the geology and interpretation of geologic events that shaped the Spokane Valley and surrounding area. These were begun in the late 1800' s and have undergone continual updating and revisions, particularly with relation to the uniquely catastrophic Spokane Floods (first postulated by Bretz, 1930, 1959). New interpretations are being made continually of the number of flood events and the relation of their various deposits and erosional features in the valley and on the Columbia Plateau beyond. The results of these studies have been reported mostly in technical publications designed for the earth sciences professional.

Among the authors of the above mentioned publications, Eugene Kiver, Paul L. Weis, and Richard Waitt provided this author with additional verbal information on their interpretations of the flood events. These people also gave encouragement to preparation of this popular-style report, so that the nonscientist might share in some of the "thrills of discovery" made possible by geologic exploration and interpretation.

Some of the reports that discuss the area's surface-water resources, geology, and related ground-water occurrence were prepared for the use of local and State water-resources managers to aid in planning for future water projects and in protecting the resource from depletion and pollution. These reports were followed by more recent (the past 25 years) studies of the ground-water quality and rate of ground-water flow in various parts of the aquifer, the relation between the aquifer and the Spokane River, and the effects of the discharges of wastes from septic tanks and industries on the aquifer. In particular, the results of such studies by Edward Bolke, Brian Drost, Harold Seitz, and John J. Vaccaro of the U.S. Geological Survey were the basis for much of the description of the aquifer's water-bearing and water-quality characteristics.

Many other reports have served as reference material for the discussions of the area's geology and related ground-water occurrence and of the streamflow characteristics and water quality. Other reports provided information on water-quality criteria, water use, and water-rights administration. A list of these reference sources is presented in the bibliography.

Of benefit to this report have been the technical reviews by colleagues. These include reviews of all or parts of the report by Norman P. Dion, John J. Vaccaro, and Dr. Paul L. Weis (retired) of the U.S. Geological Survey. In addition, Glen H. Fiedler of the State of Washington Department of Ecology provided a revised discussion of water law in the State.

A Bird's-Eye View of the Spokane Valley

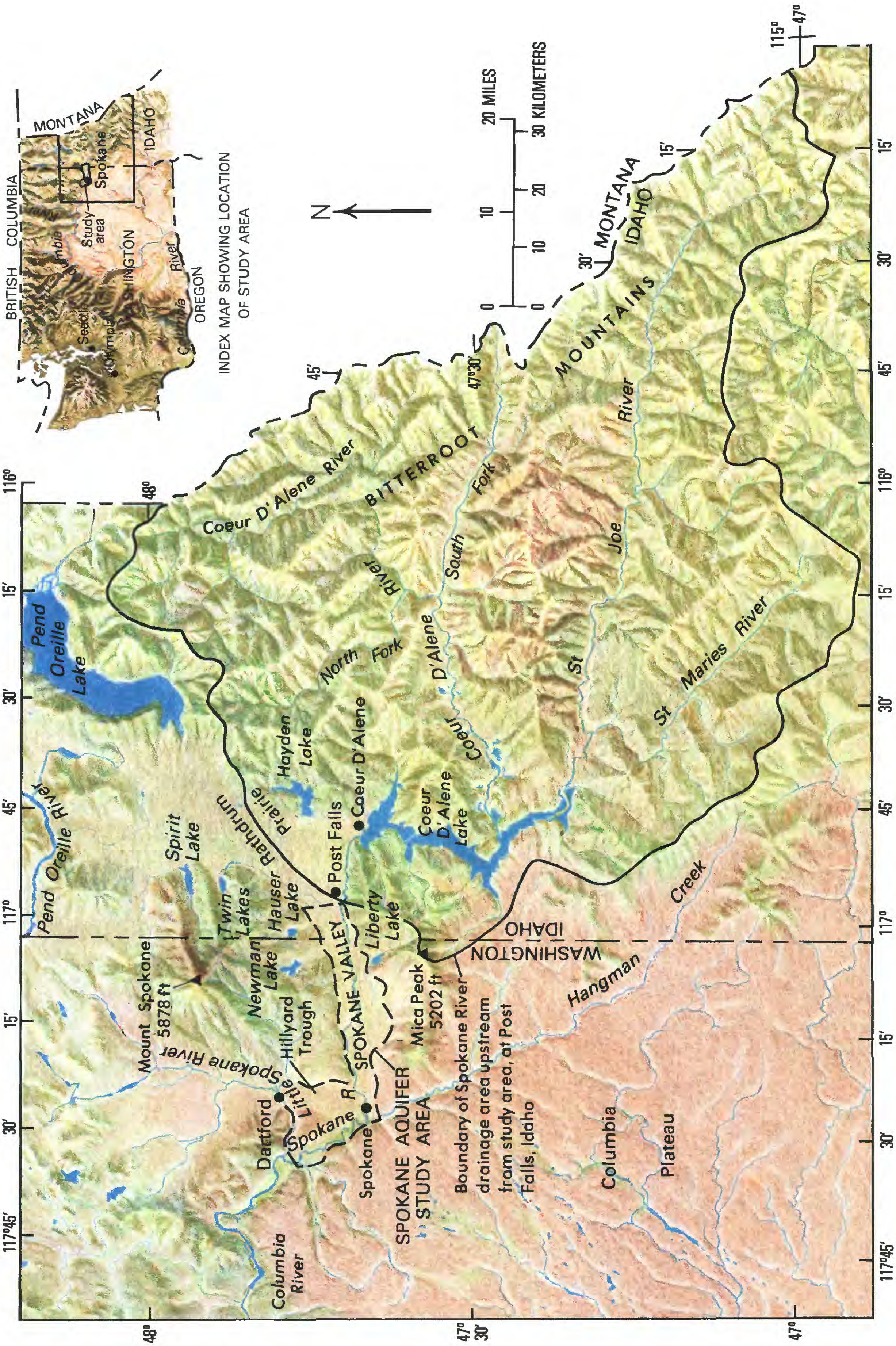
The Size and Shape of the Study Area

The Spokane aquifer underlies the Spokane Valley, a lowland area about 30 miles long, between 3 and 8 miles wide, and covering about 135 square miles in the lower part of the 6,640-square-mile Spokane River basin in eastern Washington and northern Idaho. The location of the area underlain by the Spokane aquifer as defined for this report is outlined in figure 1 and shown in detail in figure 2. The aquifer underlies the relatively flat floor of the Spokane River valley between Post Falls, Idaho, at an elevation of 2,178 feet, and near the confluence of the Little Spokane River below Spokane, at an elevation of 1,545 feet. In Idaho, the broad valley floor comprises the lower 4 miles of the southwesterly trending Rathdrum Prairie, and, in Washington, the valley trends westerly from the State line to the vicinity of Spokane, where it trends northward to the confluence with the Little Spokane River. Downstream from the study area, the valley becomes narrow, and the river is deeply entrenched along its 60-mile northwesterly course to the Columbia River. Immediately north of the Spokane city limits, the valley floor is separated into two segments by Fivemile Prairie, a plateau "island" capped by flat-lying basalt. West of the plateau, the valley floor follows the Spokane River to the confluence with the Little Spokane River, and, to the east, as the Hillyard Trough, it extends to the Little Spokane River below Dartford.

The valley is flanked by two relatively isolated highland outliers of the Selkirk Mountains; these culminate on the north at 5,878-foot Mount Spokane and on the south at 5,205-foot Mica Peak (fig. 2). Immediately adjacent to the valley sides are plateau remnants of basalt flows; these include Fivemile, Orchard, Pleasant, Peone, and Manitou Prairies.

The city of Spokane, the principal center of population, is situated in the western part of the Spokane valley. To the north and east are the incorporated towns of Mead, East Spokane, Opportunity, Millwood, Dishman, and Greenacres in Washington and Post Falls in Idaho. Often referred to as the "Capital of the Inland Empire," the city of Spokane has had a nearly steady growth since 1890, when the population was about 20,000; by 1979, the population was

Figure 1. Location of the Spokane aquifer study area and the Spokane River drainage basin upstream from the study area.


INDEX MAP SHOWING LOCATION OF STUDY AREA
BRITISH COLUMBIA
MONTANA
IDAHO
WASHINGTON
OREGON
Spokane
Study area
Seattle
Olympia
Columbia River
N
0 10 20 MILES
0 10 20 30 KILOMETERS
MONTANA
IDAHO
BITTERROOT MOUNTAINS
Coeur D'Alene River
North Fork River
South Fork
Coeur D'Alene
St Joe River
St Maries River
Coeur D'Alene Lake
Coeur D'Alene
Hayden Lake
Pend Oreille Lake
Pend Oreille River
Spirit Lake
Rathdrum Prairie
Post Falls
Twin Lakes
Hauser Lake
Liberty Lake
Newman Lake
SPOKANE VALLEY
Hillyard Trough
Mount Spokane 5878 ft
Mica Peak 5202 ft
Spokane River
Little Spokane
Dartford
Spokane R
Spokane
SPOKANE AQUIFER STUDY AREA
Boundary of Spokane River drainage area upstream from study area, at Post Falls, Idaho
IDAHO
WASHINGTON
Hangman Creek
Columbia Plateau
Columbia River
48°
47°30′
47°
116°
117°
117°45′
115°
15′
30′
45′

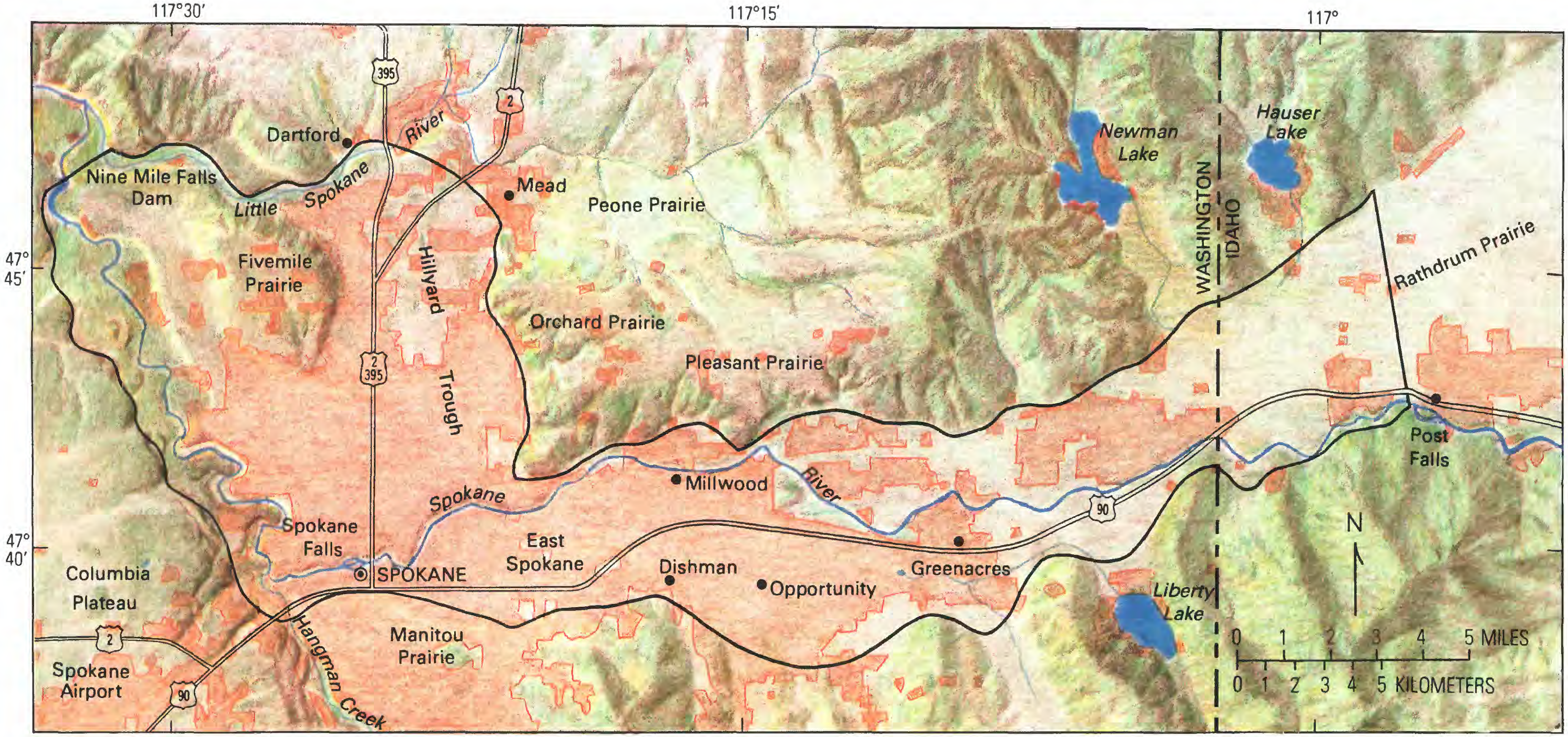


Figure 2. Topographic setting of the study area, showing drainage, principal towns and highways, and areas of developed land. Orange indicates areas of urban, suburban, commercial, and industrial development, as of 1978.

179,200. Recent growth in the eastern part of the valley has included increased suburban residential developments, which have caused county and municipal officials concern over the associated problems of adequate supplies of good-quality water for public and industrial uses.

The water supply for the residents and industries of the Spokane area depends largely on ground water obtained from the Spokane aquifer, which is a thick, highly permeable deposit of coarse sand and gravel that underlies the valley floor. The Spokane aquifer was defined in 1978 by the U.S. Environmental Protection Agency as a "Sole Source Aquifer" or "Principal Aquifer," under provisions of the Federal Safe Drinking Water Act of 1974. By this designation, the aquifer was considered to be the only economically obtainable source of water supply that was of adequate quality and quantity. Because of the "Sole Source" designation, a better understanding of the aquifer and its close relation with the surface-water system was considered important to its protection against potential water-quality degradation resulting from man's land and water-use practices. As a result, several studies of the surface- and ground-water systems and their interrelations were made, and the findings were published in various technical reports. A list of those reports is given at the end of this publication.

The varied topography of the Spokane region—the rugged, high Bitterroot Mountains on the east and north, the relatively flat expanse of the Columbia Plateau on the southwest, and the broad floor of Rathdrum Prairie and Spokane Valley—results from a variety of geologic events in the distant past. These include (1) uplift and deep erosion of ancient mountain ranges that extended across the northeastern part of the State, (2) subsequent widespread extrusion of basalt lava flows that extended to and partly inundated the foothills of the old mountains, with associated lava-dammed drainages occupied by large lakes, (3) subsequent erosion by streams draining the mountains on the north and east, resulting in a deepening of the ancestral lower Spokane Valley floor, from an elevation of about 2,500 to about 1,500 feet (about 500 feet lower than the present valley floor), (4) movement into the area of glacial ice from the north, with erosion of the mountains and deposition of sands and gravels in the lowlands, and (5) catastrophic inundation by the Spokane Floods, which resulted from periodic breakage of ice dams that impounded Glacial Lake Missoula.

The lava flows produced the plateaus that abut the mountains in the southwestern part of the region. The glacial ice moving southward from Canada produced the steep-sided, north-south-trending mountain ranges and intervening valleys north and northeast of the Rathdrum Prairie–Spokane Valley lowland, including the deep troughs containing Pend Oreille and Coeur D'Alene Lakes. The catastrophic floods produced the deeply cut surface of the Columbia Plateau on the southwest and resulted in deposition of the coarse sands and gravels in the Spokane Valley study area to form the Spokane aquifer.

Climate

The Spokane region has warm, dry summers and cool, moist winters. The area's climate ranges from subhumid in the mountains to semiarid in the Spokane Valley. Average annual precipitation is more than 70 inches in the headwater areas of the basin (near the 6,500-foot crest of the Bitterroot Mountains in Idaho) and less than 20 inches in the Spokane Valley study area. Most of the precipitation occurs during the period November–March (fig. 3), and much of it falls as snow, especially in the mountains. In the vicinity of Spokane, winter snowfall frequently accumulates to depths of a foot or more, but it usually melts in a few days.

Water on the Land: Streams and Lakes

Streamflow in the Spokane Valley and immediately bordering uplands is perennial only in the Spokane and Little Spokane Rivers and in Hangman Creek (designated in streamflow records as Latah Creek until 1958). Several streams drain areas of the adjacent uplands, but their flows cease along the valley margins, where the waters sink into the highly permeable valley-floor materials; these include the outlet streams of several lakes (fig. 2). A few short streams carry intermittent flows into the Spokane River along the plateau margins, but their drainage areas are small, and runoff is mostly from snowmelt during the spring.

Three natural lakes occupy tributary valleys along the margins of the study area. These include Newman and Hauser Lakes on the north side of the valley and Liberty Lake on the south side. As noted above, surface discharges of these lakes rapidly sink into the valley-floor materials.

The Valley's Culture and Economy

The city of Spokane is the business and cultural center of the Spokane Valley, which has

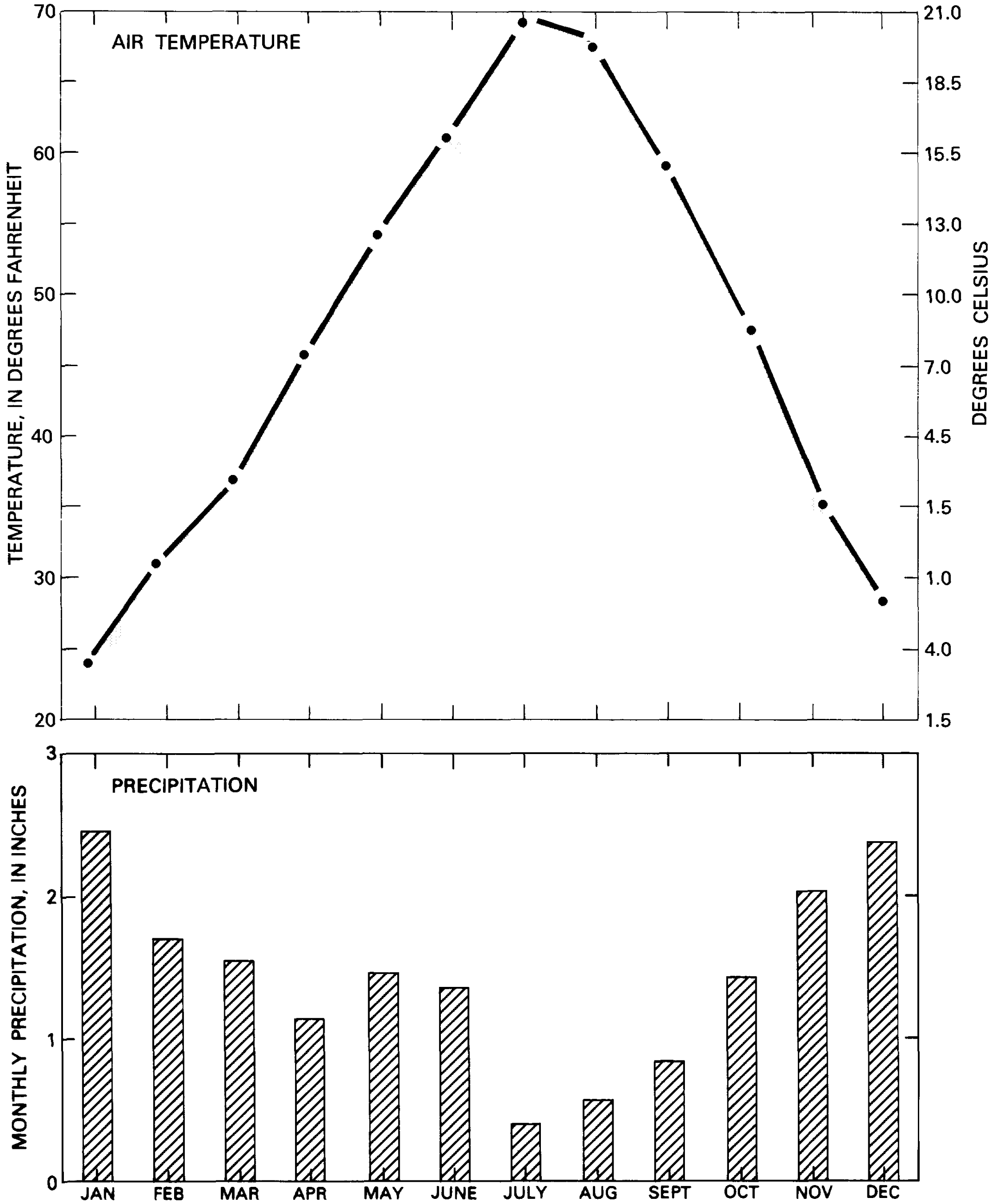


Figure 3. Average monthly precipitation and air temperature at Spokane Airport. (Data from the National Climate Center, 1978.)

an economy based on industry, agriculture, transportation, and trades and services. The principal agricultural products are grass seed, dairy products, poultry, apples, and truck vegetables, and the principal industrial activity is an aluminum processing plant and rolling mill.

Settlement of the valley began in the late 1800's as agriculture started to develop near the city of Spokane. Irrigated farming in parts of the valley was started about 1905, and the increasing agricultural growth was accompanied by industrial, commercial, and transportation enterprises. During the 1910–20 decade, several industrial plants were established, including a paper mill, a cement plant, and several large lumber mills. World War II brought substantial industrial growth, including an aluminum plant at Mead, north of Spokane, and an aluminum rolling mill at Trentwood. The population of the valley doubled during each decade between 1910 and 1950.

As industrial developments in the valley increased, farmland was subdivided into small acreages for part-time farming and suburban living, and many small communities and business districts were established. The increase in suburban growth resulted in a corresponding decrease in the area of agricultural land.

A Closer View: The Geologic Story

The Spokane Valley is a product of geologic events that have modified the landforms and rock types of the area over millions of years. Our understanding of these events and of the order in which they occurred provides a better comprehension of the occurrence of ground water in the area. The geologic time scale is shown in figure 4; this is according to age estimates by Sohl and Wright (1980). For easier comprehension, the illustration includes a column that relates the various periods of the Earth's geologic past to a calendar year, with January 1 representing 3.6 billion years ago, the estimated age of the oldest known rocks found in the United States. This will provide the reader with a greater appreciation of the magnitude of geologic time and of the relative recency of the events that shaped the landscape of the Spokane area; for example, from the chart conversion of the age of the Earth to a year, we can see that the 2-million-year Pleistocene Epoch began about 7 p.m. on New Year's Eve; by this standard, the final catastrophic Spokane Flood, which profoundly affected the study area about 14,000 years ago, would have occurred at about 2 minutes before midnight.

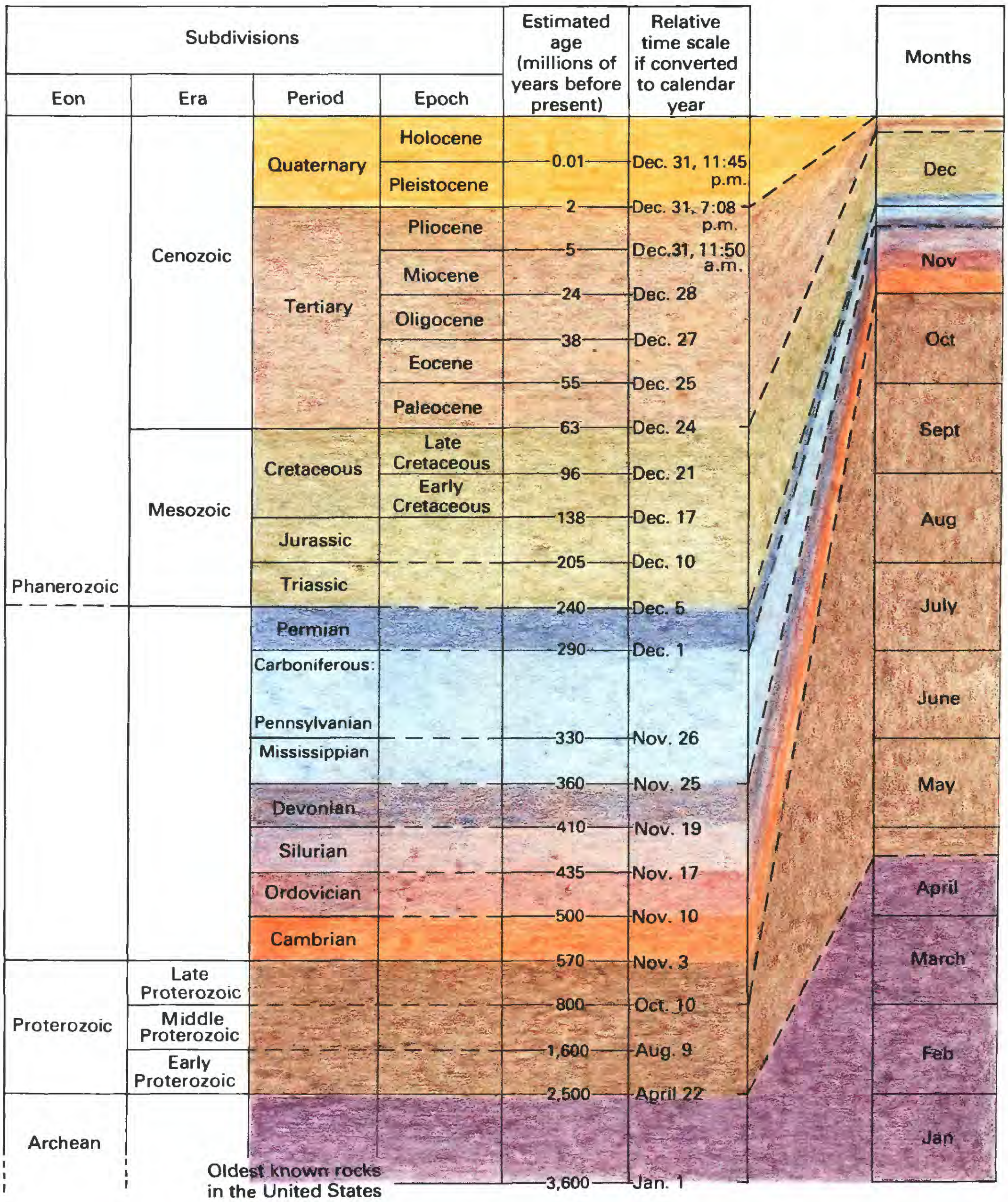


Figure 4. Generalized geologic time scale, including conversions to show time units relative to a calendar year.

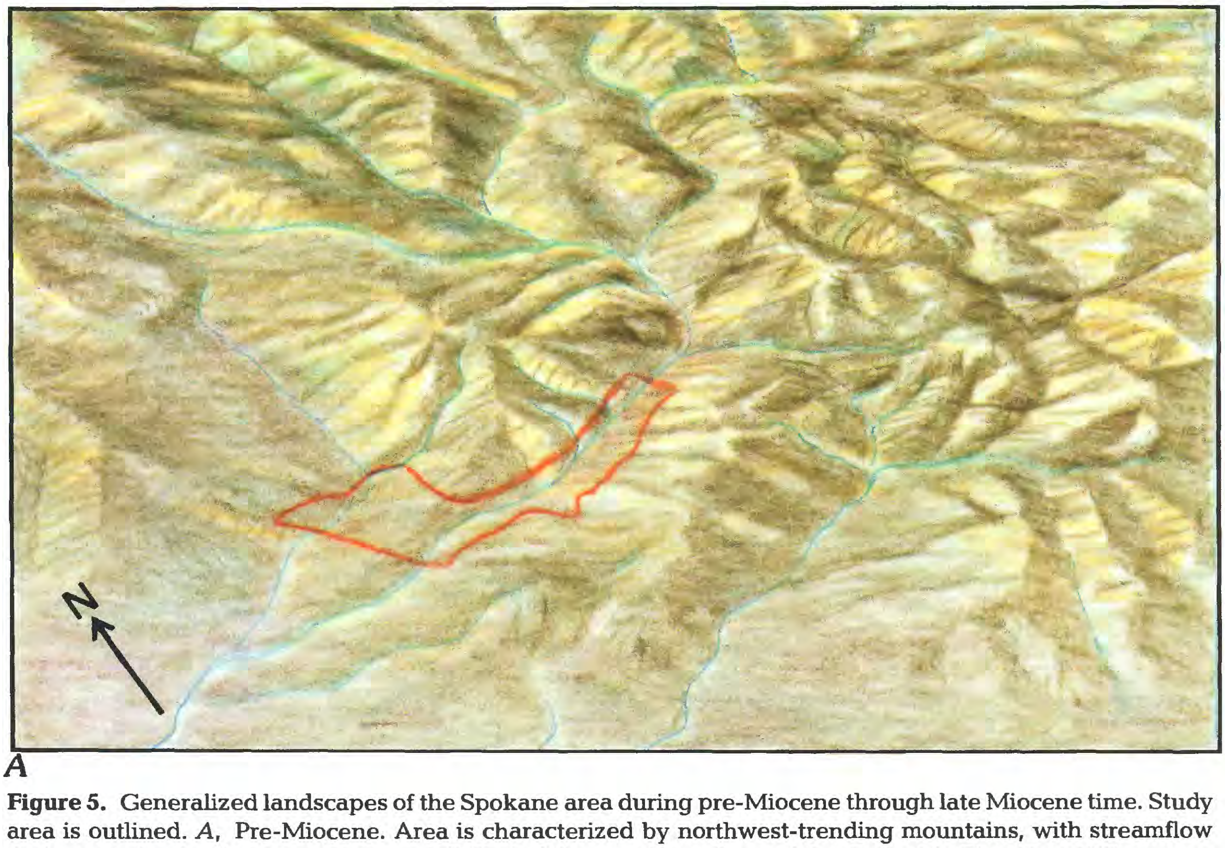
The Pre-Miocene Landscape

The oldest rocks in the Spokane region are metamorphic rocks of Precambrian age. These and other igneous and metamorphic rocks of pre-Tertiary age underlie the Spokane Valley at depth and compose the adjacent mountains; they form the base upon which the younger rocks are laid. The ancient rocks have been deeply eroded and, therefore, have a surface of considerable relief, probably 4,000 feet or more in some places. These rocks formed a northwesterly trending mountain range with a surface that was higher in the north and east and lower toward the southwest (fig. 5). The ridge crests and valley bottoms of these older mountains had relatively gentle, rounded forms. Streams draining the mountains flowed to lowlands to the southwest.

The Miocene Landscape

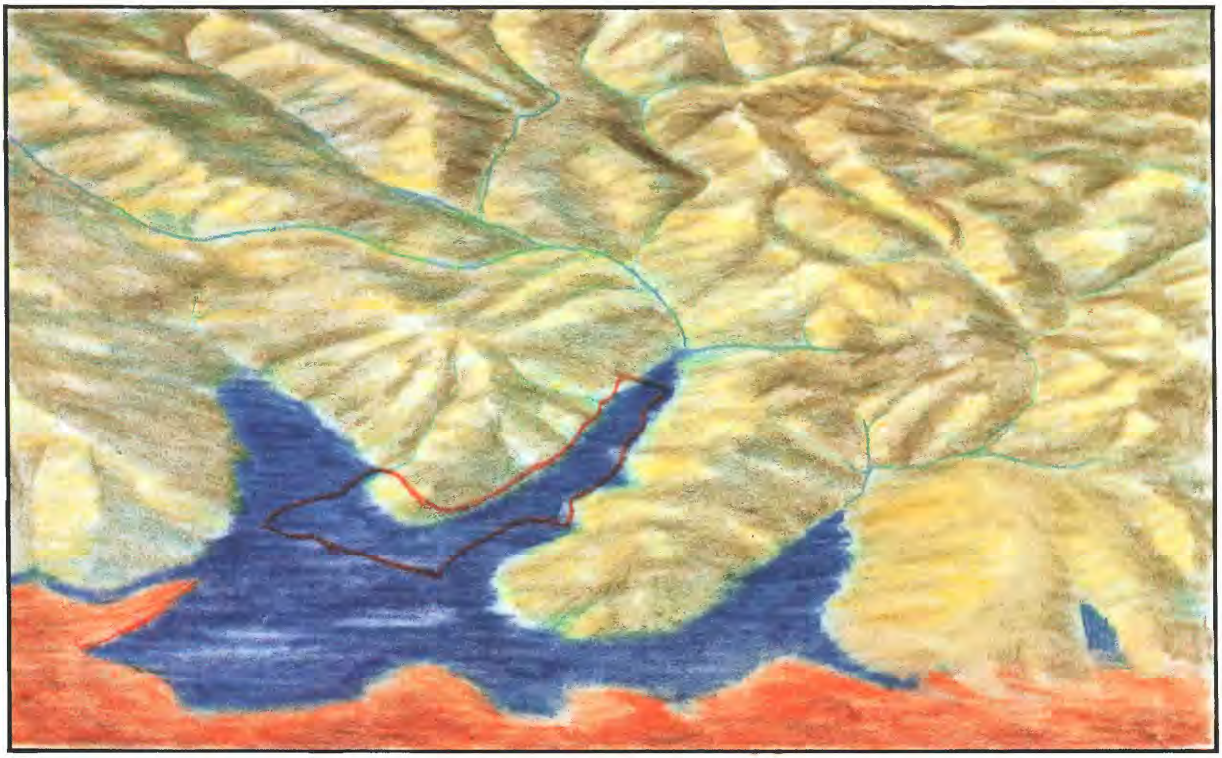
Between 5 and 24 million years ago, during the Miocene Epoch of late Tertiary time, extensive flows of basaltic lava, known as basalt of the Columbia River Basalt Group (which also includes interlayers of sedimentary materials), flooded a vast region of more than 100,000 square miles in parts of Washington, Oregon, and Idaho, including the present Spokane Valley. In many separate flow units, some more than 75 feet thick and with the total thickness in places attaining more than 10,000 feet, the lavas were extruded over many millions of years from long fissures situated to the south and southwest, covering the lower valleys and foothills and abutting the present mountains. The flows blocked stream drainages, including those of the ancestral Spokane and Columbia Rivers, and repeatedly formed small- to medium-sized lakes; at the bottoms of the lakes were deposited fine-grained sediments eroded from adjacent uplands. Named the Latah Formation, the lake-bottom deposits overlie some older basalt flows and underlie a few younger flows; these rock sequences are exposed in valley sides south, west, east, and north of Spokane. The photographs of figure 6 show selected exposures of the basalt and the Latah Formation.

Following the outpouring of the basalt, the ancestral Spokane River cut its course in what is essentially its present valley between the Idaho



A

Figure 5. Generalized landscapes of the Spokane area during pre-Miocene through late Miocene time. Study area is outlined. *A*, Pre-Miocene. Area is characterized by northwest-trending mountains, with streamflow drainage to lowlands in the southwest. *B*, Early Miocene. Lava flows of the Columbia River Basalt Group are extruded from fissures in the Columbia Plateau area southwest of the Spokane area and extend into the study area, blocking drainages and creating lakes into which silts and clays of the Latah Formation are deposited. *C*, Late Miocene. Basalt lava flows extend up valleys of the Spokane area, and lake deposits of the Latah Formation are extended farther up the valleys.



B

C

Figure 5. Continued.

border and the city of Spokane. However, the ancient valley floor was probably at least 900 feet lower than the surface into which it was cut (represented by the surface that includes Fivemile and Orchard Prairies) and 500 feet lower than the present Spokane Valley floor. The ancestral river cut into the Latah Formation and some younger basalt units in the process. North of Spokane, the river's course probably followed the Hillyard Trough on the east side of

Figure 6. Exposures of the Latah Formation and of basalt flows of the Columbia River Basalt Group. *A*, Silt and clay of the Latah Formation capped by a basalt lava flow, at 24/42–11. *B*, Aerial view to the north over the basalt flow capping the southwestern end of Orchard Prairie, at 25/43–2, with the Spokane River below. *C*, Columnar-jointed basalt, at 25/42–27B.

the basalt plateau of Fivemile Prairie. The river then turned westward, along the lower present reach of the Little Spokane River Valley, and then rejoined the present main valley. The deep valley thus formed was the trough into which were subsequently deposited glacial outwash sands and gravels and then the coarser sands and gravels of the Spokane Floods, which today form the Spokane aquifer.

The Pleistocene Landscape

Ice Sheets and Glacial Lakes

Between about 10,000 and 2 million years ago, during the Pleistocene Epoch (or Ice Age), the Earth's climate underwent periods of alternate cooling and warming. During the periods of cooling, with an average annual temperature probably between 5 and 10 degrees Fahrenheit cooler than that at present, vast continental ice sheets grew in and extended far beyond the polar regions. In addition, alpine glaciers developed locally in the higher mountains. In southern Canada, the ice sheets periodically thickened and advanced southward, some reaching the northern parts of the United States before retreating (melting back) to the north as the climate again became warmer. Evidence indicates that at least four, and perhaps six or more, major glaciations affected the study area. The last of these, which occurred between 12,000 and 22,000 years ago and had the most significant effect on the present landscape, is described here.

The Cordilleran Ice Sheet, as it is known, was that part of the southward-moving continental ice mass that covered much of the Rocky Mountains Cordillera in Canada and eventually extended into the northern part of the United States. In the western part of Washington State, it covered parts of the northern Cascade Range and the northern margins of the Olympic Mountains, and a thick ice lobe (a separate "tongue" of the glacier mass) extended down the Puget lowland, and, in eastern Washington, ice lobes extended down the principal valleys and onto the margins of the Columbia Plateau. The Spokane area was covered partially by ice lobes that advanced from the north down the Purcell Trench and present valleys of the Priest and Pend Oreille Rivers. Melt-water streams draining these lobes carried large quantities of sand, gravel, silt, and clay and deposited these in and along the lower valleys. The deeply entrenched Spokane Valley was filled partially with these glacial materials.

Eventually, the Purcell ice lobe moved into the valley of the north-flowing Clark Fork River, northeast of the Spokane Valley, and formed a massive ice dam across the valley. At the maximum advance of several advances and retreats, the dam was nearly 2,150 feet high—about four times the height of Grand Coulee Dam. As a result, melt water from other ice lobes far up the Clark Fork River drainage became ponded behind the ice dam and eventually formed a vast lake, Glacial Lake Missoula, which occupied the intricate system of valleys in northern Idaho and western Montana (fig. 7). At its highest level, the lake covered an area of about 3,000 square miles and contained an estimated 500 cubic miles of water—one-half of the volume of present-day Lake Michigan. At the same time, many other lakes were formed by the melt water from local mountain glaciers and snowfields elsewhere in the valleys and basins of the Northwest interior.

Traces of the ancient shorelines of Glacial Lake Missoula in western Montana indicate that, at its maximum elevation, the lake was about 950 feet deep at present-day Missoula and more than 1,100 feet deep at the south end of Flathead Lake. The lake's wave-cut shorelines are faint, however, suggesting that no one level of the lake was of long duration. The close spacing of the shorelines may indicate one or more of the following possibilities: (1) successive water levels as the lake gradually filled, (2) periodic loss of water as the ice dam was breached partially, or (3) seasonal variations in contributions of melt water from other glaciers draining into arms of the lake.

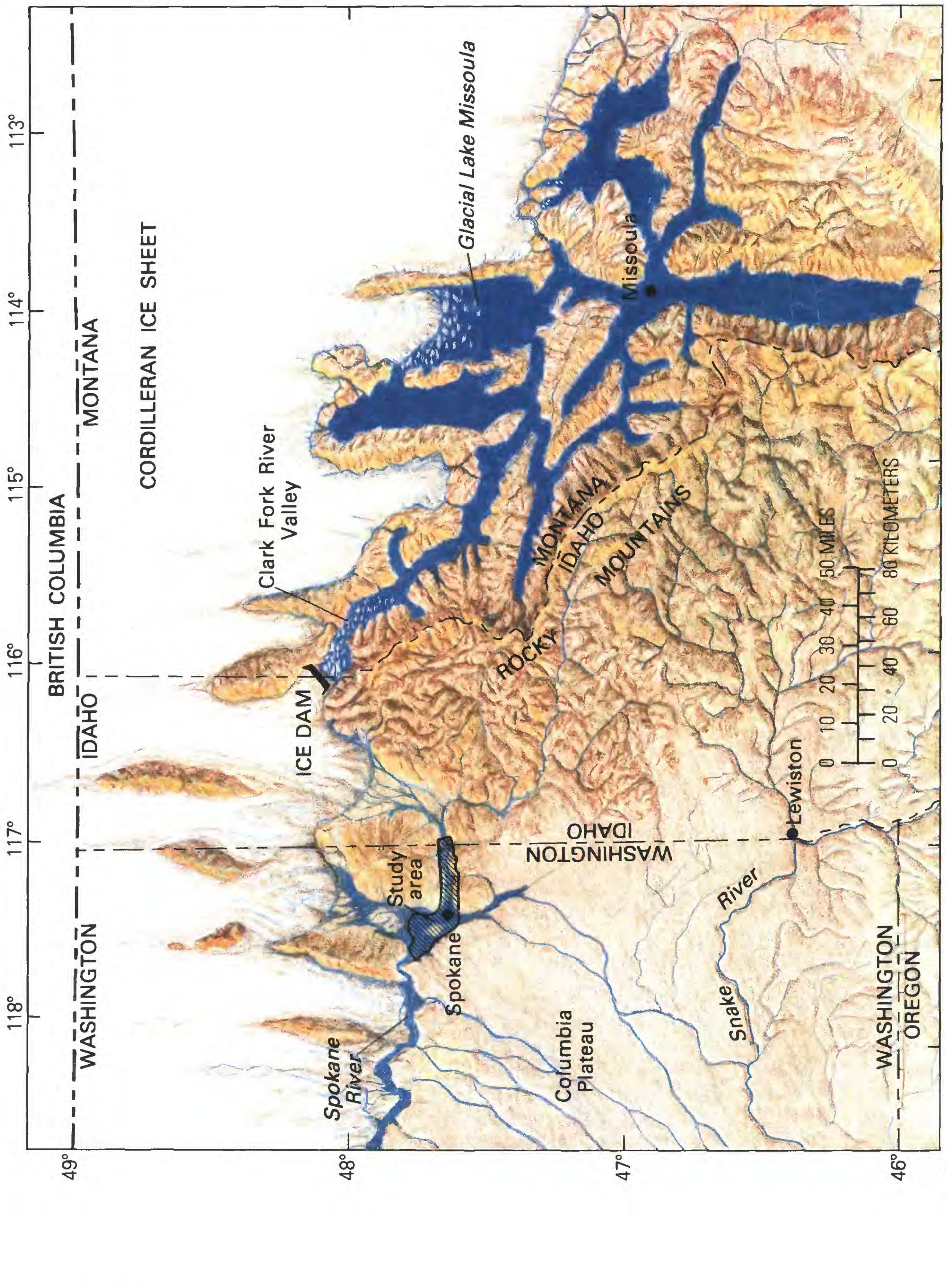
The Spokane Floods

The water surface of Glacial Lake Missoula probably varied most significantly because of periodic advances and retreats of the ice as it blocked the valley of the Clark Fork River and of the lake water partially draining out over and around the crest of the ice dam many times. Evidence indicates, however, that, in its final stage, the ice attained a maximum blockage that set the stage for what most geologists now believe to have been the largest flood event the world has ever known. After rising to its highest stage (water-surface elevation), Glacial Lake Missoula eventually overtopped the lowest part of the ice dam, and an outlet stream began flowing across the ice. The stream of melt water rapidly cut downward into the ice and then laterally undercut its channel sides, weakening the glacial dam. Finally, the ice dam could no longer withstand the tremendous pressure and cutting power of the increasing volume of water pouring through the breach, and the dam gave way completely. The resulting rapid draining of 500-cubic-mile Glacial Lake Missoula—probably in only a few days—resulted in a maximum discharge across the Columbia Plateau calculated by Baker (1973) to be 750 million cubic feet per second—20 times the combined flow of all the rivers of the world today.

The floodwaters of the lake rapidly shot southwestward down the length of the present sites of Pend Oreille and Coeur D'Alene Lakes and the Rathdrum Prairie–Spokane Valley area and out across the Columbia Plateau beyond (fig. 8). Attaining speeds estimated to be as great as 45 miles per hour, the water swept across the Columbia Plateau, through the Pasco and Umatilla Basins, down the Columbia River Gorge, and eventually into the Pacific Ocean beyond the Coast Range. The most prominent testimony to the cutting power of the floodwaters is observed clearly today in the numerous coulees carved into the basalt surface of the Columbia Plateau; this forms an area of unique topographic relief known as the channeled scabland (Bretz, 1930). Other features that indicate the magnitude of the flood event and the amount of rock debris carried and dumped along the flood's pathway include giant current ripples and gravel bars, some more than 50 feet high and 500 feet between crests. These are found today along much of the flood's course, from the valleys of western Montana to the lowlands along the Columbia River beyond the Cascade Range.

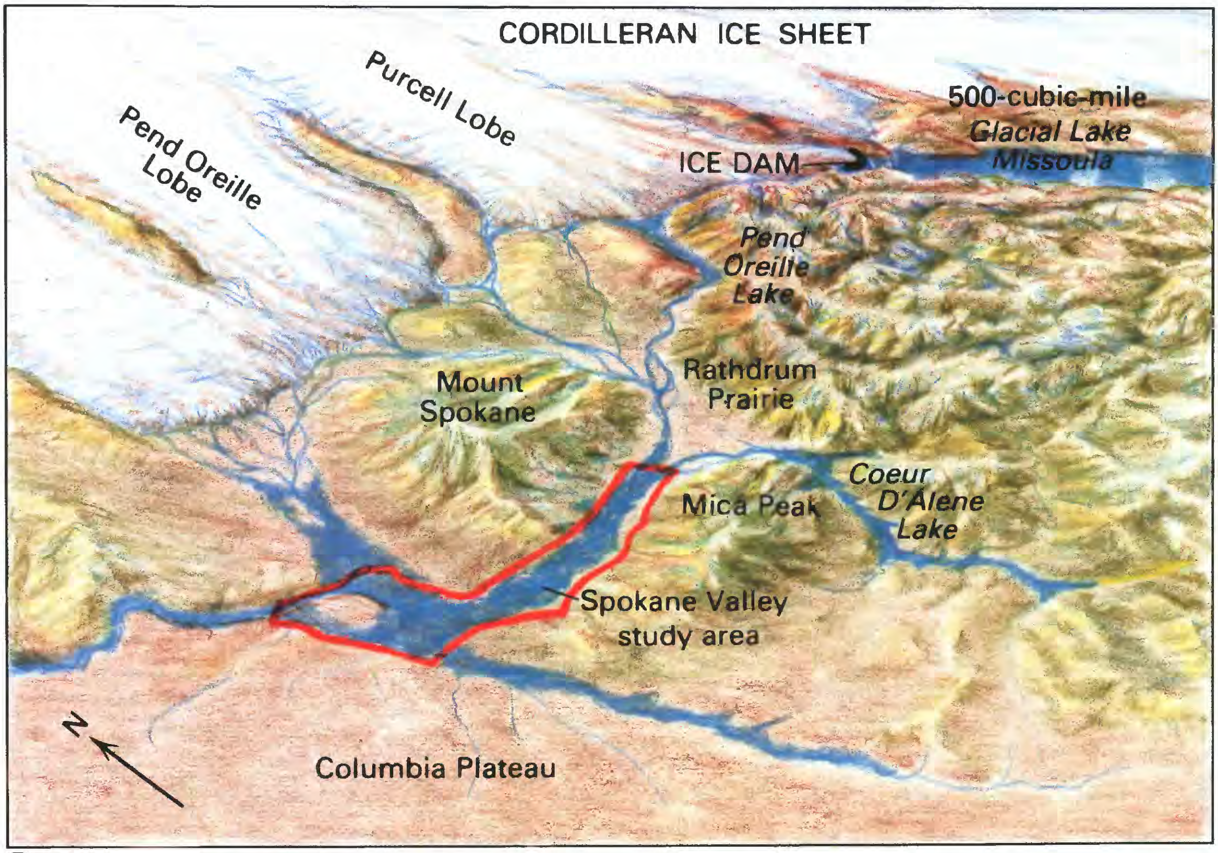
Along its journey to the ocean, at various reaches where the river valley narrows, the floodwater was impounded temporarily by restrictions and formed several large temporary lakes. These include (1) Lake Lewis in the Pasco Basin above Wallula Gap and extending upstream along the Snake River beyond Lewiston, Idaho, (2) Lake Umatilla (also known by geologists as Lake Congdon) in the Umatilla Basin above the Columbia Gorge, and (3) Lake Allison in the Willamette Valley above the restriction below Longview. The lakes formed along the path of the final Spokane Flood are shown in figure 8, which presents a generalized view of the Pacific Northwest during the near-maximum extent of Pleistocene glaciers and related lakes.

In passing through the Rathdrum Prairie–Spokane Valley area, the floodwaters carried large volumes of rock debris in the masses of ice broken from the glacier's morainal terminus, which included large boulders that



CORDILLERAN ICE SHEET
Glacial Lake Missoula
Missoula
BRITISH COLUMBIA
MONTANA
IDAHO
WASHINGTON
Clark Fork River Valley
ICE DAM
ROCKY
MONTANA
IDAHO
MOUNTAINS
Study area
Spokane
Spokane River
Columbia Plateau
Snake River
Lewiston
WASHINGTON
IDAHO
WASHINGTON
OREGON
0 10 20 30 40 50 MILES
0 20 40 60 80 KILOMETERS
113°
114°
115°
116°
117°
118°
49°
48°
47°
46°

A



B

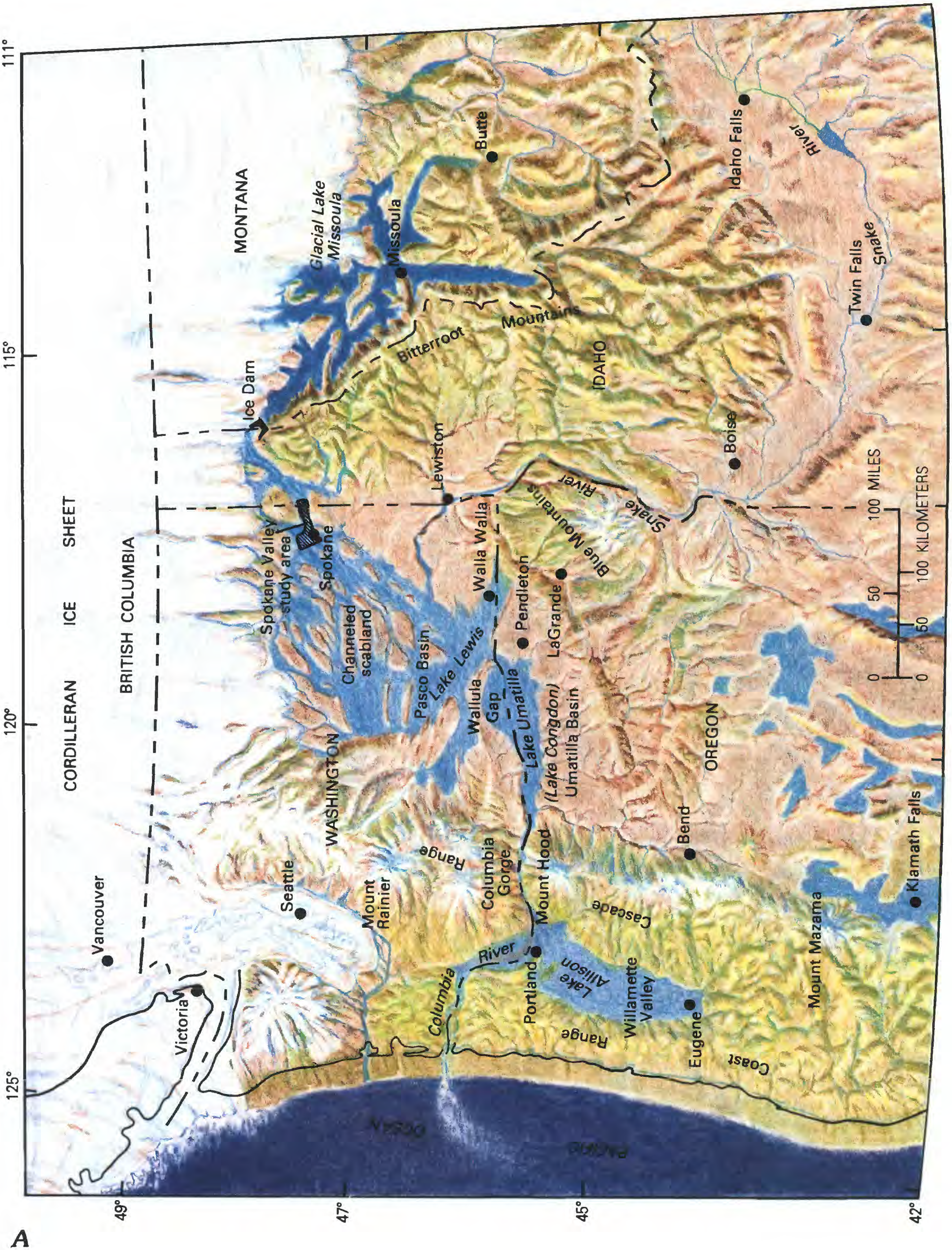
Figure 7. Views of the ponding effects of the Cordilleran Ice Sheet. *A*, The ice dam of the Cordilleran Ice Sheet blocked the Clark Fork River valley and formed Glacial Lake Missoula in the mountains of western Montana. *B*, View to the northeast over the Spokane region, showing the Purcell lobe of the Cordilleran Ice Sheet blocking the Clark Fork River valley. The Spokane aquifer area is outlined.

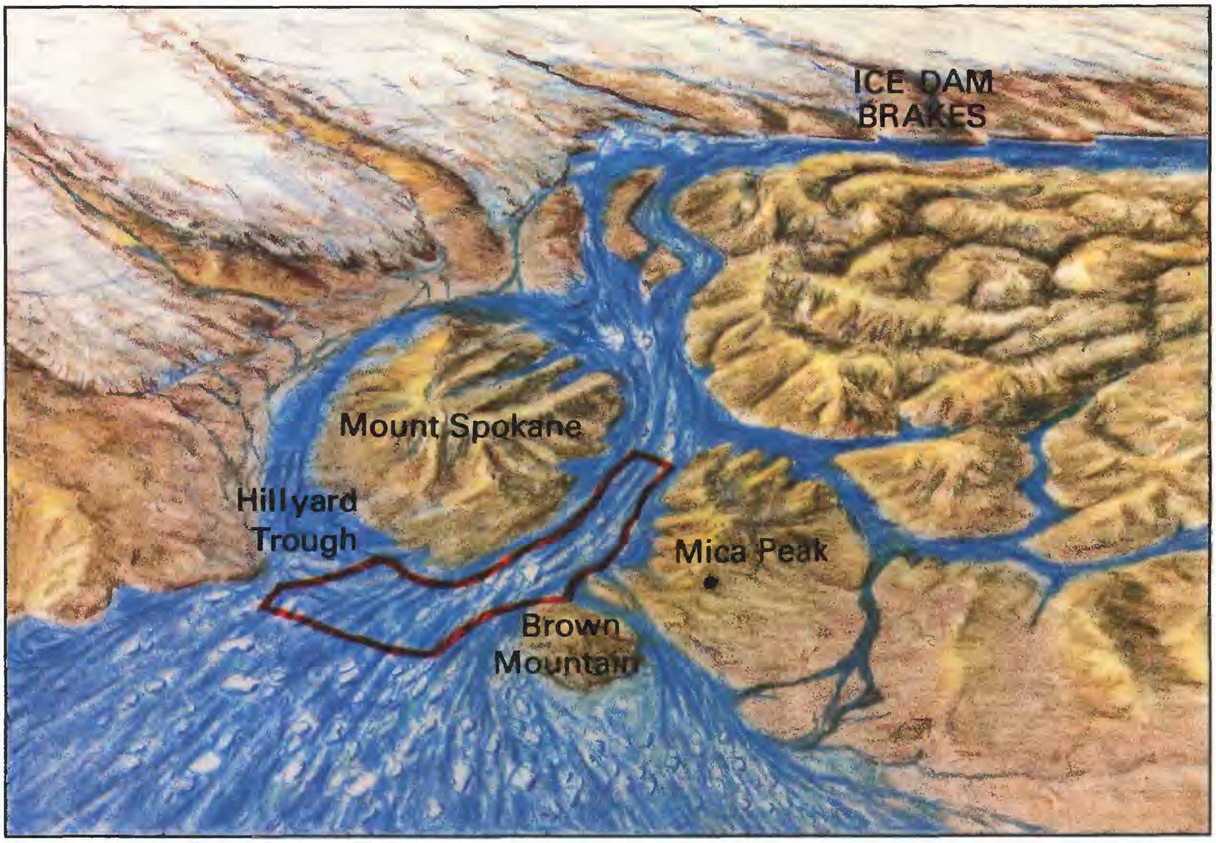
came from the mountains farther north. The flood carried great quantities of sediment of all sizes, from clay particles to large cobbles and boulders, picked up from the flood channels. The heavier, large materials, such as boulders, cobbles, and coarse gravel, were deposited first. These coarse materials were deposited along the main valley in the line of greatest flow and velocity; much of these materials were deposited on top of the previously deposited "normal" glacial outwash silts, sands, and gravels. Some of the smaller particles in these earlier outwash materials were "winnowed out" (separated from) and carried in suspension, then eventually either deposited in side "eddy" valleys, such as the Hillyard Trough, or carried out onto the Columbia Plateau and beyond. Thus were deposited the coarse materials that today underlie the Rathdrum Prairie–Spokane Valley lowland; some isolated localities contain boulders as much as 8 or 10 feet across. These flood deposits form the present, highly permeable aquifer beneath the Spokane Valley study area (fig. 9).

The Holocene Landscape

The subsidence of the floodwaters following the final emptying of Glacial Lake Missoula was followed by a gradual northward retreat of the Cordilleran Ice Sheet, and, eventually, during Holocene (recent) time, the region acquired its present aspect and drainage system (fig. 1). After the disappearance of the ice from the Pend Oreille Valley north of the study area, the Clark Fork River drained through Pend Oreille Lake and then west and north to the Columbia River. To the east, the Coeur D'Alene, St. Joe, and St. Maries Rivers drained to Coeur D'Alene Lake, the source of the Spokane River. The broad, flat, gravel-filled flood pathway between Pend Oreille Lake and the Spokane Valley became virtually devoid of a surface drainage system, with streams from marginal side valleys flowing only short distances before sinking into the coarse materials.

In the study area, the Spokane River resumed its course westward to Spokane; then, instead of flowing north through the Hillyard Trough, which now had a higher surface


CORDILLERAN ICE SHEET
BRITISH COLUMBIA
MONTANA
WASHINGTON
IDAHO
OREGON
Glacial Lake Missoula
Missoula
Butte
Ice Dam
Bitterroot Mountains
Spokane Valley study area
Spokane
Lewiston
Channeled scabland
Pasco Basin
Lake Lewis
Walla Walla
Wallula Gap
Lake Umatilla
(Lake Condon)
Umatilla Basin
Pendleton
LaGrande
Blue Mountains
Snake River
Boise
Idaho Falls
Twin Falls
Snake River
Vancouver
Victoria
Seattle
Mount Rainier
Range
Columbia Gorge
Mount Hood
Columbia River
Portland
Lake Allison
Willamette Valley
Cascade
Eugene
Range
Coast
Bend
Mount Mazama
Klamath Falls
PACIFIC OCEAN
111°
115°
120°
125°
49°
47°
45°
42°
0 50 100 MILES
0 50 100 KILOMETERS
A



B

Figure 8. The Pacific Northwest during late Pleistocene time. *A*, The margin of the Cordilleran Ice Sheet, Glacial Lake Missoula, temporary lakes along the path of the last of the Spokane Floods, and other lakes of the interior. *B*, Water in Glacial Lake Missoula rises and cuts a channel through the ice dam, which is rapidly widened until the dam fails and the lake empties down the Spokane Valley and across the Columbia Plateau. The Spokane Flood waters have profound erosive and ponding effects all the way to the Pacific Ocean.

created by flood deposits, the river followed a new, lower course along the margin of the Columbia Plateau lava to its confluence with the Columbia River.

A few small lakes remained in the lower parts of tributary mountain valleys. Although their outlets were dammed originally by terminal moraines of local alpine glaciers, the morainal blockages were partially increased—and streamlined—by the flood gravels. They include Spirit, Twin, Hauser, and Newman Lakes on the lower east and south flanks of the Spokane Mountain area, Hayden Lake at the base of the Coeur D'Alene Mountains, and Liberty Lake below Mica Peak. Discharges from the lakes percolated rapidly into the main valley gravels, and only a few short stream channels were formed.

As the climate became warmer, vegetation began developing over the area; eventually coniferous forests covered parts of the adjacent uplands and mountains, and cottonwoods and other deciduous trees, along with small groups of conifers, lined the river channel. Parts of the valley floor and nearby slopes became covered by grasses and other small plants. This was the Spokane Valley as inhabited by Indians when first visited by the early white explorers, fur trappers, and traders.

Figure 10 presents a generalized cutaway block diagram of the geologic units underlying the Spokane area, and the photographs in figure 11 show selected aerial views of the Spokane Valley, the Spokane River, and principal lakes along the valley margins.

The Hydrologic Cycle: Where Does the Water Come From and Where Does It Go?

The Spokane Valley has an ample supply of water from the Spokane River and from the valley's highly permeable aquifer. The combination of heavy precipitation in the mountainous headwaters, including rain and snowfall (with snowpack storage for release during the spring and summer), and the highly permeable character of the aquifer help to ensure abundant water supplies for the Spokane Valley for many years to come. However, the natural system also responds to changes resulting from man's activities in the basin, his use of the water, and his methods of disposing of wastewater. Therefore, for man to properly manage and protect the quantity and quality of the Spokane aquifer, it is essential that he understand the natural hydrologic cycle, of which the aquifer and the Spokane River are integral parts.

Figure 12 diagrammatically illustrates the natural hydrologic cycle as it applies to the Spokane Valley. Water enters the valley by way of precipitation, inflow from the Spokane River, and ground-water underflow. Most underflow is from beneath the Rathdrum Prairie in Idaho, but some is from beneath small tributary valleys along the aquifer margins, such as at Liberty Lake. Water leaves the valley (1) below Nine Mile Falls as discharge of the Spokane River and as ground-water underflow from the aquifer, (2) by evapotranspiration, and (3) by pumpage from wells and diversions from the river. However, part of the water pumped and diverted by man eventually is returned to the ground-water system by percolation or is lost to evapotranspiration. Some water is returned to the Spokane River by discharges of treated sewage water.

The hydrologic cycle is the pattern of water movement as it circulates through the natural system. It includes precipitation from

Figure 9. Surface exposures of materials deposited during the Spokane Floods. *A*, Aerial view northeast to the gravel quarry, at 25/43–13. The pond indicates the proximity of the water table to the land surface. *B*, Coarse gravel exposed in the quarry, at 25/43–13. *C*, Flood gravels at top, overlying the normal glacial outwash deposits of sand and finer gravel, above the east side of Hangman Creek, at 25/42–31M. *D*, Closeup view showing the coarseness of the gravels, with many cobbles.

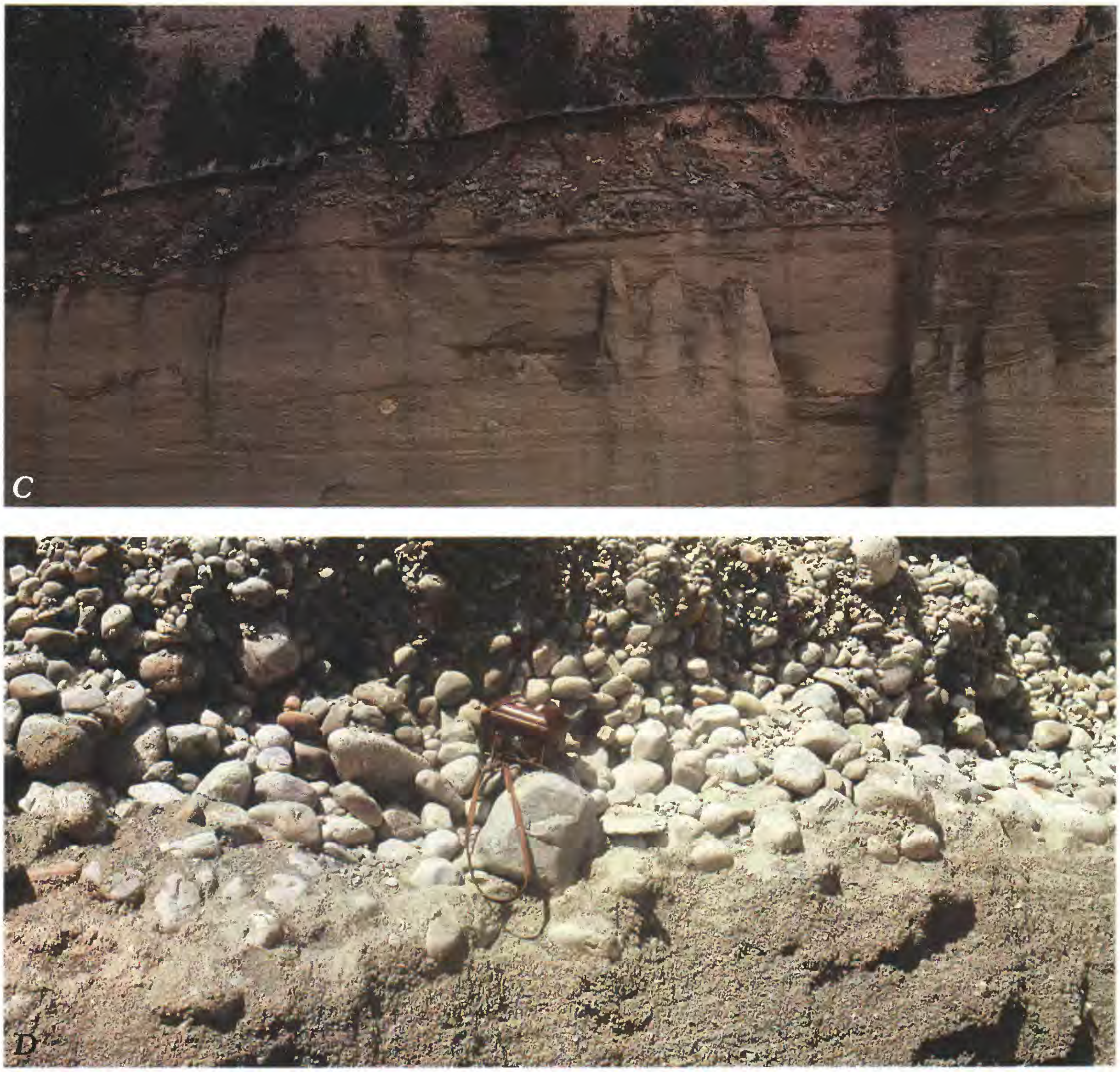
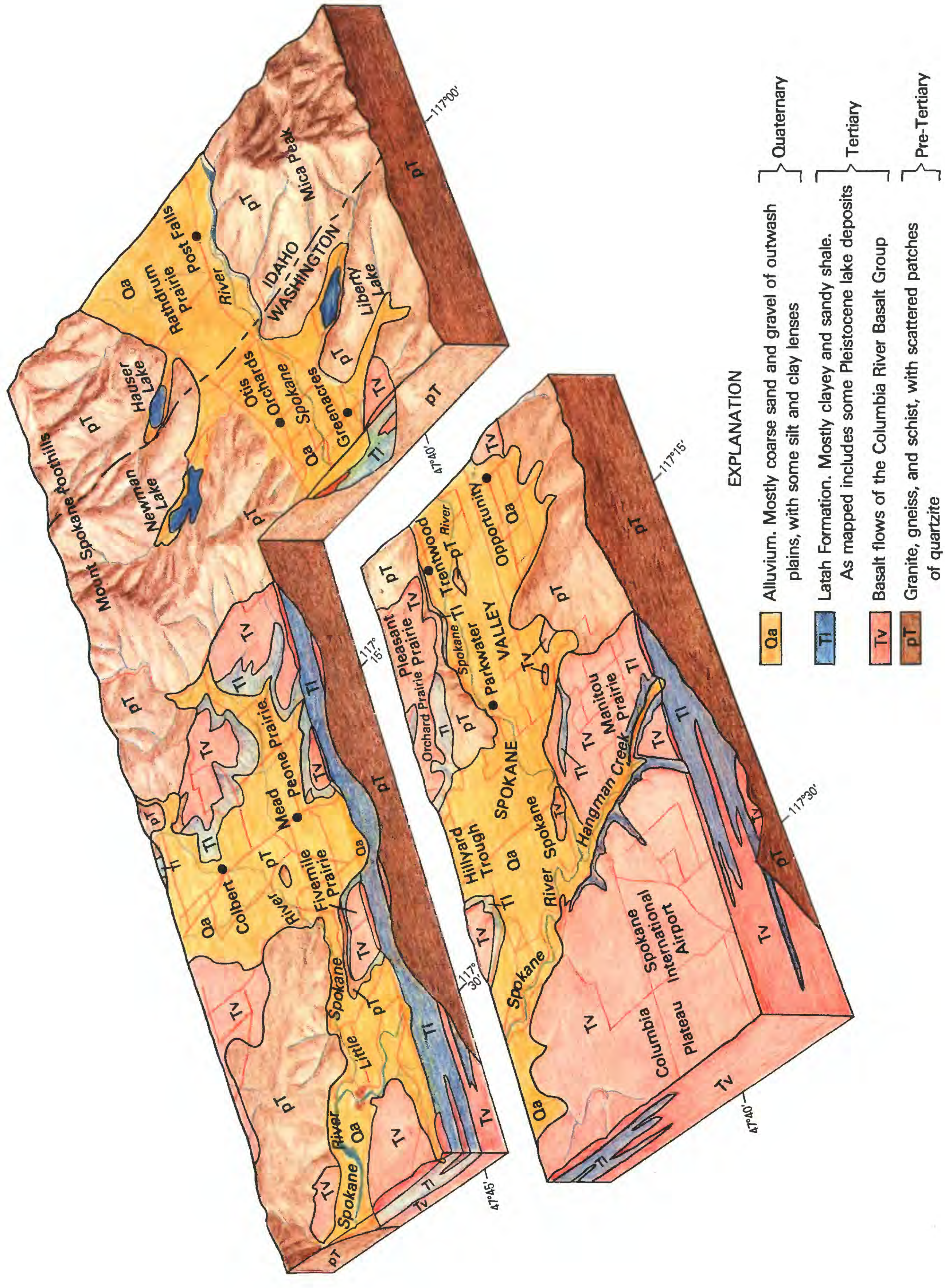


Figure 9. Continued.

the atmosphere to the earth, surface runoff and streamflow to the sea or lakes, percolation of precipitation to ground-water bodies (aquifers), seepage of ground water back to the surface, and evaporation and transpiration.

Precipitation as rain or snow is the most obvious part of the endless hydrologic cycle, but it soon becomes broken into many components. A part of the precipitation on the land surface might be stored temporarily as snowpack and becomes surface runoff to streams and lakes where some might be stored temporarily as snowpack; some soaks into the ground; and some is evaporated directly back to the atmosphere from the soil (or snowpack) and from streams, lakes, and plant surfaces. The remaining precipitation, that which is not surface runoff or evaporated, enters the soil. A part of the water entering the soil is drawn up by plants and returns to the atmosphere by transpiration from leaves; the combination of evaporation and transpiration is called evapotranspiration. The remaining water that enters the ground continues to percolate downward, where some might remain for a period of time in the unsaturated zone and the remainder enters the zone of saturation to become ground water. In turn, most of the ground water returns to the surface as seepage to springs, lakes, streams, and the sea.

Figure 12 shows considerable interplay between parts of the natural hydrologic cycle in the Spokane Valley. Not shown, however, are the effects that man's activities in one part of the system may have on other parts of the system; for example, water pumped from the river affects its flow, which in turn affects the river's capacity to assimilate municipal or in-



Mount Spokane Foothills
Hauser Lake
Newman Lake
Rathdrum Prairie
Post Falls
River
IDAHO
WASHINGTON
Mica Peak
Liberty Lake
Otis Orchards
Spokane
Greenacres
Colbert
Mead
Peone Prairie
Fivemile Prairie
Little Spokane River
Spokane
Pleasant Prairie
Orchard Prairie
Trentwood
Spokane River
Parkwater
SPOKANE VALLEY
Opportunity
Hillyard Trough
SPOKANE
Manitou Prairie
Hangman Creek
Spokane International Airport
Columbia Plateau
117°00'
117°15'
117°30'
47°40'
47°45'
EXPLANATION
Qa Alluvium. Mostly coarse sand and gravel of outwash plains, with some silt and clay lenses
Quaternary
Tl Latah Formation. Mostly clayey and sandy shale. As mapped includes some Pleistocene lake deposits
Tv Basalt flows of the Columbia River Basalt Group
Tertiary
pT Granite, gneiss, and schist, with scattered patches of quartzite
Pre-Tertiary

Figure 10. Generalized geology of the Spokane Valley region. (Modified from Pardee and Bryant, 1925, and Bolke and Vaccaro, 1981.)

Figure 11. Aerial views of the Spokane Valley, the Spokane River, and the principal lakes. *A*, View to the south over Nine Mile Falls Dam, at 26/42–6. *B*, View to the west over Riverside State Park, at 26/42–17C, showing the bluffs above the valley-floor gravels formed by the basalt flows of the Columbia River Basalt Group; the Columbia Plateau is in the distance. *C*, View to the northeast over the city of Spokane and Spokane Falls. *D*, View to the southeast over Liberty Lake. *E*, View to the northwest to Newman Lake.

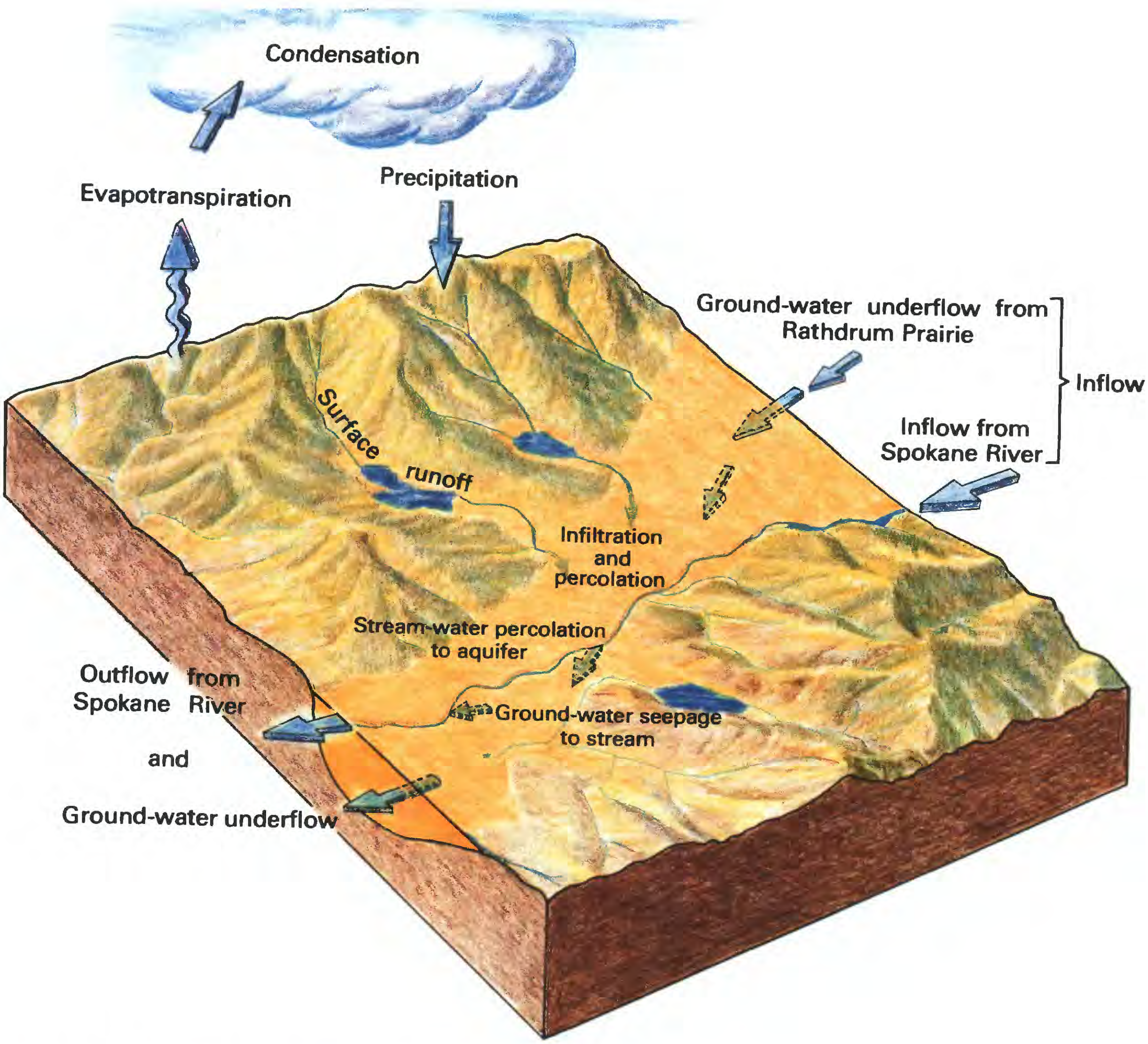


Figure 12. The natural hydrologic cycle in the Spokane Valley.

dustrial wastes. A reduction in streamflow also might cause certain reaches of the stream to drop below the level of the water table, resulting in ground-water flow toward, rather than away from, the river. However, the pumping of ground water could cause the water table to drop locally below river level, which would result in river water flowing toward the aquifer. This, in turn, decreases the river flow locally and possibly further downstream. As stated above, a decrease in river flow can affect the river's waste-assimilation capacity and also results in less water being available for downstream users.

The Spokane River: Principal Avenue of Discharge To and From the Spokane Aquifer

The Spokane River is of interest and importance to a discussion of the Spokane aquifer because of the close hydraulic connection between the river and the aquifer. The river, with its seasonal and year-to-year variations in discharge, has a direct influence on the storage and flow of water in the aquifer. Therefore, the streamflow characteristics of the river are pertinent and preliminary to a discussion of the aquifer. Streamflow characteristics are defined as the amount, duration, and timing of stream discharges, which are determined from statistical analyses of streamflow measurements obtained throughout the year and over many years at selected gaging stations on the river.

The Spokane River drains an area of about 6,600 square miles above the river's confluence with the Columbia River (Franklin D. Roosevelt Lake); about two-thirds of the drainage basin (4,300 square miles) is in Idaho, and one-third (2,300 square miles) is in Washington. The Spokane River proper begins at the outlet of Coeur D'Alene Lake; inflow to the lake is principally from the Coeur D'Alene, the St. Joe, and the St. Maries Rivers, which drain parts of the Bitterroot Mountains of Idaho. These mountain streams are unregulated and free flowing. Coeur D'Alene Lake is a natural lake with a natural outlet to the Spokane River. However, the lake level, and thus the flow of water through the lake, is regulated by the Washington Water Power Company for optimum waterpower production. Because the lake is long and narrow and is, in effect, a large river in which the water is in continual movement throughout its entire length, it plays an important role in the water quality of the Spokane River and aquifer.

The Spokane River enters the study area below Post Falls, Idaho, and leaves the area below Nine Mile Dam, Washington. The only perennial tributaries to the river in the study area are Hangman Creek (690-square-mile drainage area) and the Little Spokane River (700-square-mile drainage area). Selected views of the Spokane River at various points in the Spokane Valley are shown in figure 13.

The seasonal and long-term changes in ground-water storage in the Spokane aquifer are related closely to the discharge characteristics of the Spokane River. For this reason, an evaluation was made of streamflow records from long-term gaging stations to determine maximum, minimum, and average annual and monthly discharges of the Spokane River. The flow of the river has been measured at several gaging stations for many years (fig. 14), dating back as far as 1891 at the station at Spokane (site 5) and 1912 at the station near Post Falls, Idaho (site 1). Although Hangman Creek contributes small amounts of water to the Spokane River below Spokane, the Post Falls station on the Spokane River essentially records the only significant "input" of surface water to the Spokane Valley study area. It should be emphasized, however, that the discharge of the river below Post Falls does not represent the natural flow of the river. It is affected by streamflow controls at the dam at Post Falls, by storage in Coeur D'Alene Lake, and by irrigation diversions to the Rathdrum Prairie Canal.

The average annual discharge of the Spokane River near Post Falls during the 66 years of record (1913-78 water years) was 6,307 cubic feet per second; this excludes the amount diverted above the falls for irrigation. The maximum discharge recorded was 50,100 cubic feet per second on December 25, 1933, and the minimum was 65 cubic feet per second on July 25 and 30, 1973.

For the purpose of this report, streamflow records from the 25-year period of 1954-78 water years were selected for defining streamflow characteristics of the river where it enters the study area near Post Falls. Analyses of these records provide information on annual and monthly discharges, flow durations, low- and high-flow frequencies and durations, and peak-flow frequencies.

The average annual discharge of the Spokane River near Post Falls during the 1954–78 water years was 6,746 cubic feet per second. The annual average discharges, however, varied considerably, as shown in figure 15. They ranged from 2,143 cubic feet per second during the 1977 water year (drought year) to 11,600 cubic feet per second during the 1974 water year. The river discharges also varied seasonally as indicated by the mean monthly discharges during 1954–78 (fig. 16); they ranged from 842 cubic feet per second in August to 19,390 cubic feet per second in May (the month of greatest runoff from snowmelt). Figure 15 also shows the relation between river discharge and average monthly precipitation as recorded at the Spokane Airport.

Flow Duration: How Much Water and For How Long?

Based on statistical analysis of past streamflow records, flow duration refers to the length of time, measured in number of consecutive days, that a given stream discharge will occur. The durations of various flows are best represented by flow-duration curves, which show the percentage of time that specified discharges are equaled or exceeded; for example, the flow-duration curve for the Spokane River near Post Falls (fig. 17) indicates that the discharge during the 1954–78 water years was 9,600 cubic feet per second for 25 percent of the time and at least 19,000 cubic feet per second for 10 percent of the time.

Low-Flow Frequency: Late-Summer Flows

A knowledge of the magnitude (amount) and frequency of low flows is important to many water-management agencies in their considerations of the availability of water at certain times of the year. This information is generally necessary for planning for such water-dependent needs as fish propagation, irrigation, hydroelectric power generation, and pollution dilution (the water required to mix with and dilute concentrations of industrial and sewage discharges). The magnitude and frequency of low flows is determined from low-flow-frequency curves, which show the discharges that can be considered available for periods of selected durations; usually, these are calculated for periods of 7, 30, 90, and 183 days and for frequencies of from 1 to 100 years.

The low-flow-frequency curves for the Spokane River near Post Falls are shown in figure 18. Use of the curves will show, for example, that a discharge of about 320 cubic feet per second lasting 7 days (7-day low-flow discharge) would occur on the average of once every 2 years, whereas a 7-day low-flow discharge of about 120 cubic feet per second would occur only once every 10 years.

High-Flow Frequency: Amount, How Long, and How Often

The frequencies of occurrence of given discharges during the high-flow period of the year are shown by the curves in figure 19. Similar to the curves of figure 18, those in figure 19 show the percentage of time that any high flow of a given duration was equaled or exceeded, on the basis of data from the 1954–78 water years; for example, the curves indicate that a high flow of at least 27,000 cubic feet per second lasting 7 days would occur

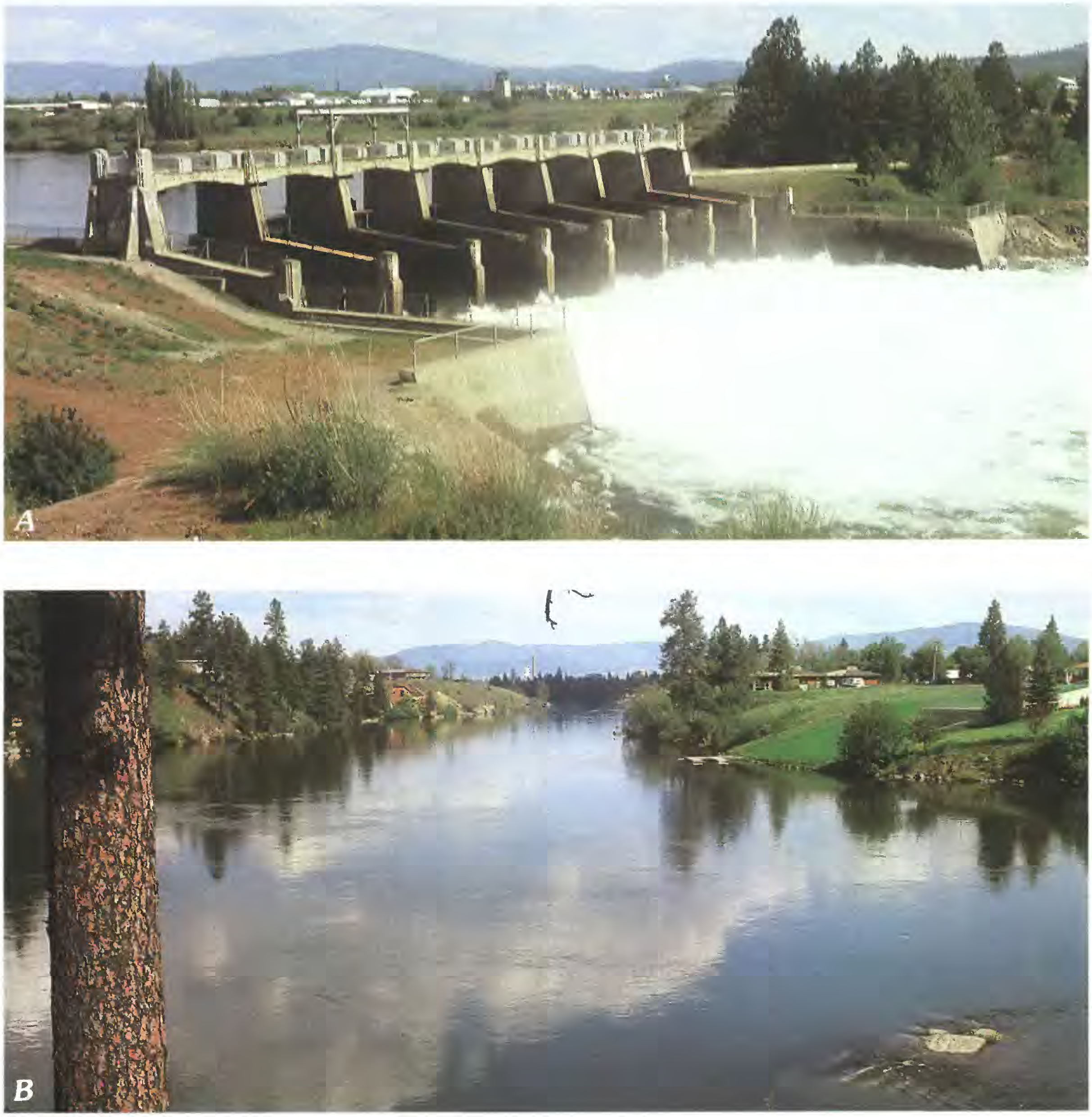


Figure 13. Selected views of the Spokane River. *A,* View to the southeast to the hydropower dam, at 25/43–11. *B,* View upstream, at 25/43–1G. *C,* Spokane Falls, at 25/43–25L. *D,* View to the east showing the Spokane sewage treatment plane, at 25/42–2,3. *E,* View to the north showing Nine Mile Dam, at 26/42–7.

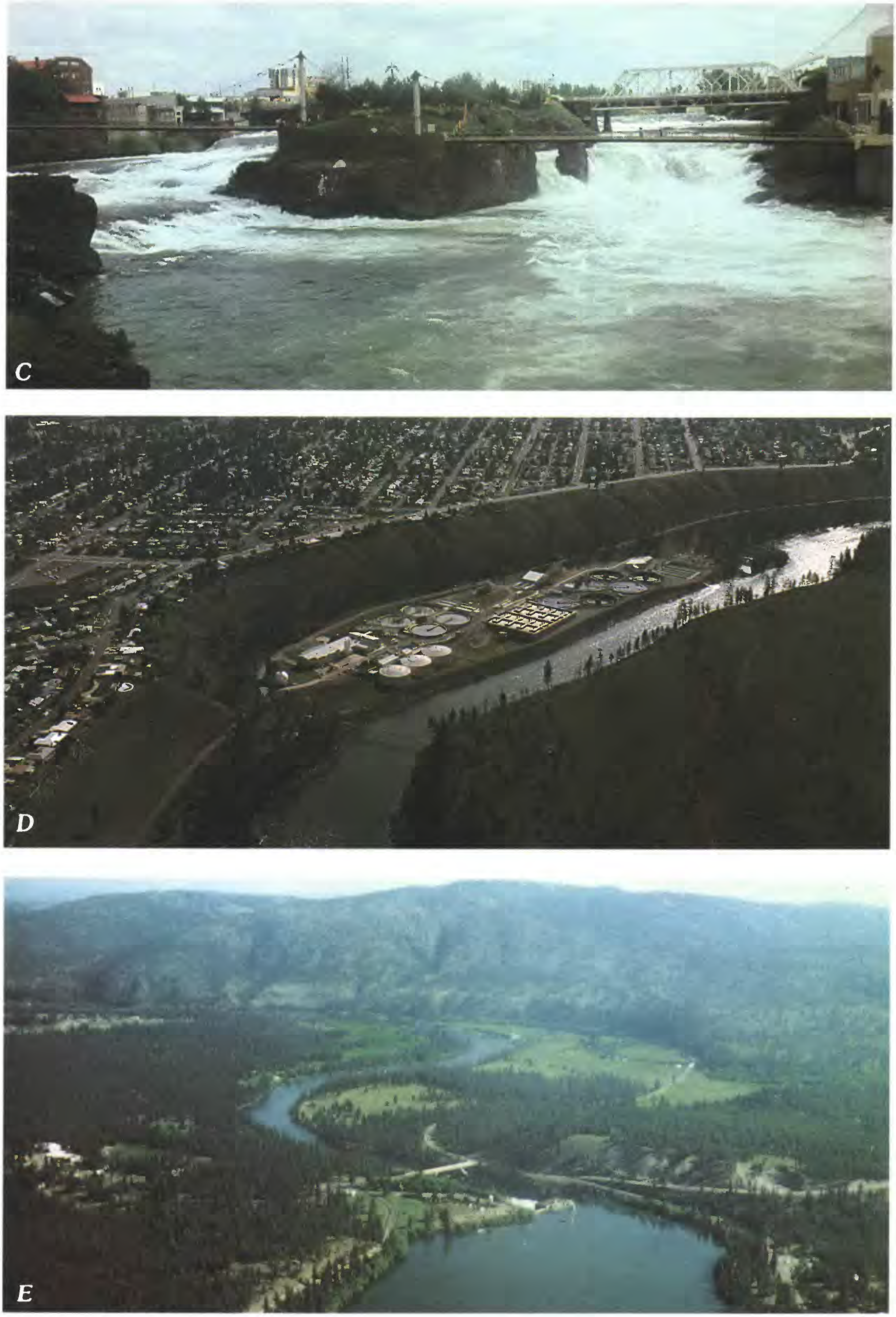


Figure 13. Continued.

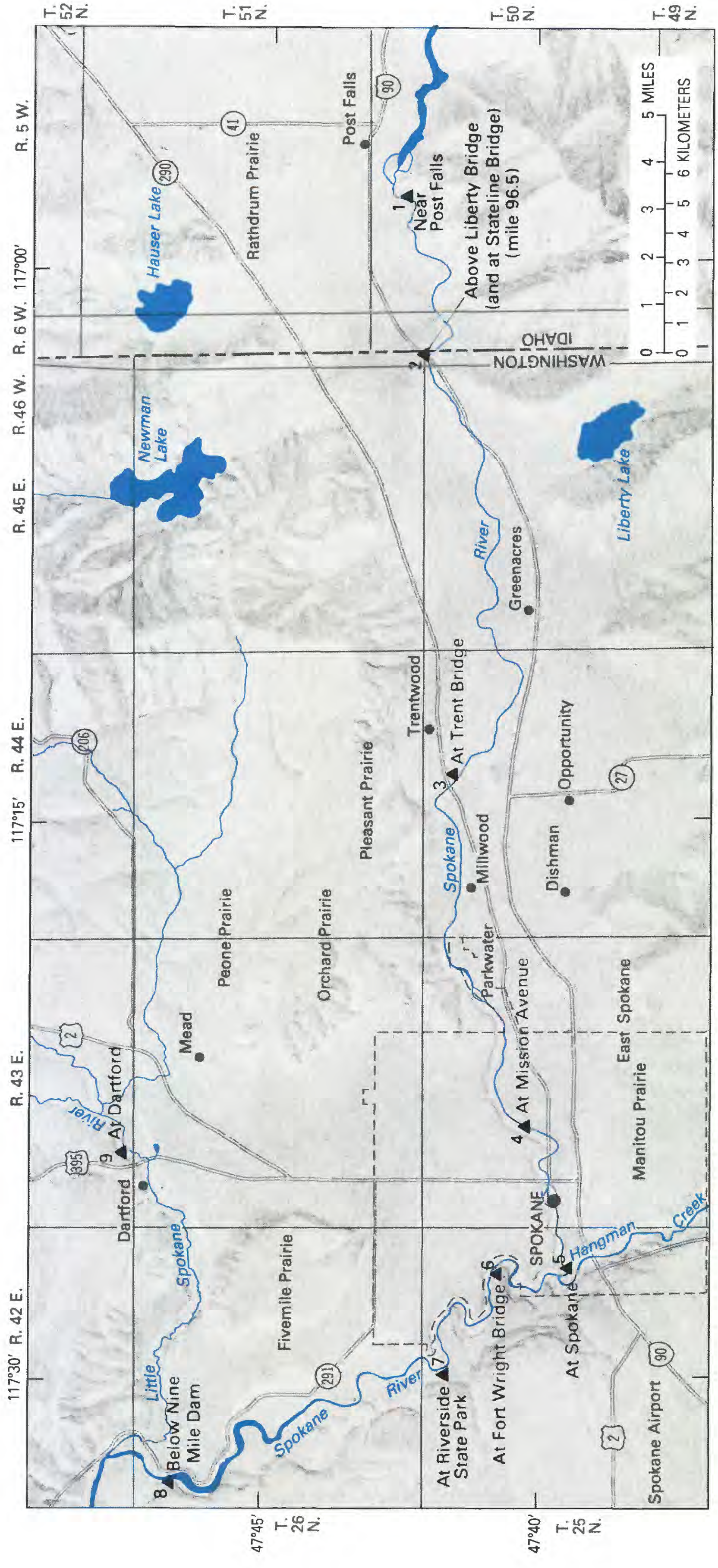


Figure 14. Pertinent streamflow stations and water-quality sampling sites in the study area.

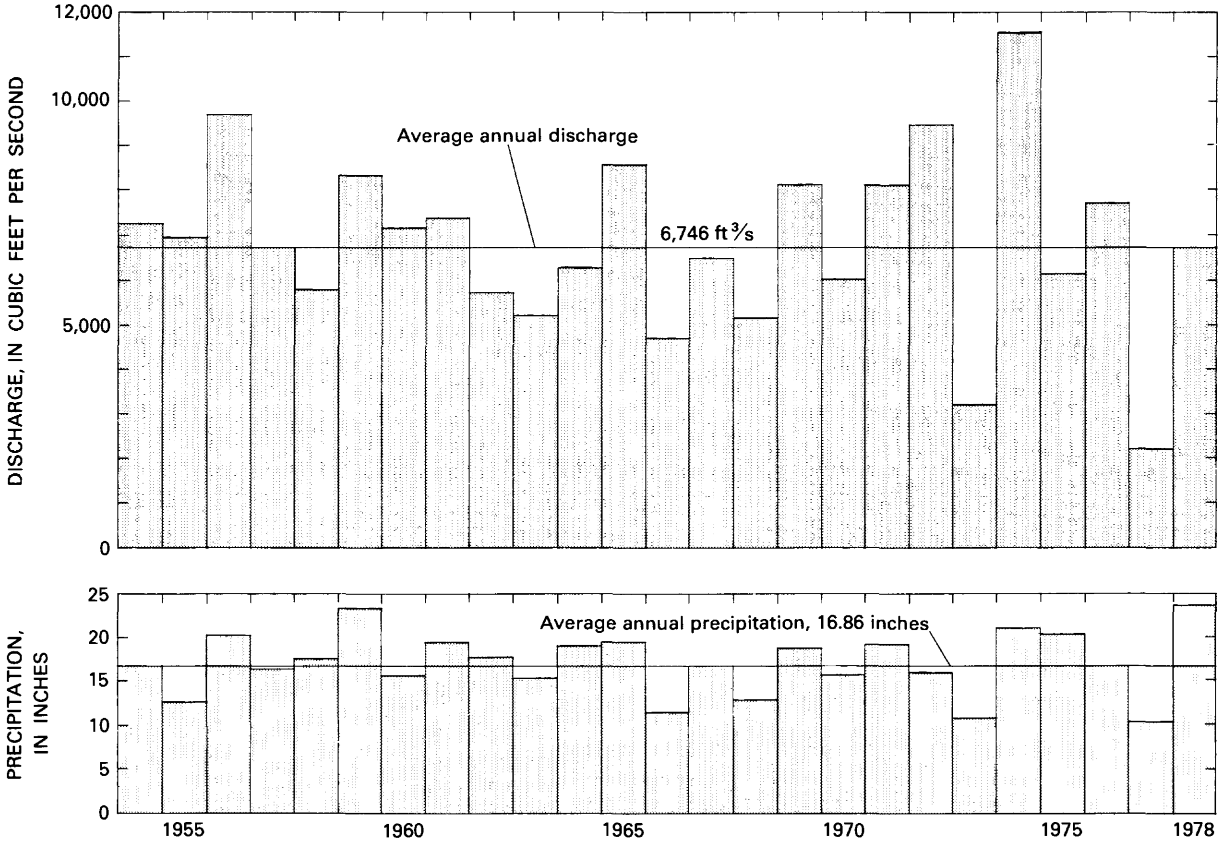


Figure 15. Annual average discharges of the Spokane River near Post Falls and annual precipitation at Spokane Airport, 1954–78 water years.

every 2 years and that a high flow of 33,400 cubic feet per second lasting 7 days would occur every 5 years.

Little or no overbank flooding of lands along the Spokane River, not even during the maximum recorded discharge of 50,100 cubic feet per second on December 25, 1933, has been reported; this is undoubtedly because the discharge of the Spokane River has been well regulated at Coeur D'Alene Lake and Post Falls. In a report on the magnitude and frequency of floods in the Columbia River basin by Rantz and Riggs (1949, p. 401), it is noted that, for the Spokane River at Post Falls, "* * * no computations of flood frequency are warranted owing to effects of regulation."

Water in the Ground: Aquifer Definition and Types

An aquifer is defined as the saturated part of geologic materials that is capable of yielding water to wells or springs. Various rock materials differ in their abilities to contain and yield water, depending upon the degree of compaction and amount of interconnected space (holes) within the rock material. The rock material may be either consolidated or unconsolidated. The water can occur in fracture zones in consolidated rock, in interstices (small openings) between grains of sedimentary materials (clay, silt, sand, gravel, and cobbles), or in large open caverns or conduits, such as the solution cavities found in limestone and dolomite. Figure 20 illustrates the various types of aquifers that are common in various parts of the United States.

Ground water in an aquifer may occur under either confined (artesian) or unconfined (water-table) conditions, as shown in figure 21. An unconfined or water-table aquifer is one in which the upper surface of the aquifer is the water table. Under normal conditions, all permeable rocks below the water table are saturated. Pressure at the water table is at atmospheric pressure.

A confined or artesian aquifer is one that is overlain by materials of significantly lower permeability than those of the aquifer; this would impede the upward movement of water from the underlying, more permeable materials. The water within this aquifer is thus "confined" under additional pressure, and, where the aquifer is tapped by a well, the water will rise in the well above the top of the aquifer to the level of the potentiometric surface for that aquifer. Such a well is an *artesian well*, and, if the pressure is sufficient to raise the water above land surface, it is a *flowing artesian well.*

THE SPOKANE AQUIFER: ITS PHYSICAL AND HYDROLOGIC CHARACTERISTICS

The Spokane aquifer is an unconfined (water-table) aquifer formed in the coarse sand, gravel, cobbles, and boulders deposited by the Spokane Floods (see section, this report). Examples of these coarse materials, which are well exposed in several gravel quarries near Spokane, are shown in figure 9. The materials contain large amounts of water, and the aquifer is one of the most productive in the United States. As the only significant source of good-quality water in the valley, the aquifer has been designated as a "Sole Source Aquifer" by the U.S. Environmental Protection Agency. For a better understanding of the aquifer, a discussion is presented here of its physical and water-yielding characteristics—its areal extent and thickness, depth, areas and quantities of recharge and discharge,

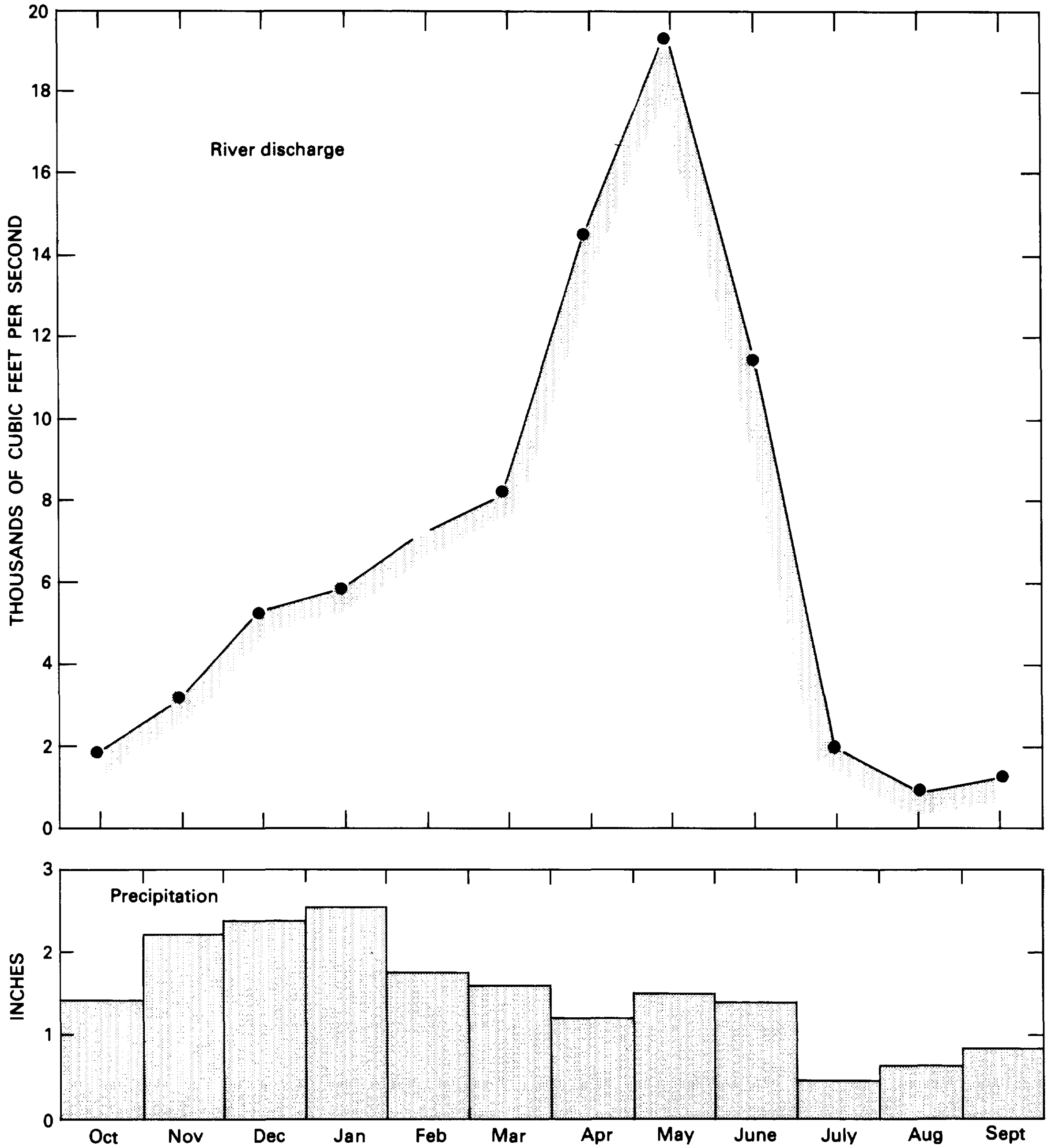


Figure 16. Average monthly precipitation at Spokane Airport and average monthly discharge of the Spokane River near Post Falls, Idaho, 1954–78 water years. Data from annual summaries of U.S. Geological Survey (1954–78).

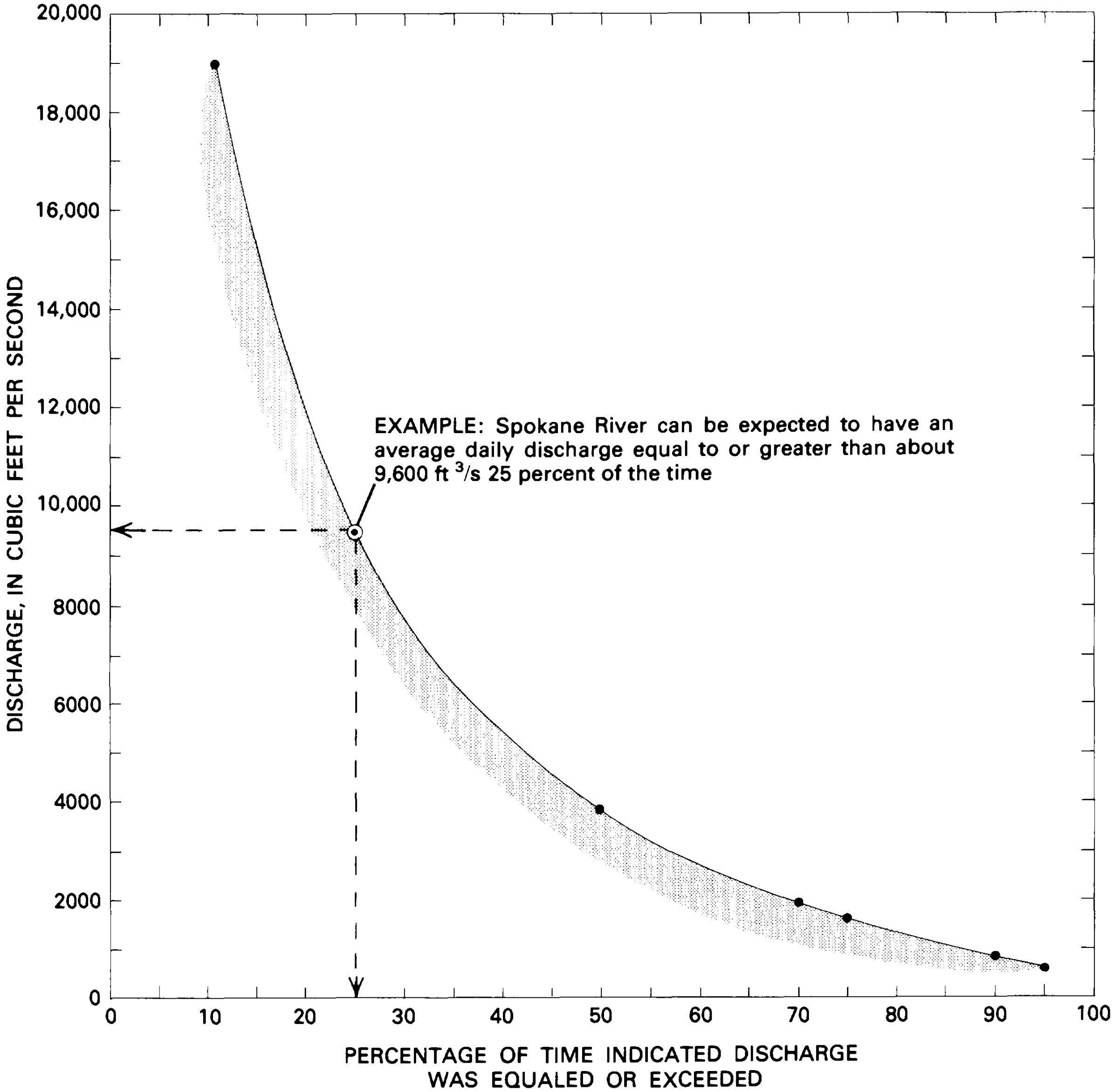


Figure 17. Flow-duration curve for the Spokane River near Post Falls, 1954–78 water years.

specific yield, and direction and rate of ground-water flow. Also discussed is the close connection between the aquifer and the Spokane and the Little Spokane Rivers.

Occurrence of Water in the Aquifer

As is typical of aquifers in sedimentary deposits, water in the Spokane aquifer occurs in the interstices between the grains of coarse sand, gravel, cobbles, and boulders that form the aquifer. These spaces vary in size according to the size of particles, and this directly influences the amount of water stored. Because only small amounts of finer material, such as silt and clay particles, are present to "clog" these openings, the aquifer contains large amounts of stored water that are free to flow through the openings.

The open, highly permeable character of the material allows the ready percolation of precipitation and snowmelt through the unsaturated zone to the water table and a rapid lateral movement of water through the aquifer. The high rate of lateral ground-water movement is reflected in the close hydraulic connection bewteen the aquifer and the Spokane River (discussed in "Direction of Ground-Water Flow").

Areal Extent and Thickness of the Aquifer

The coarse outwash materials that form the Spokane aquifer, and its extension as the

Rathdrum Prairie aquifer to the east and northeast, underlie an area of about 425 square miles in the broad lowland plain that extends from Pend Oreille Lake in Idaho southwesterly and westerly to beyond Spokane. The Spokane aquifer study area, as defined for this report, underlies about 135 square miles in the Spokane Valley between Post Falls, Idaho, and the confluence of the Spokane and the Little Spokane Rivers (fig. 2).

In most places along the valley sides, the aquifer boundary has abrupt lateral contacts with the sloping surfaces of the bedrock hillside. In some places, however, the boundary grades into less permeable unconsolidated materials that are not readily distinguishable from the aquifer materials (fig. 10). At the city of Spokane, basalt bedrock forms the picturesque gorge containing the upper and lower Spokane Falls and extends north and across the valley at shallow depth. Northward from the falls area, the bedrock is near land surface and extends to and beneath the plateau upland of Fivemile Prairie, which also is capped by basalt. Because of the basalt extension across the area between Spokane Falls and Fivemile Prairie, the thickness of unconsolidated aquifer deposits is decreased considerably from that in the areas to the east (Hillyard Trough) and west (Spokane River).

The saturated thickness of the unconsolidated aquifer deposits beneath the Spokane Valley is shown rather generally in figure 22. However, the thickness of the aquifer beneath much of the valley is not well defined, as only 10 wells are recorded as penetrating the aquifer to its base on the underlying Latah Formation and (or) the basalt, and only localized seismic studies have been made. A seismic study by Newcomb (1953) indicated

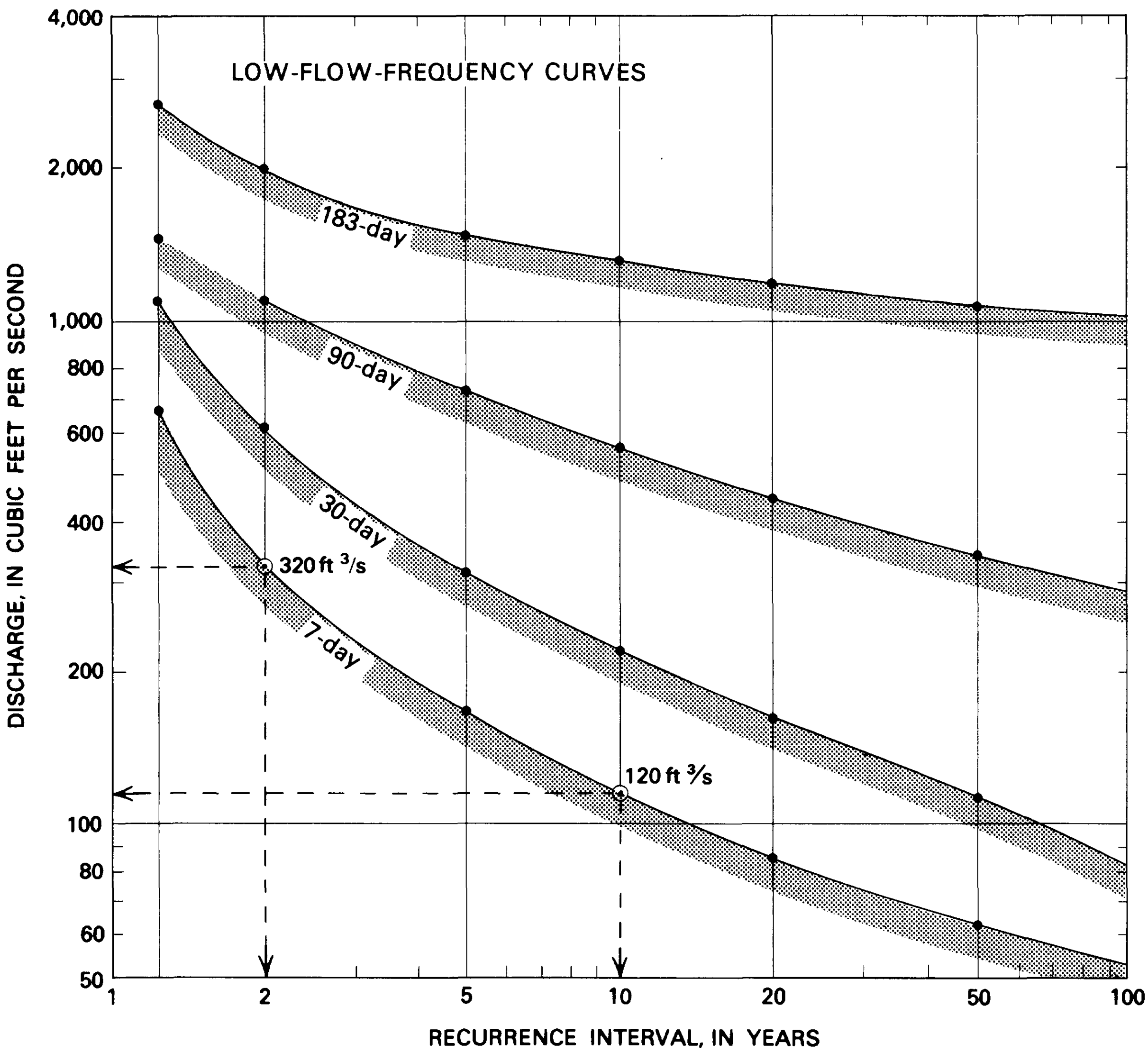


Figure 18. Recurrence intervals of annual low flows for selected periods of consecutive days, Spokane River near Post Falls, 1954–78 water years.

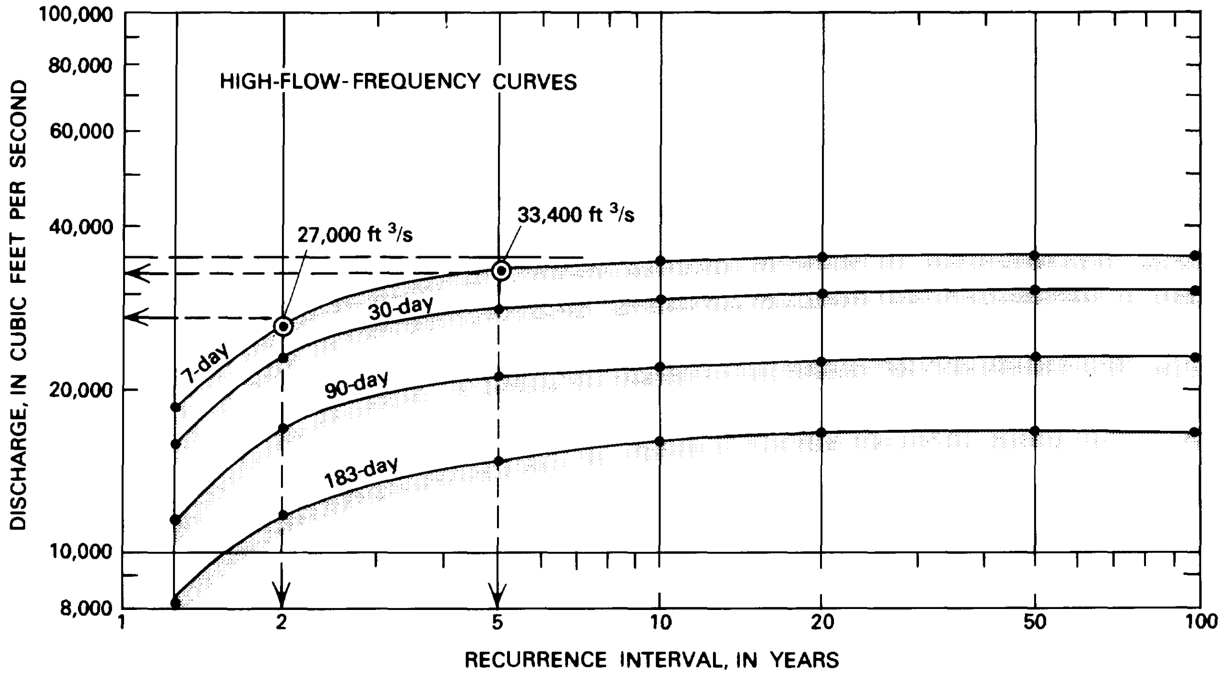


Figure 19. Recurrence intervals of annual high flows for selected periods of consecutive days, Spokane River near Post Falls, 1954–78 water years.

that the thickness of the aquifer material is about 240–375 feet near the State line and about 150 feet in the Hillyard Trough. Records of wells in the Hillyard Trough, however, indicate that the penetrated thickness of gravel and sand is, at least locally, more than 300 feet.

A map prepared by Bolke and Vaccaro (1981, fig. 3) shows the estimated saturated thickness of the aquifer, which is based on information combined from several assumptions. These include (1) the contoured altitude of the water table during 1977–78, which marks the top of the aquifer, (2) the seismic studies by Newcomb (1953), which provided interpretations of the bottom of the aquifer, (3) a gravity-survey map by Purvis (1969), and (4) drillers' records of wells.

Recharge and Discharge: Replenishing and Losing the Ground Water

The Spokane aquifer gains water by recharge and loses water by discharge. The aquifer is recharged (receives water) principally by (1) ground-water underflow from the Rathdrum Prairie on the east and from tributary valleys on the north and south, (2) percolation of precipitation and snowmelt that infiltrates the land surface, (3) percolation of irrigation water, particularly in the eastern agricultural area, and from septic-tank drain fields, and (4) some local percolation of water from a few reaches of the Spokane River. Discharge of water from the aquifer occurs principally by (1) leakage to the Spokane and Little Spokane Rivers along some reaches, (2) pumpage from wells, (3) evapotranspiration through plants whose roots tap the aquifer where the water table is near land surface along some reaches of the two rivers, and (4) ground-water underflow beneath the lowermost (northwestern) part of the valley below Nine Mile Falls.

The average annual recharge to and discharge from the aquifer were calculated from the average annual values of the various components of the hydrologic cycle. For recharge, these components include percolation of water from precipitation, from ground-water underflow from the Rathdrum Prairie on the east and streams along the valley margins, and from irrigated lands and septic-tank drain fields. Discharge components include loss through evapotranspiration, seepage to streams, and pumpage from wells. The generalized locations and calculated quantities of recharge to and discharge from the Spokane aquifer (fig. 23) are based on interpretations in the study by Bolke and Vaccaro (1981). As can be seen, the largest single underflow component supplying recharge is that from beneath Rathdrum Prairie; only minor amounts come from the smaller stream drainages along the valley margins. The largest quantities of discharge occur as leakage to the Spokane and the Little Spokane Rivers and ground-water pumpage.

The Water Table

The depth of the water table—the surface of the saturated zone in an unconfined aquifer—below land surface varies over broad areas, but it is generally determined locally by the depth to water in nonpumping wells—the static water level. The delineation of the water table beneath a broad area usually requires water-level data (measurements of depth to water) from many wells, preferably from measurements made about the same time of year. Otherwise, discrepancies will result in the interpretations resulting from, for example, trying to match the usually higher springtime water level in one well with the usually lower autumn water level in a nearby well.

The water table is portrayed graphically with water-table contours. As shown diagrammatically in figure 24, the contours are imaginary lines that connect points of equal altitude of the water table.

The generalized surface of the water table is shown by a water-table-contour map. The general gradient (slope) of the water table over a broad area indicates the direction of ground-water flow, from high points (areas of ground-water recharge) to lower points (areas of ground-water discharge).

A water-table map is a useful tool for determining how deep a well must be drilled to obtain water and for evaluating the directions of flow at various points in the aquifer. This, in turn, allows one to esimate the direction that foreign substances, such as contaminants from sewage, industrial wastes, and septic-tank discharge, will move through an aquifer. Thus, a partial evaluation of the effects on ground-water quality can be made.

Direction of Ground-Water Flow

Ground water beneath the Spokane Valley is not a static, motionless body of water in stor-

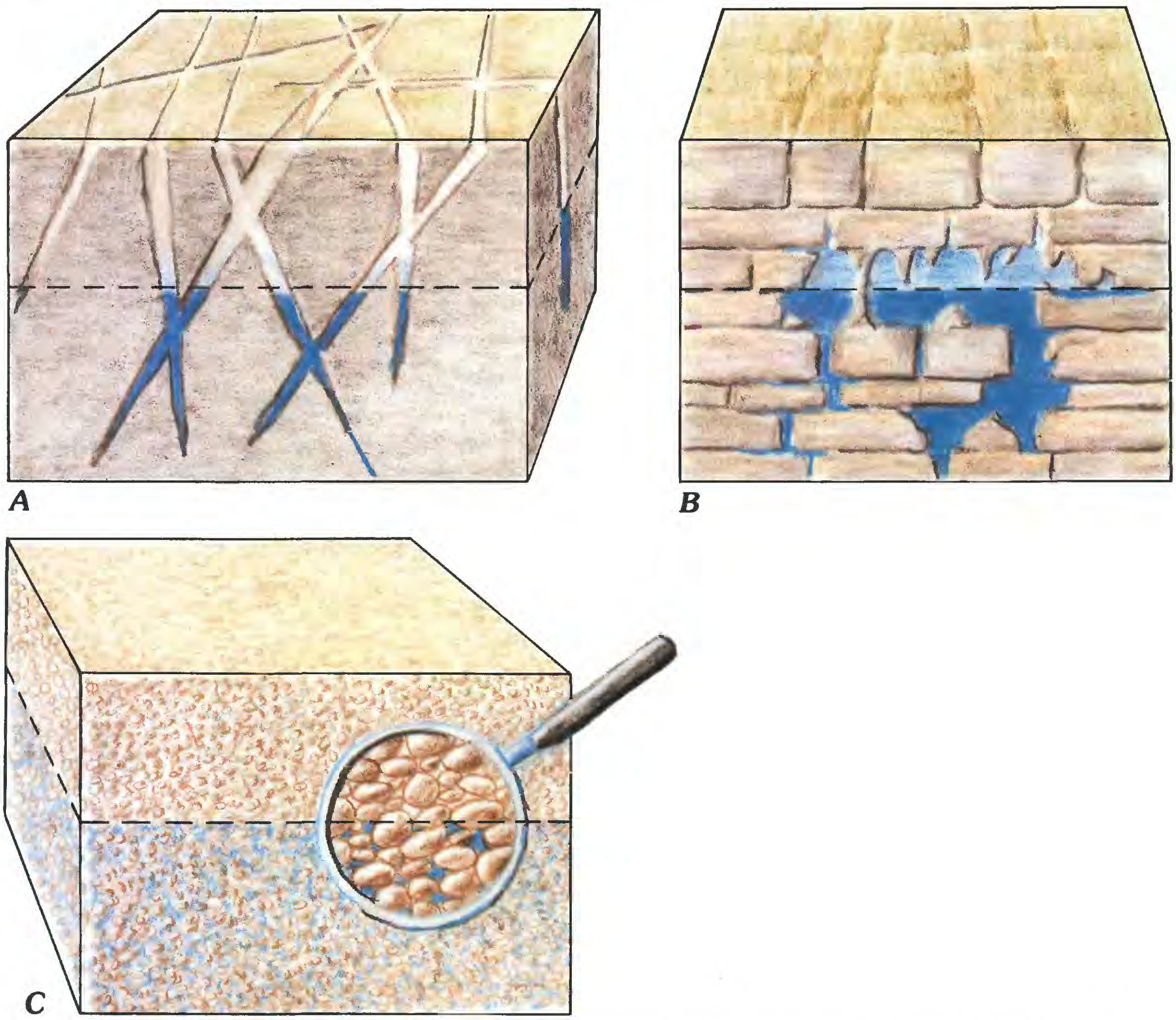


Figure 20. Generalized occurrence of ground water in various types of aquifers. *A*, Fractures and joints in igneous and metamorphic rocks. *B*, Solution cavities in limestone. *C*, Spaces between particles in unconsolidated sedimentary deposits.

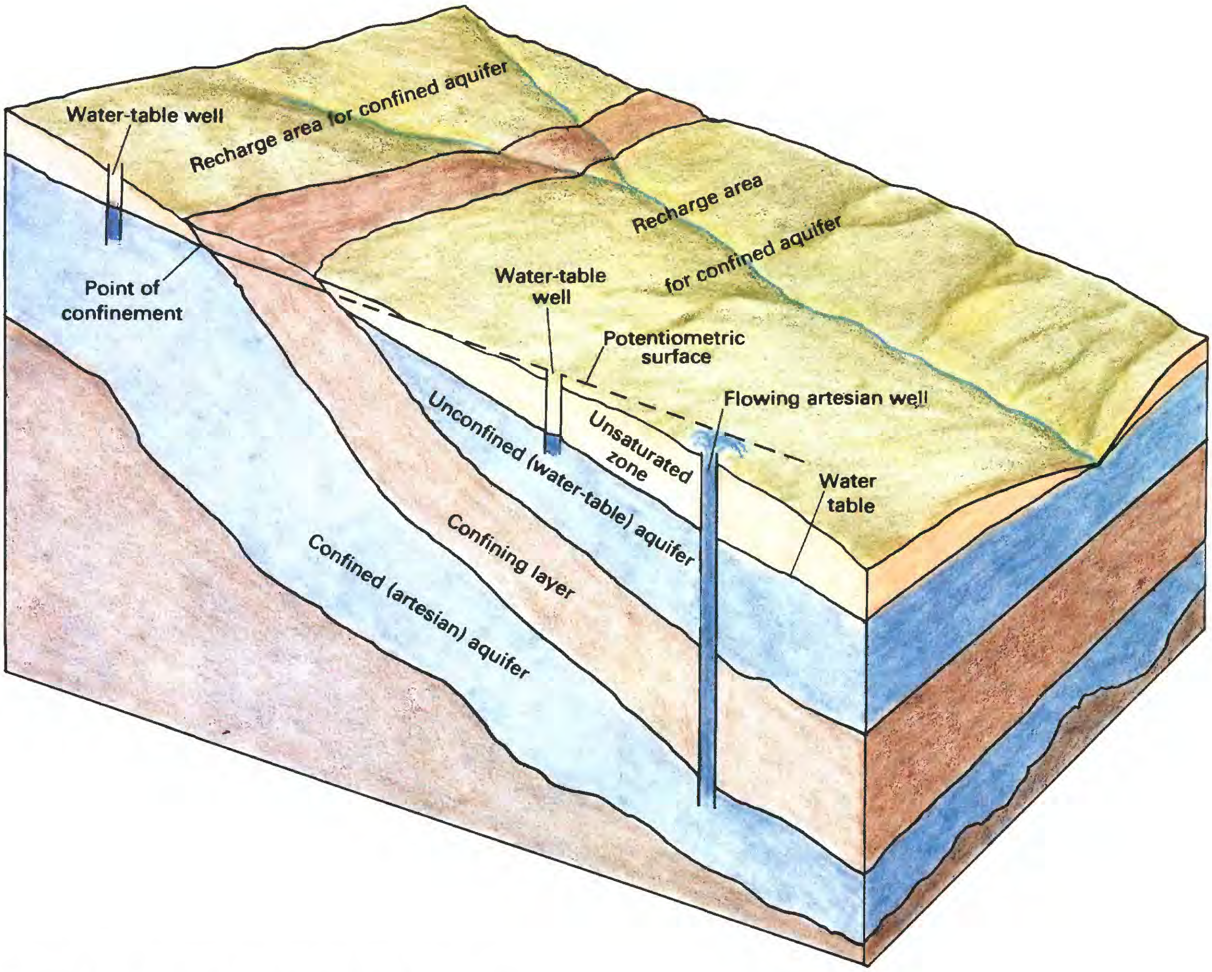


Figure 21. Confined and unconfined aquifers.

age. Instead, as shown by the water-table-contour map of figure 25, it is in continual flow downvalley and locally to and from the Spokane and the Little Spokane Rivers. The river water moves away from rivers where the water table is lower than the river levels, and, conversely, ground water moves toward the rivers where the water table is above river levels.

Ground water moves from areas of recharge to areas of discharge, and, as shown by the arrows in figure 25, the direction of flow is at right angles to the water-table contours. The general westward movement of ground water is obstructed partially by poorly permeable bedrock, which protrudes as a small hill above the valley gravels north of Opportunity. Farther downvalley, an increase in silt, clay, and fine sand also may contribute to reduced permeability and to a corresponding reduction in well yields in the area.

Water-Level Changes

The water level in an aquifer is affected by seasonal and yearly recharge to and discharge from the aquifer. As shown in figure 26, graphs of water levels in several wells representative of conditions throughout the valley indicate that seasonal changes are small, generally less than 10 feet between the highest levels of spring and lowest levels of late summer and early fall. The graphs also show only minimal long-term changes; year-to-year changes during the period 1963-78 were generally less than 5 feet.

A close relation among monthly precipitation, discharge of the Spokane River, and the water level is best displayed in the hydrograph for well 25/44-23D1. The graph indicates how rapidly the aquifer responds to river discharge. This close connection was first observed during the period 1937-38 by Piper and LaRocque (1944), who compared the water levels in the three wells and the stage (level) of the nearby Spokane River. (The stage is related directly to the discharge of the river, which is used in the comparison in fig. 26.)

Seasonal water-level changes in wells in the Hillyard Trough are only 2 to 3 feet. The water levels do not respond as quickly to changes in the river stage of the Spokane River

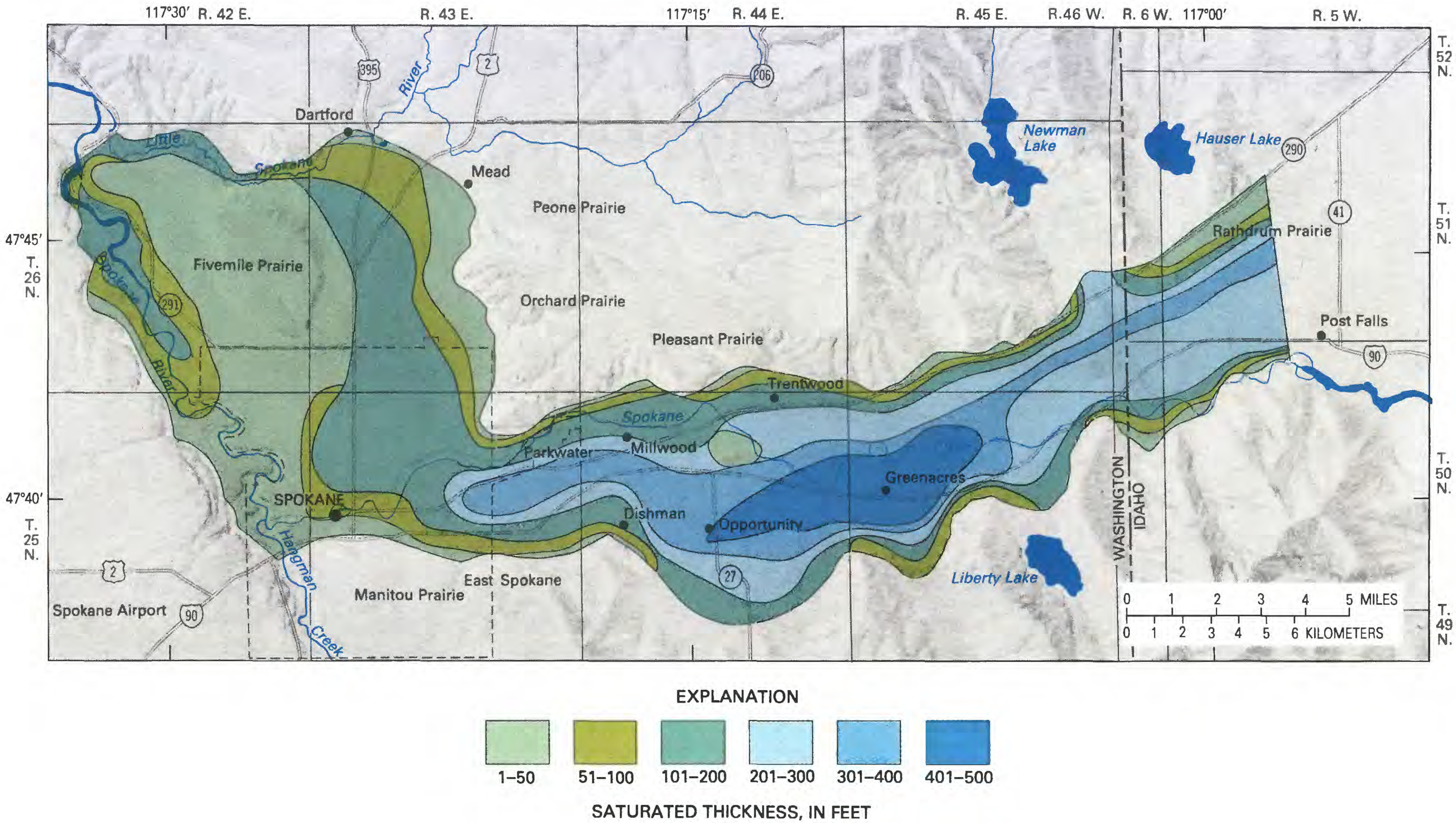
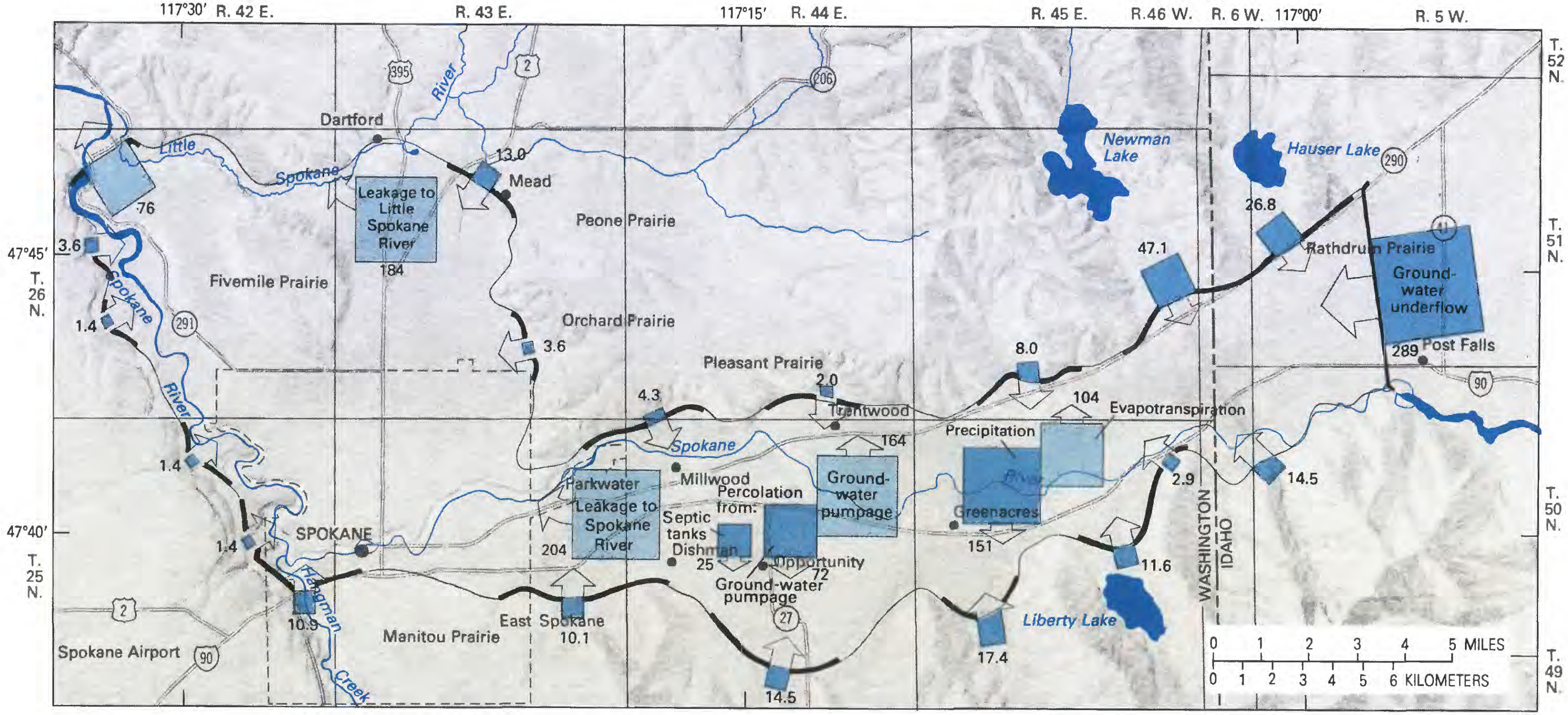


Figure 22. Saturated thickness of the Spokane aquifer. (From Bolke and Vaccaro, 1981.)



SUMMARY

	Thousands of acre-feet
Recharge:	
Ground-water inflow from boundaries	484
Precipitation	151
Percolation of pumped ground water applied to land surface	72
Percolation from septic-tank drain fields	25
Total (rounded)	732
Discharge:	
Leakage to Spokane River	204
Leakage to Little Spokane River	184
Ground-water pumpage	164
Evapotranspiration	104
Ground-water outflow below Nine Mile Dam	76
Total (rounded)	732

EXPLANATION

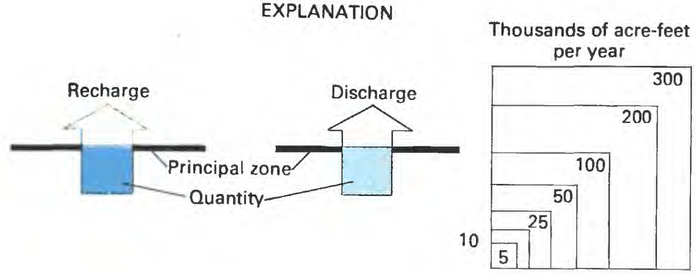


Figure 23. Types and quantities of ground-water recharge and discharge within the aquifer area and along principal marginal zones. (Modified from Bolke and Vaccaro, 1981.)

as do wells in the eastern part of the valley because they are farther from the river and the aquifer materials are less transmissive. Other things being equal, these factors result in a correspondingly slower, reduced response to river-level changes.

Permeability and Transmissivity: The Rate of Ground-Water Flow

The rate at which ground water flows through an unconfined aquifer depends upon the thickness, width, and permeability of the saturated material and the hydraulic gradient. Explanations of permeability and the related term of transmissivity are shown graphically in figure 27.

Permeability is a measure of the ability of the aquifer material to transmit water and is, to some extent, an indicator of the shape, size, and arrangement of the spaces within the aquifer materials; for example, water moves much more readily through the large, connected spaces as compared to smaller, partly connected spaces. More permeable material has larger, more completely connected spaces between the rocks than does less permeable material.

Permeability is usually reported in cubic feet per second per square foot, which is mathematically reduced to feet per second. It indicates the quantity of water (in cubic feet) that flows in 1 second through a square-foot cross section of the aquifer under hydraulic slope of 1:1, or 1 foot horizontally to 1 foot vertically, as shown diagrammatically in figure 27.

Transmissivity is a measure of the quantity of water flowing through a 1-foot-wide cross section of the entire thickness of the aquifer. In the case of an aquifer of homogeneous rock type, it is the permeability value of that rock type times

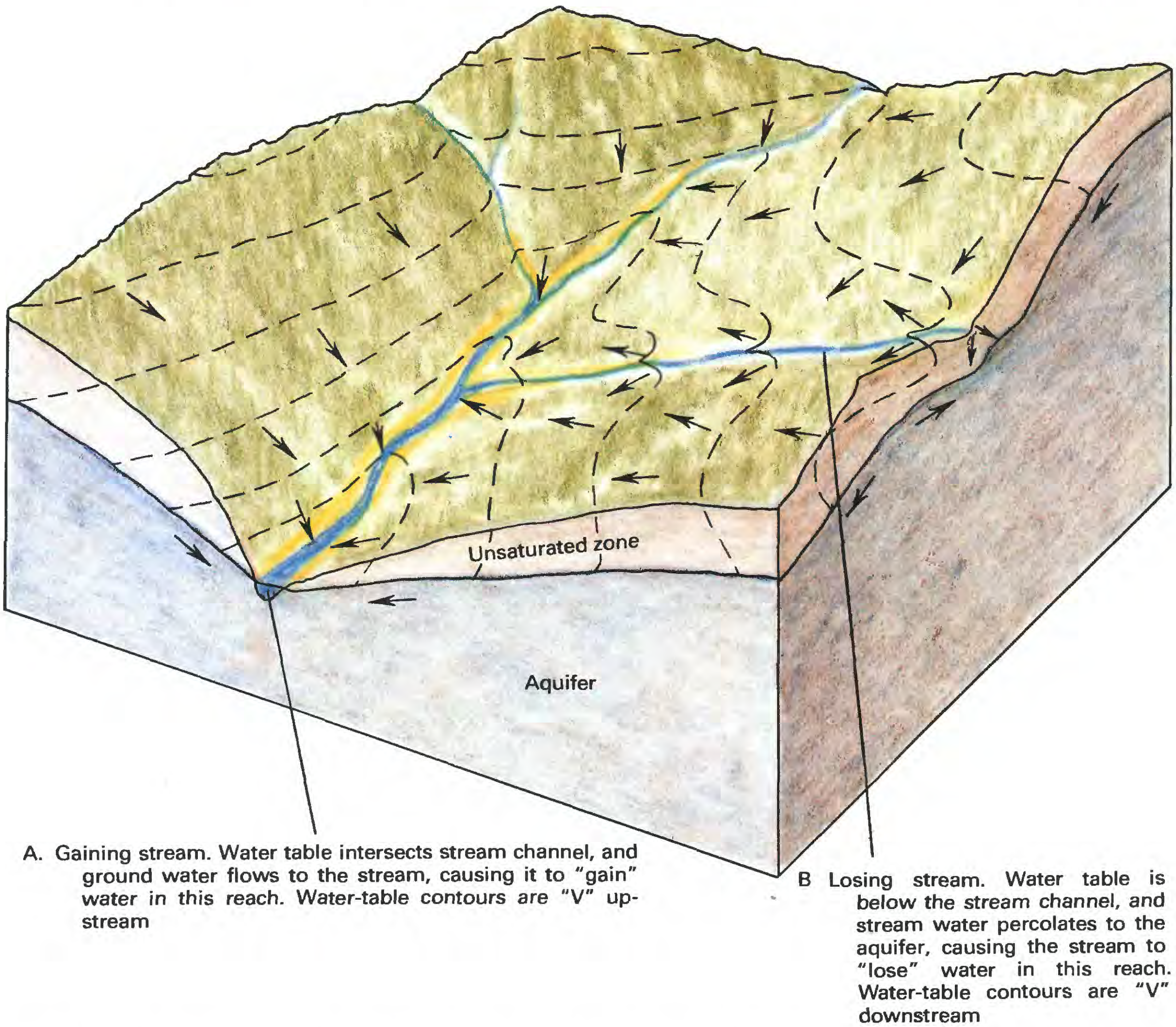


Figure 24. The water table of an unconfined aquifer and the general hydraulic relations with losing and gaining streams. Also shown are the water-table contours (dashed lines) and the direction of ground-water flow (arrows).

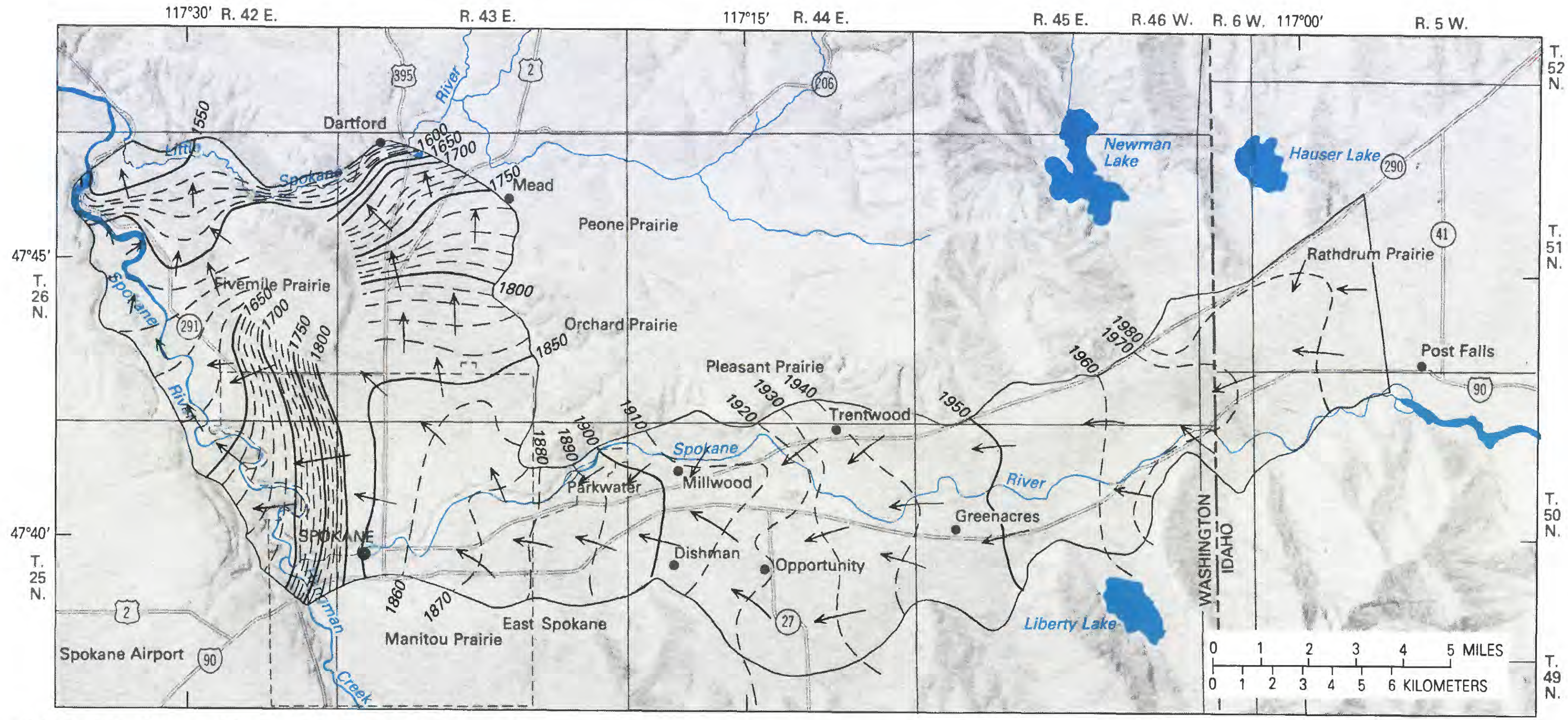


Figure 25. Water-table contours and the direction of ground-water flow in the Spokane aquifer, May 1978. (From Bolke and Vaccaro, 1981.)

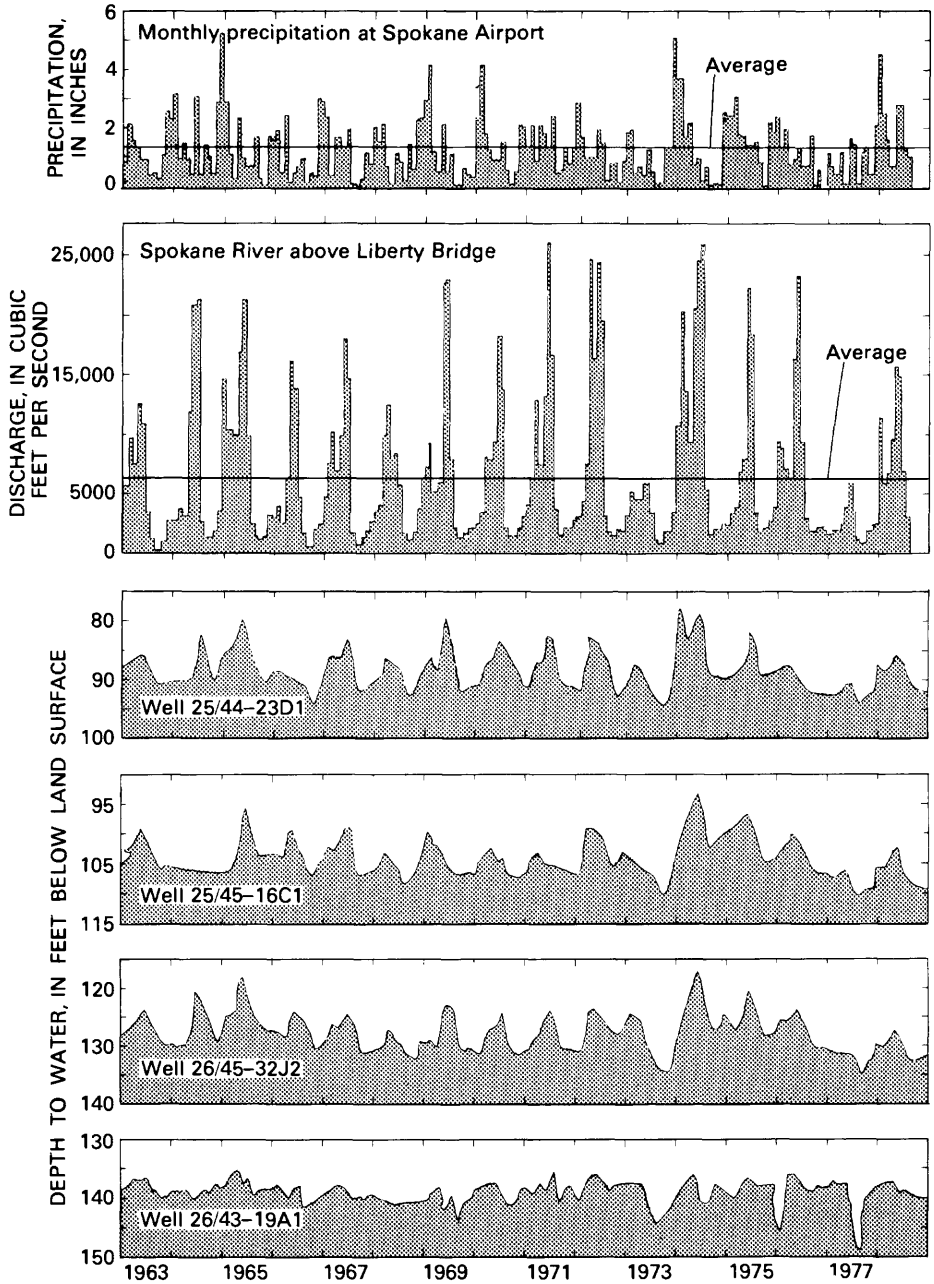


Figure 26. Water levels in selected wells, discharge of the Spokane River above Liberty Bridge, and monthly precipitation at Spokane Airport. (Modified from a report by Drost and Seitz, 1978.)

the thickness of the aquifer, in feet, as shown in figure 27, and is, therefore, cubic feet per second per square foot times the thickness of the aquifer in feet, which is mathematically condensed to feet squared per second. Where there are several layers of different rock types (for example, a layer of sand above a layer of gravel) within an aquifer, the transmissivity of that aquifer is the sum of the transmissivities of each contained layer.

Calculations of transmissivity in the Spokane Valley, which were based on the types of materials penetrated as determined from drillers' logs, on the map of aquifer thickness (fig. 22), and on pumping tests of wells, were made indirectly by Bolke and Vaccaro (1981). The pumping-test data from drillers' records not only provides information on the efficiency of the pump and of the method of well construction but also indirectly indicates the permeability of the aquifer material surrounding the well. As a well is pumped, the water level is drawn down inside the casing, causing a similar drawdown of water outside the casing to form a "cone of depression" in the water table immediately around the well. The shape of the cone of depression—its steepness and areal extent—reflects the permeability of the aquifer material; for example, in a well tapping an aquifer of fine materials of relatively low permeability, the water level will be drawn down rapidly many feet, and the cone of depression will be steep sided (fig. 28). The steepness of the cone, like a steep water table, reflects slow movement of water through fine materials. Conversely, as shown for the well tapping coarse, highly permeable materials—as in the Spokane aquifer—the drawdown will be minimal, and the cone of depression will be relatively shallow.

From the information obtained as described above, the accompanying map of transmissivity (fig. 29) was prepared. The map shows that transmissivity is higher in the part of the valley east of Spokane and that it generally decreases downvalley beyond Spokane. The highest transmissivity is in the area of Greenacres, where the aquifer is the thickest (fig. 22).

Specific Yield: An Index to the Amount of Water Available From an Aquifer

The specific yield of materials in an unconfined aquifer is defined as the ratio of the volume of water that the aquifer materials will yield by gravity or by pumping to the total vol-

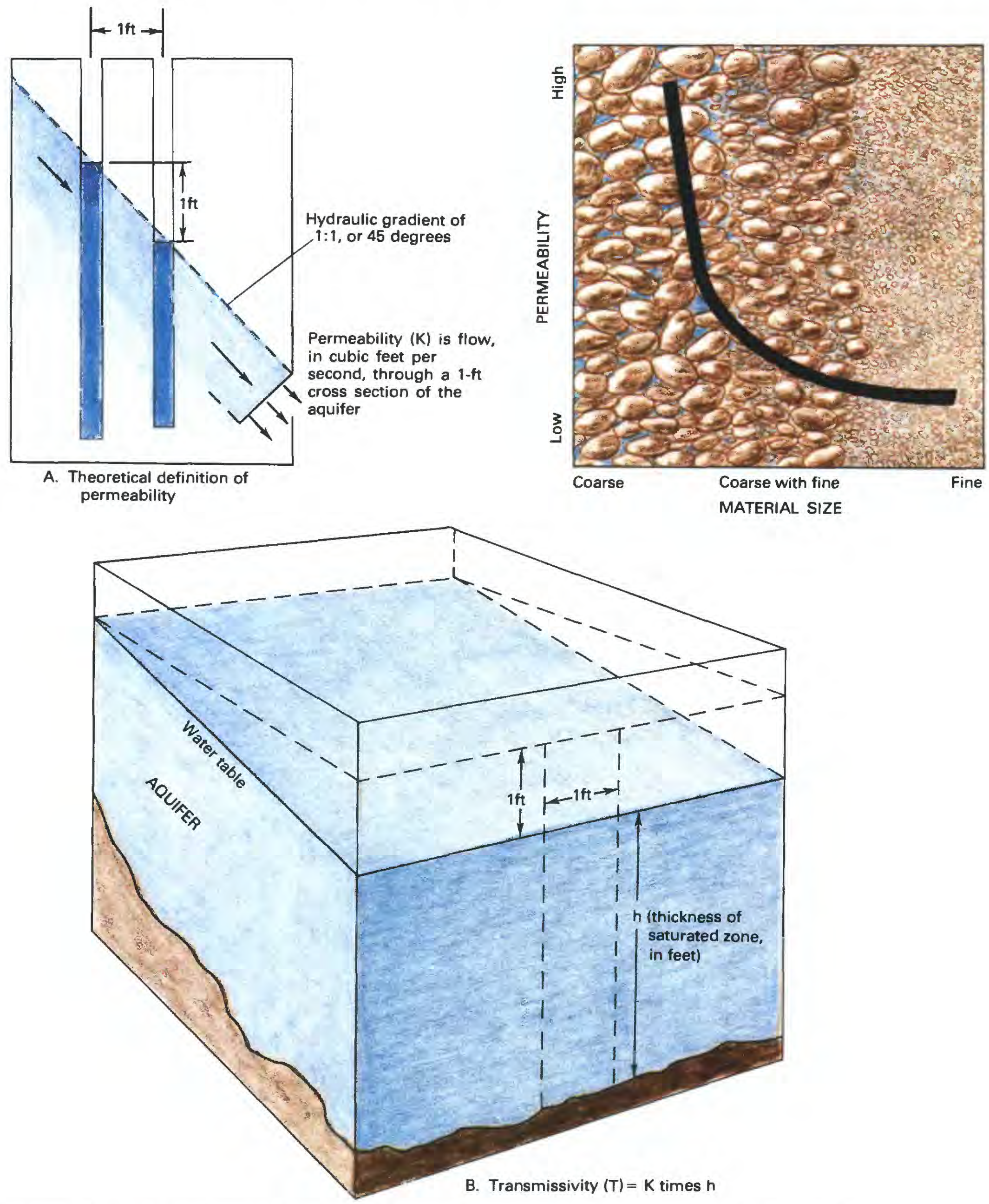


Figure 27. Explanations of permeability and transmissivity in an unconfined aquifer.

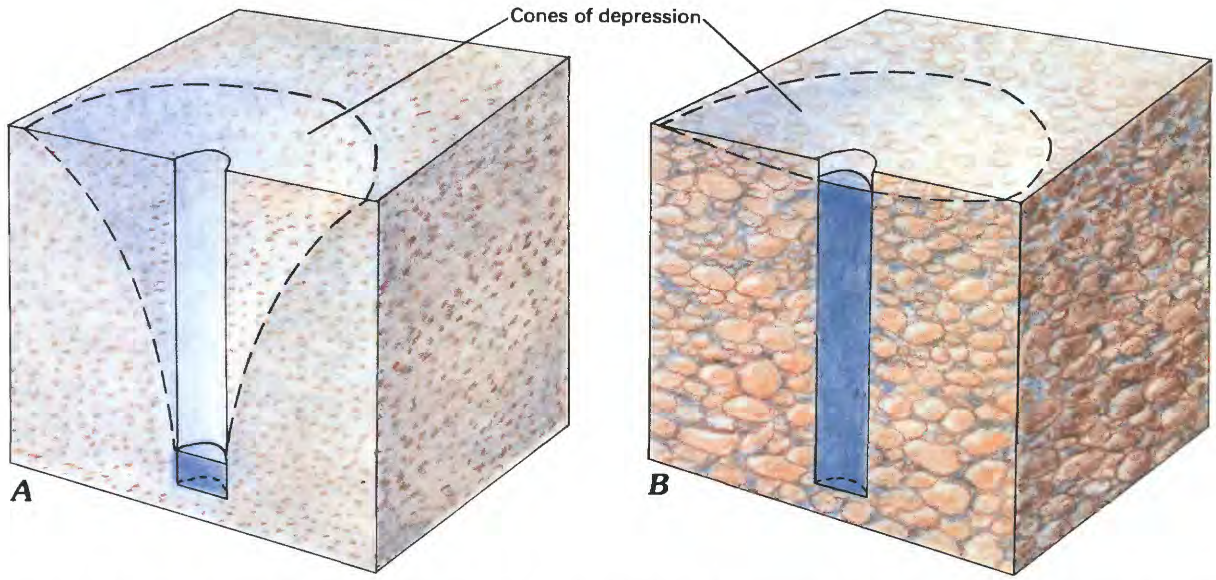


Figure 28. Diagrammatic sketches comparing typical cones of depression during pumping of wells tapping aquifers in unconsolidated deposits of different permeabilities. *A*, Fine sand and silt of low permeability. *B*, Coarse sand and gravel of high permeability, as in the Spokane aquifer.

ume of the aquifer materials. The specific yield of clay and silt generally is only 2–15 percent of the total rock volume, whereas that of gravel and coarse sand is often 25–35 percent of the total rock volume. These concepts are shown diagrammatically in figure 30. The lowest specific yields are those of aquifers composed of poorly sorted materials, such as cobbles and boulders in a matrix of fine silt and clay.

The specific yield of the Spokane aquifer generally decreases in the downvalley direction, as shown in figure 31. According to the study by Bolke and Vaccaro (1981), the specific yield in the valley east of Spokane ranges from 15 to 20 percent of the aquifer volume. However, beneath the lower reach of the valley, from the city of Spokane north to the Little Spokane River, on both sides of Fivemile Prairie, the specific yield is generally less than 5 percent of the aquifer volume.

Use of Water From the Spokane Aquifer

Ground water provides virtually all domestic, municipal, and industrial (other than aluminum production) water needs and a large part of the irrigation supply not satisfied by the Spokane River. Besides that obtained from individual household wells, domestic water is provided by nearly 150 separate community-supply wells. The fact that some of these are former irrigation wells indicates the conversion of farmland to suburban developments.

Converting ground-water pumpage values from cubic feet per second (Bolke and Vaccaro, 1981) to acre-feet, the total amount of ground water pumped during 1977 was about 164,000 acre-feet. About 70 percent of this, or 116,000 acre-feet, was used for municipal supplies, which include minor domestic irrigation supplies (for lawns and small gardens) and some industrial and commercial supplies. Most of this amount was pumped from a group of Spokane city wells located near Parkwater; about 26,200 acre-feet was withdrawn in 1977. The major irrigation and industrial water supplies each totaled about 15 percent of the amount of ground water pumped, or 24,000 acre-feet each. The areal distribution of ground water pumpage in 1977 is shown in figure 32.

Quality of Water in the Spokane Aquifer

General Statement About Water Quality

The quality of ground water depends upon the natural and man-affected environments through which the water has passed. Water quality is influenced in various ways as the water moves through the hydrologic cycle, as summarized below.

1. Rain and snow falling through the atmosphere usually pick up some gaseous im-

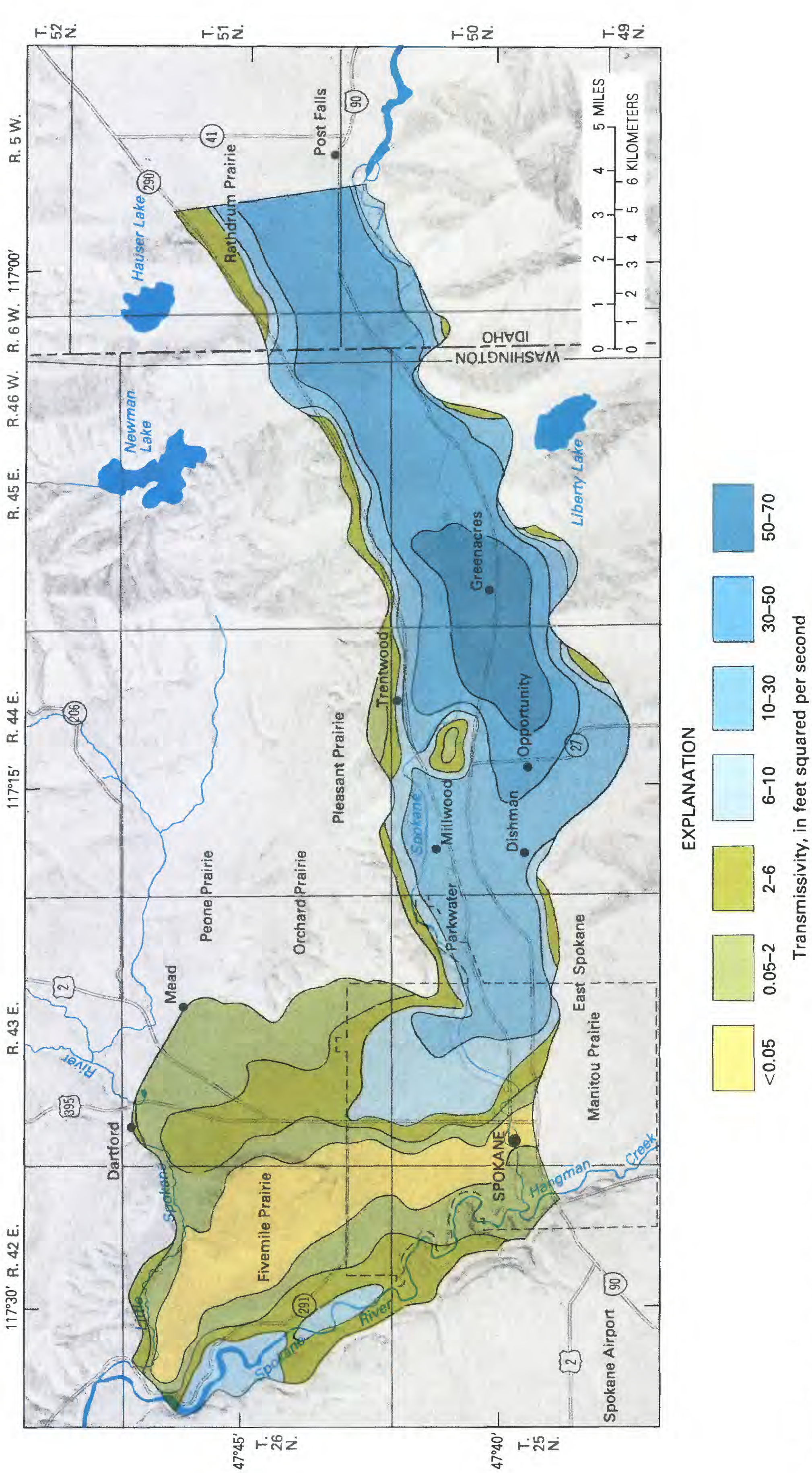


Figure 29. Areal variations in transmissivity in the Spokane aquifer. (From Bolke and Vaccaro, 1981.)

purities and minute particles that are natural, such as Mount St. Helens ash and gases, and man-caused, such as gas and smoke emissions from automobiles, factories, and trash burnings;

2. Rainfall and snowmelt runoff passes over and through soils, rocks, vegetation, and artificial cover and picks up soluble minerals, organic materials, and residues of man's domestic, agricultural, and industrial activities and waste products;
3. Percolation through soils, unsaturated rock materials, and waste-disposal sites causes water to dissolve and take on additional substances;
4. During its time in and flowing through the aquifer, ground water, to some extent, is continually dissolving and (or) precipitating constituents; and
5. In coastal areas, spray from the ocean, carried inland by storms, may increase the salt content of clouds and precipitation back to the land surface.

In all these pathways, the water continually is subject to the chemical and biological variations in and between these environments,

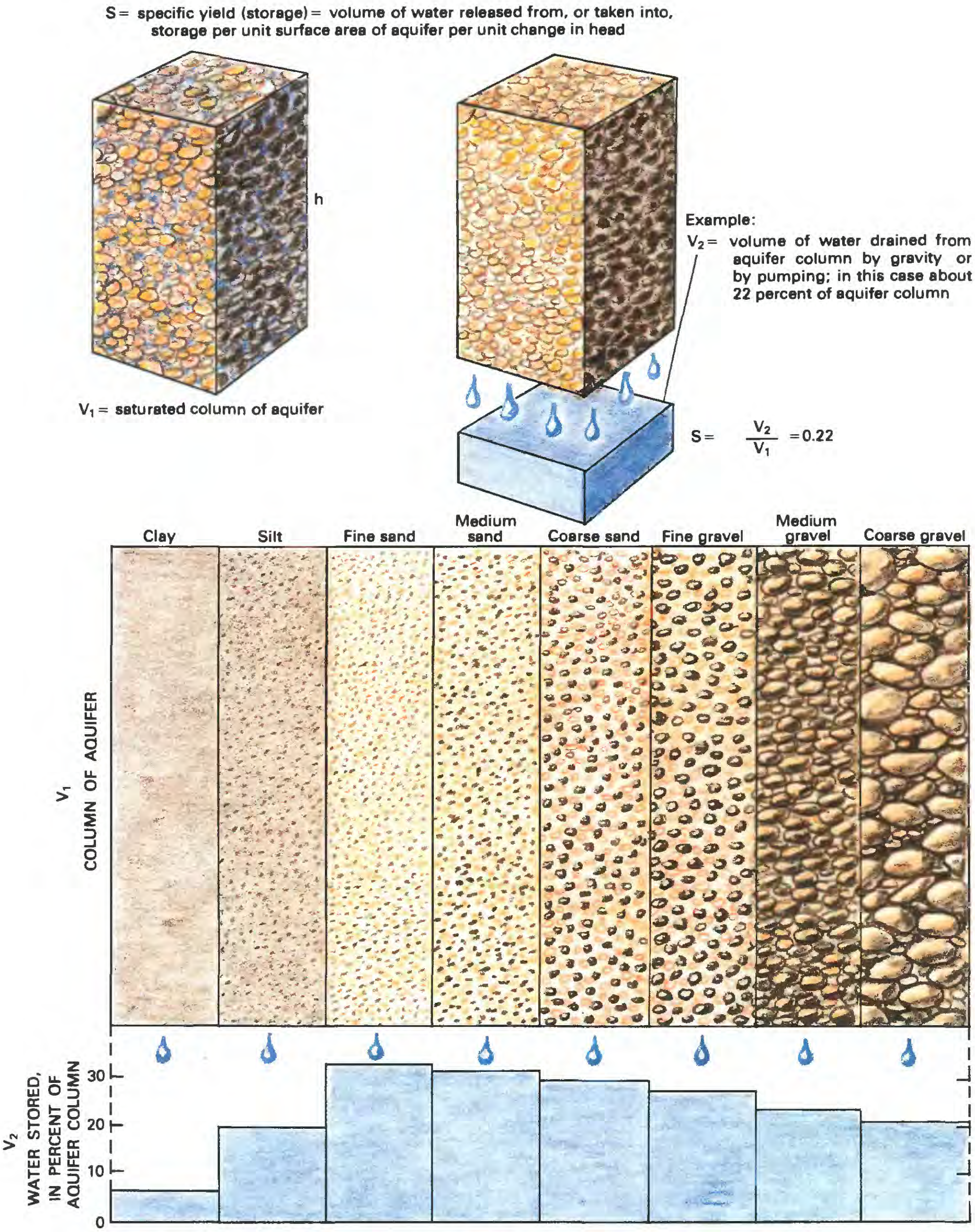


Figure 30. Explanation of the specific yield of an unconfined aquifer and generalized specific yields of various unconsolidated aquifer materials.

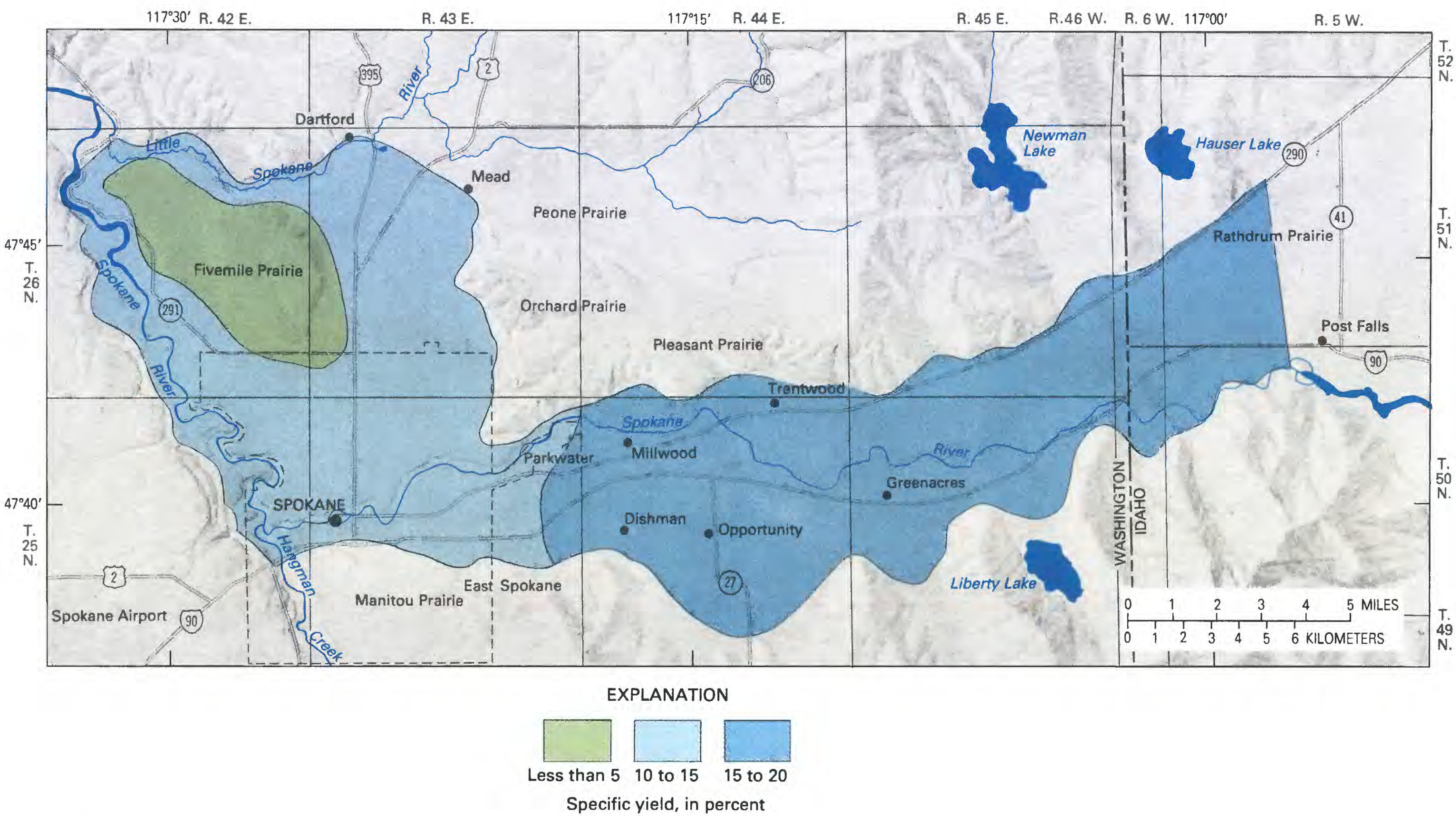


Figure 31. Areal variations in specific yield of the Spokane aquifer. (From Bolke and Vaccaro, 1981.)

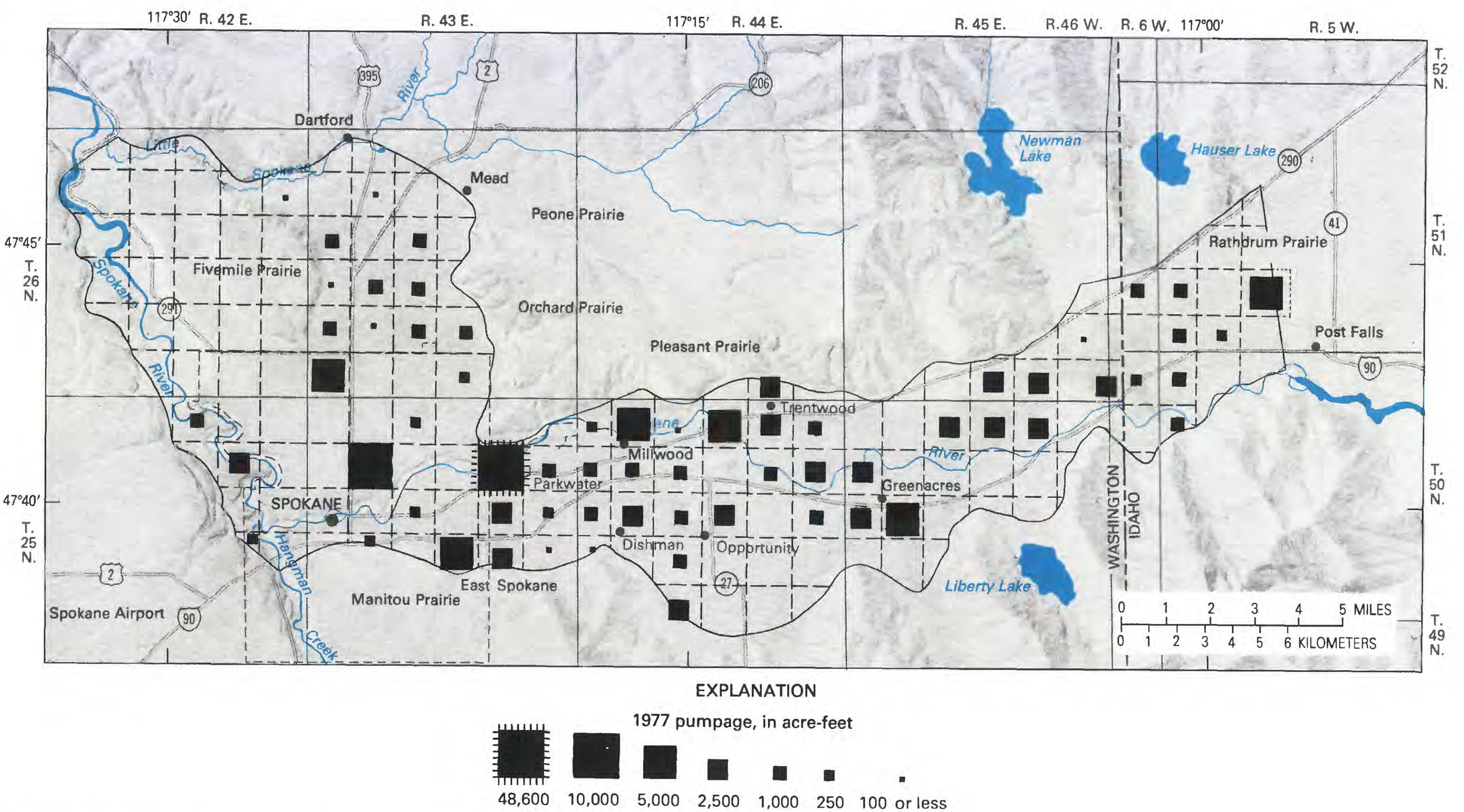


Figure 32. Distribution of ground-water pumpage in the Spokane aquifer in 1977, by section. (Modified from Bolke and Vaccaro, 1981, fig. 5.)

not only in the types of substances in the water but in their concentrations. Of significance to the concentrations of various substances is the amount of water—which directly relates to its diluting abilities—that flows through the hydrologic system seasonally and from year to year. From the foregoing, we can see that the quality of water in the Spokane aquifer can be affected locally by the Spokane River and by man's activities on the land surface.

An evaluation of the quality of water in the Spokane aquifer requires that we have a general understanding of the chemical characteristics of water in its purest form—rainwater (which is considered the cleanest natural water). Yet, we find that even rainwater contains impurities gained along its route from the clouds to the earth.

According to a study of the chemical characteristics of natural water (Hem, 1970), the specific conductance—the ability to transmit an electrical current—of the purest water that can be made would be near 0.05 micromho, but ordinary distilled water will normally have a conductance of at least 1.0 micromho. Because rainwater has ample opportunity before touching the earth to dissolve gases and particles of dust or other airborne material, it may have a conductance much higher than distilled water, especially near the ocean or sources of atmospheric pollution. According to a study by Feth, Rogers, and Roberson (1964), specific conductance of melted snow in the northern Sierra Nevada and other mountainous areas of the Western United States ranged from 2 to 42 micromhos. A study by Whitehead and Feth (1964) of several rainstorms over urbanized areas, as at Menlo Park, California, revealed values greater than 100 micromhos.

The specific conductance of surface and ground water has a wide range across the country, and, in some areas, where rainfall is low in dissolved substances and rocks contain minerals that are poorly soluble, it may be as low as 50 micromhos. In other places, such as along some coastal areas, conductances of 50,000 micromhos or more may be found; this is approximately the conductance of seawater.

Concerns About the Quality of Water in the Aquifer

The high permeability of the Spokane aquifer and its hydraulic connection with the Spokane River—and the potential for surface activities to affect ground-water quality in most areas—has been the cause for increasing concern about the long-term water quality in the aquifer. This has been relevant particularly because of the potentially detrimental effects of man's increasing developments on the land above the aquifer. Because the aquifer is the principal source of water for the valley's municipal, industrial, domestic, and irrigation needs, preservation of the good water quality is important to man's continuing developments in the valley. Recognition of this goal has resulted in the formation of a citizens' advisory committee and a water-quality-management plan designed to protect the existing water quality from degradation. The plan was prepared, in part, with Federal funds administered by the U.S. Environmental Protection Agency under Section 208 of Public Law 92-500 and with State funds administered by the Washington State Department of Ecology under State Referendum 26. The plan enlisted the support and technical expertise of representatives of government agencies and consultants, and implementation of the plan has been the responsibility of governmental agencies serving the public interest.

The principal concern is the possibility of degradation of the quality of drinking-water supplies. This concern is based principally on the belief that industrial wastes and sewage from the rapidly expanding residential development across the valley floor—in most cases discharged into the ground via individual septic tanks and drain fields—will result in contamination of the underlying ground water. Understandably, this concern has resulted in numerous studies relative to ground-water quality, land use practices, and the necessity and feasibility of planning for centralized sewage-disposal systems for such residential developments.

Water-Quality Criteria: What Makes the Water Drinkable?

The principal water-quality properties used to determine whether or not water in the Spokane aquifer is safe for drinking are the amounts of dissolved solids, chloride, and nitrate nitrogen in the water. The presence and amounts of these constituents provide a basis for evaluating the effects that man's land use developments and sewage-disposal systems may have on water quality in the underlying aquifer.

In 1962, the U.S. Public Health Service established standards for public drinking-water supplies in the United States; these subsequently were updated by the U.S. Environmental Protection Agency (1975, 1977a, b). For constituents analyzed in water samples collected from the Spokane aquifer and Spokane River, table 1 lists the maximum allowable and

Table 1. Maximum allowable and maximum recommended constituent concentrations in drinking water
[Milligrams per liter;—, not applicable]

Constituent	Concentration: Allowable	Concentration: Recommended
Iron	—	0.3
Chloride	—	250
Fluoride	2.0	—
Nitrate nitrogen	10.0	—
Dissolved solids	—	500
Arsenic	.05	—
Cadmium	.010	—
Copper	—	1
Lead	.05	—
Mercury	.002	—
Selenium	.01	—
Zinc	—	5
Endrin	.0002	—
Lindane	.004	—
Toxaphene	.005	—
Phenols	—	.001

the maximum recommended concentrations. (The recommended values apply to constituents that are not in themselves hazardous to health but may cause the water to be distasteful.)

The following general discussion of the foregoing constituents is from a comprehensive report on water-quality criteria by the National Academy of Sciences, National Academy of Engineering (1973).

Dissolved Solids

The dissolved-solids concentration in a water sample represents the sum of all the dissolved minerals in the sample. A high dissolved-solids content usually indicates that the water has passed through rocks composed of readily soluble minerals and (or) that the water has moved relatively slowly through the aquifer materials, thereby allowing a longer period for it to act upon and dissolve minerals of lesser solubility. Because man's land use and waste-disposal practices also can increase dissolved-solids concentrations in the underlying ground water, this property of the water is considered important to a general evaluation of man's effects on the water quality in the Spokane Valley.

A high dissolved-solids content generally is considered objectionable because of possible physiological effects, mineral tastes, and economic consequences. High dissolved-solids concentrations may have a laxative effect; high concentrations of sulfate and chloride are often associated with costly corrosion damage to water systems; and excessive amounts of iron and manganese will stain plumbing fixtures.

Because drinking water with a high concentration of dissolved solids is likely to contain an excessive amount of some specific substances that, in addition to causing the foregoing effects, would be esthetically objectionable to the consumer, the limit for dissolved solids has been established as 500 milligrams per liter. However, at concentrations of 250 milligrams per liter or more, the water may still have a laxative effect on some people.

Chloride

Chloride generally is found in low concentrations in natural waters, except in coastal areas where airborne sea salts are carried inland. It also is found in water that occurs in or has passed through evaporitic rocks—those formed from evaporation of salt-rich solutions, such as seawater and water in closed-basin lakes (such as the Great Salt Lake in Utah).

High concentrations of chloride can be detected by a brackish or salty taste and can lead to rejection of the water for drinking purposes; for example, a sodium chloride (sodium plus chloride) concentration of 395 milligrams per liter is noticeable to the taste, and the taste of coffee is affected when brewed in water containing about 200 milligrams per liter of sodium chloride or about 220 milligrams per liter of calcium chloride (calcium plus chloride). On the basis of taste, and because of the wide range in taste perceptions by humans, a limit of 250 milligrams per liter of chloride in public drinking-water supplies was considered to be a reasonable criterion.

Nitrate Nitrogen

The presence of nitrate in water indicates one or more of the following sources of contamination from the land surface: (1) surface-water runoff from cultivated and fertilized soils, (2) leaching of substances contained in certain industrial wastes and of soils with organic substances, (3) percolation from septic-tank drain fields and from areas of animal concentration, such as feedlots and corrals, and (4) percolation of liquid wastes from uranium-processing plants.

Potential Causes of Poor Water Quality

The percolation of poor-quality water from the land surface, either concentrated at local sources or through distribution over broad areas, can have a detrimental affect on ground-water quality. Ground-water quality can be detrimentally affected by percolation of poor-quality water from the land surface, either concentrated at local sources or through distribution over broad areas. The water quality also can be degraded by percolation of poor-quality stream or lake water. The principal potential point sources of biological and chemical degradation include seepage from (1) solid-wastes disposal sites and sanitary landfills, (2) industrial-wastes disposal sites, (3) gravel-mining operations, (4) individual septic-tank drain fields and cesspools, and (5) municipal and smaller public sewage systems. Impact also may occur from infiltration of irrigation water that contains liquid fertilizers and pesticides and from seepage of storm-water runoff. Some processes by which such sources of potential contamination reach and are dispersed within an aquifer are shown in figure 33.

Land Use Over the Aquifer

To evaluate the potential for contamination of the Spokane aquifer by man's activities, we might examine the areal distribution of various types of land use in the valley, as shown in figure 34. As indicated in the figure, agricultural activities predominate mostly between the State line and the community of Greenacres, along with small localized areas north and south of Opportunity. Within this reach, however, much agricultural land is being replaced by urban and residential developments, which has resulted in related changes in water use and demand.

More than one-quarter of a million people live and work in the Spokane Valley; water for most of their domestic and industrial needs is obtained from the Spokane aquifer. Once the water is pumped from the aquifer, distributed, and utilized by man in his various activities, the unconsumed part is returned by various pathways of percolation to the ground-water system. These include percolations from septic-tank drain fields, irrigated areas, and sites used for disposal and storage of solid and liquid municipal and industrial wastes.

West of Greenacres, in a narrow east-west strip through the central part of the valley into and through the city of Spokane, commercial and light industrial activities predominate; urban developments exist on the perimeter. Immediately northwest of Greenacres are the Spokane Industrial Park and an aluminum plant. The Opportunity and Dishman areas and the area to the south are residential areas characterized by domestic wastes discharges through individual septic-tank systems.

Within much of the city limits of Spokane, residential and commercial land use predominates. West and southwest of the city limits of Spokane, much of the land is agricultural or undeveloped, with only small, scattered areas of residential development.

Water Spread Over the Land Surface

The amount of water applied over the land surface (essentially all by domestic and agricultural irrigation) has the potential to affect ground-water quality, depending upon the amount of fertilizing agents or pesticides carried in the water. Therefore, a general accounting of the amount of water applied to the land provides a basis for understanding the potential for contamination of the Spokane aquifer.

All the water pumped from the aquifer for irrigation is applied to the land surface, as is some of the water used primarily for municipal and industrial purposes. About one-half of the water withdrawn by seasonal pumping of Spokane city wells is applied to the land surface in the form of lawn and garden irrigation, and the other one-half eventually is discharged to the sewer system after various uses. About 10 percent of the water withdrawn by continuously pumped city wells is applied to the land surface, and 90 percent is discharged to sewers. About 70 percent of the municipal water pumped by cities other than Spokane is applied to the land surface by domestic irrigation, but very little, if any, of the water pumped from the industrial wells is applied to the land surface.

Point-Source Contamination

Point-source contamination refers to contamination resulting from pollutants being dumped, stored, or injected at distinct, individual locations (point sources). Examples of point sources are cesspools, septic-tank drain fields, and sites used for the disposal (landfills) and storage of liquid or solid wastes and materials. Potential point sources include underground gas and diesel-fuel storage areas and hazardous material spills resulting from train or

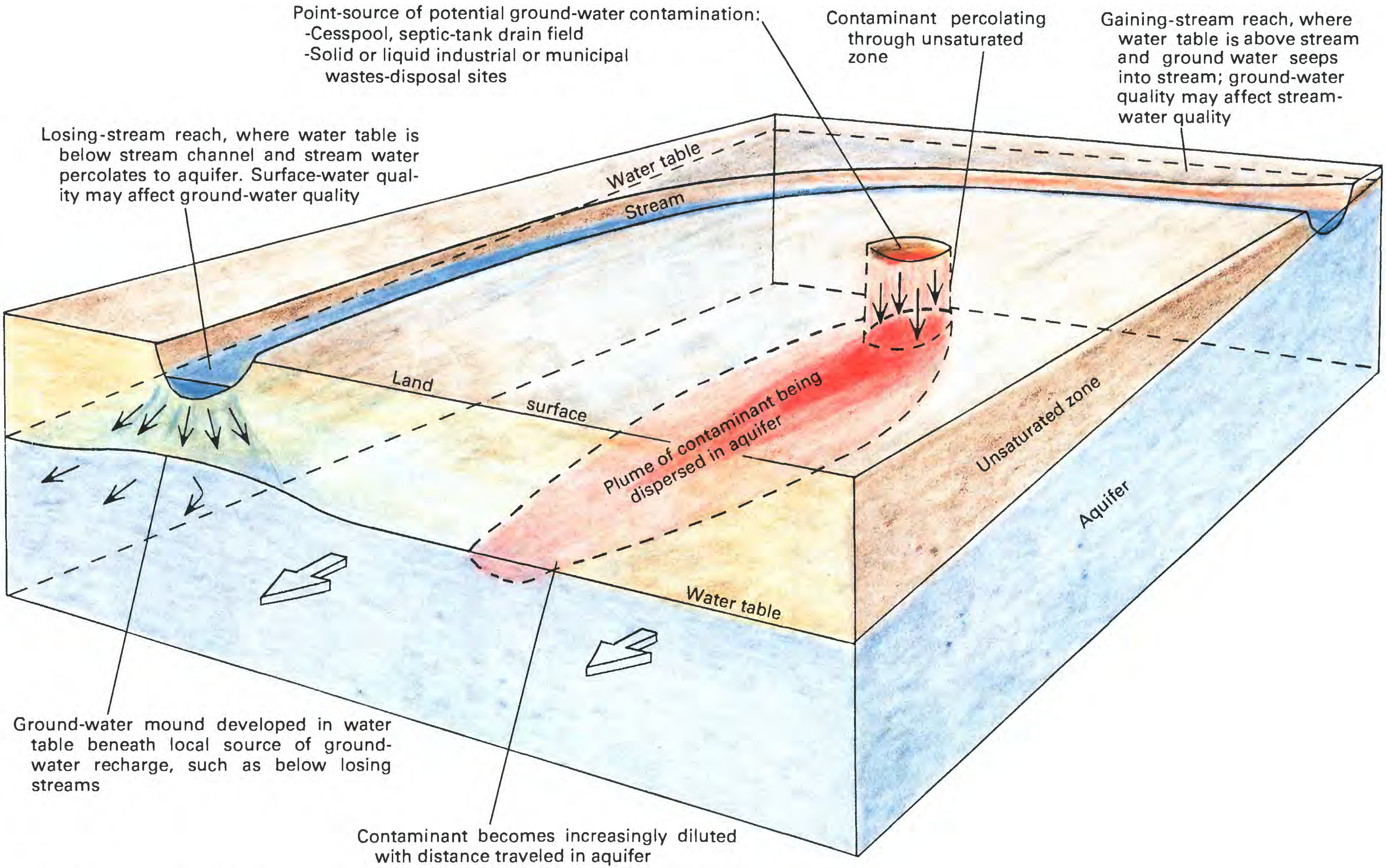


Figure 33. Processes by which potential contaminants reach and disperse within an aquifer.

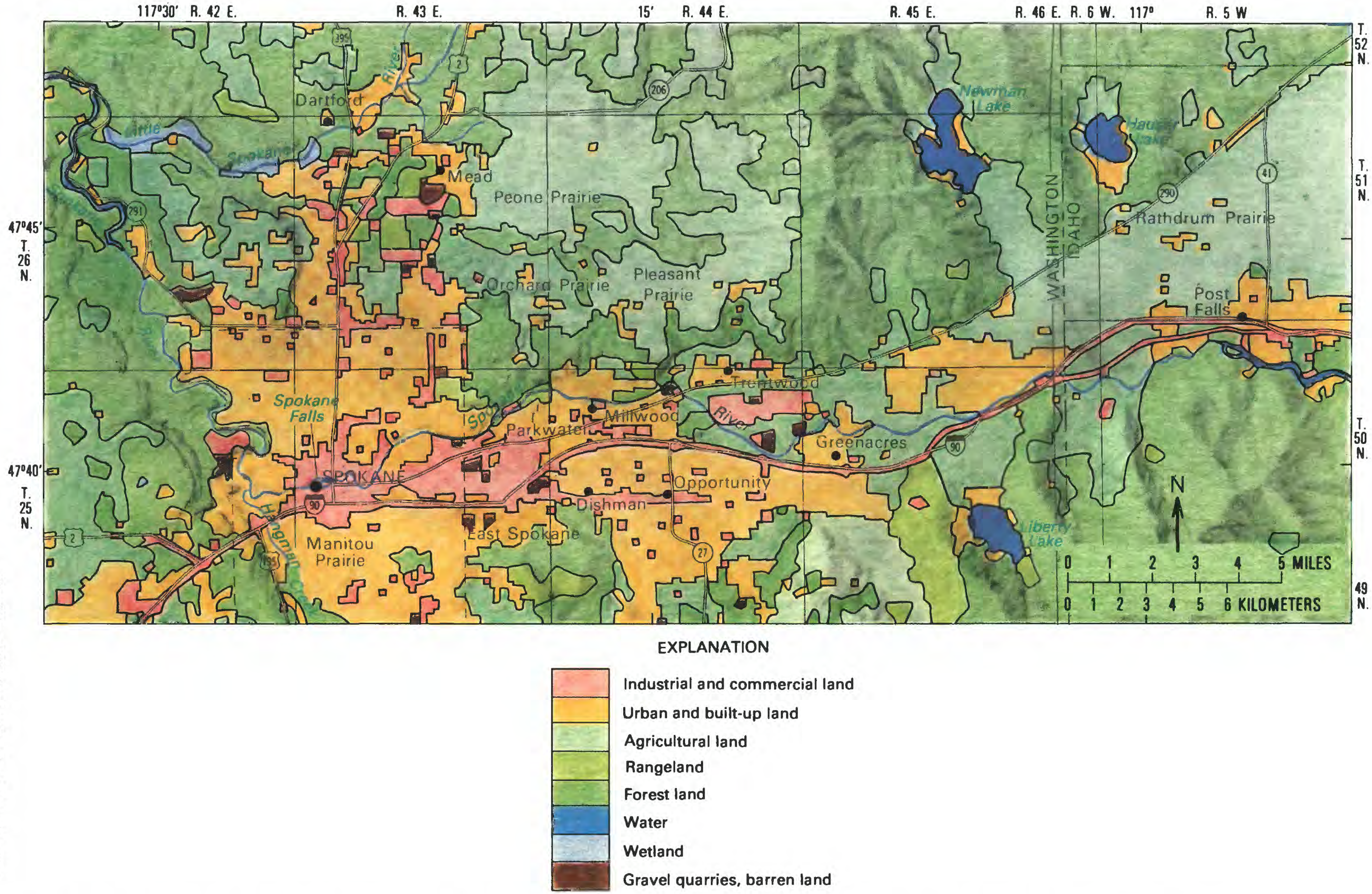


Figure 34. Types of land use and vegetal cover in the Spokane Valley. Generalized from a more detailed map by the U.S. Geological Survey (1978a).

truck accidents. The general areal distribution of various types of sewage-disposal systems and point sources of potential ground-water contamination throughout the Spokane Valley are shown in figure 35.

Septic-tank drain fields in residential and industrial areas are located mostly outside the Spokane city limits. Within the city, however, the aquifer has little potential for point-source contamination from septic tanks because most of the sewage is collected in a central sewer system, treated, then discharged to the Spokane River at a single facility in the northwestern part of the city (fig. 35). Four small areas outside the city also are served by the central sewer system.

According to calculations by Bolke and Vaccaro (1981), which were based on the average values of 164,000 acre-feet of water pumped from the aquifer for the period May 1977–April 1978, 25,000 acre-feet, or 15 percent, was returned to the aquifer by percolation from wastewater-disposal systems. Of this amount, 21,000 acre-feet was from numerous individual septic-tank drain fields, and only 4,000 acre-feet was from interim sewage-treatment plants. The treatment plants are generally small and collect, treat, and dispose of wastewater from apartment complexes, shopping centers, mobile-home parks, housing developments, schools and colleges, recreational areas, military installations, motels, and hotels. The effluent from these systems is discharged to drain fields, lagoons, or seepage ditches. The systems are not considered permanent and may be replaced in the future by extensions of existing sewer systems or more elaborate small systems.

Results of the Water-Quality Analyses

Evaluation of the present quality of ground water in the valley is based on interpretations by Vaccaro and Bolke (1983). One of their objectives was to assess areally and vertically the water-quality variations of the principal chemical constituents of drinking water in the aquifer over a 1-year period. Areal representation was achieved by collecting water samples from 142 wells; of these, data were collected from 100 existing wells at least three times during the study period. Vertical variations were assessed by collecting data from 18 test wells drilled specifically for water-quality evaluations. These test wells were drilled to depths of approximately 50 feet below the water table along selected cross sections of the valley.

Discussed below are results of the water-quality sampling, the variations observed, possible cause-and-effect relations, and references to water-quality criteria mentioned earlier. The principal properties analyzed are dissolved solids (calculated from specific-conductance values), chloride, and nitrate nitrogen.

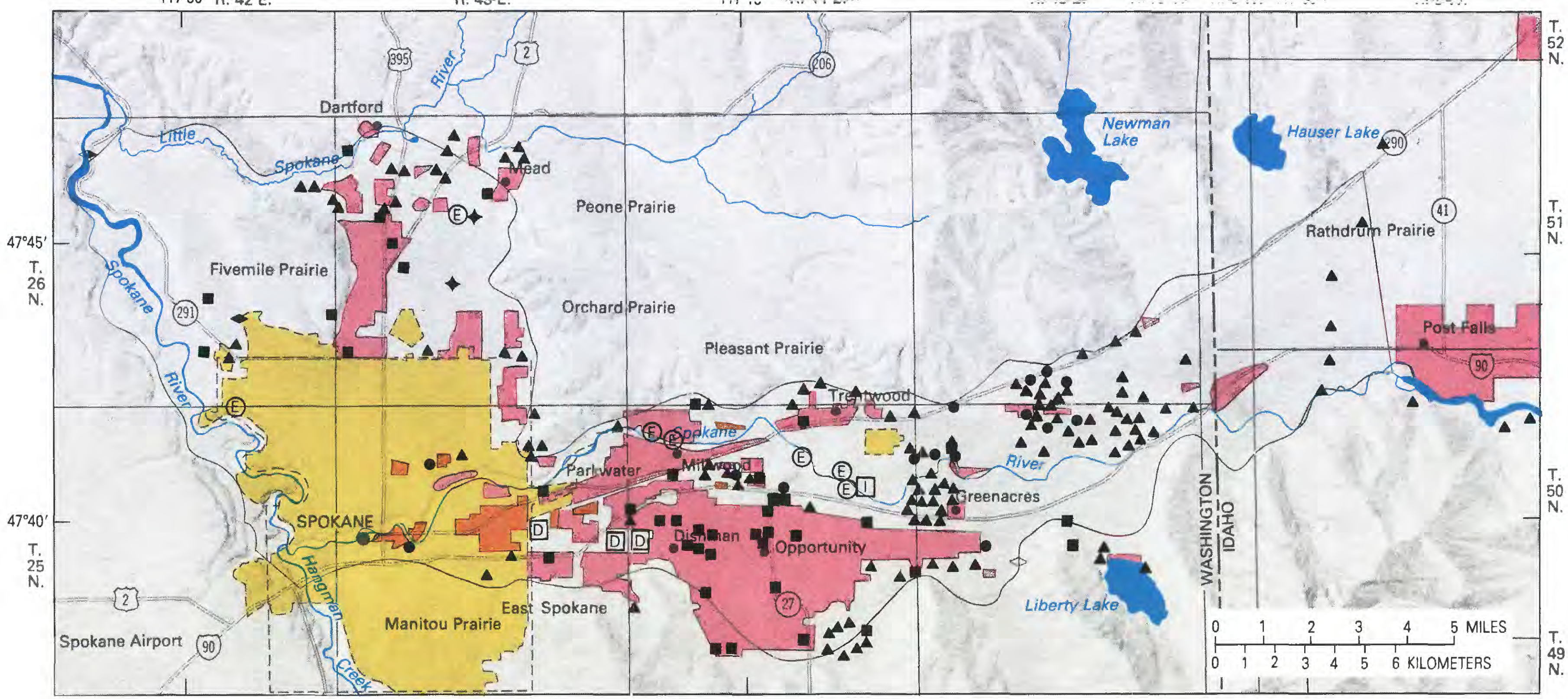
Specific Conductance and Dissolved Solids: The Mineral Content

The amount of dissolved minerals in water, also called the dissolved-solids content, is measured indirectly by its specific conductance. Therefore, where direct dissolved-solids values are lacking, values of the more readily measured specific conductance generally are used. According to the study by Vaccaro and Bolke (1983), the maximum recommended dissolved-solids concentration of 500 milligrams per liter in the Spokane aquifer is approximately equal to a specific-conductance value of 920 micromhos per centimeter at 25 degrees celsius. The graph of figure 36 shows the approximate relation between dissolved solids and specific conductance in the Spokane aquifer.

Results of the analyses of water samples from the Spokane aquifer during the 1977-78 study by Vaccaro and Bolke (1983) show that the water is very diluted, with a low specific conductance and related dissolved-solids content. The maximum recommended concentration of 500 milligrams per liter for dissolved solids (as estimated from the specific conductance) was not exceeded in any water samples analyzed. Specific conductance ranged from 73 to 820 micromhos and averaged 307 micromhos, about equal to dissolved-solids values of 40, 445, and 170 milligrams per liter. The maximum recorded specific conductance was 820 micromhos at well 26/42-21R3 on May 19, 1977; this is equivalent to a dissolved-solids content of 447 milligrams per liter.

The areal variations in specific conductance of ground water in the Spokane aquifer are shown in figure 37. The values represent the averages of the values obtained during the three sampling times, May and October 1977 and May 1978; in most cases, variations between sampling dates were minor. The specific conductance was lowest (less than 100 micromhos) along the Spokane River in the

Figure 35. Types of sewage-disposal systems and potential point sources of ground-water contamination in the Spokane Valley. (From Drost and Seitz, 1978.)



EXPLANATION

- Area served by sewer system
- Interim sewage-treatment plant
- Residential area served by individual septic tanks, cesspools, or aerobic treatment units
- Localized residential area served by individual septic tanks, cesspools, or aerobic treatment units. Approximately 50 or more people
- Industrial area served by septic tanks, cesspools, or aerobic treatment units
- Localized industrial area served by septic tanks, cesspools, or aerobic treatment units
- Point of discharge to surface water of effluent from sewage-treatment facility
- Point of discharge to land surface of effluent from sewage-treatment facility
- Sanitary landfill
- Landfill, open or substandard
- Inactive landfill
- Solid-wastes-disposal site
  - I - Industrial materials
  - D - Demolition materials

easterly 6–7 miles of the valley, which is in the area where the aquifer receives the most leakage—and diluting effect—from the Spokane River. The highest values (500 micromhos) were recorded in the marginal parts of the valley south of Opportunity and near Mead. It is apparent that these valleyside areas of highest specific conductance (and dissolved solids) are those farthest from the main ground-water flow system and the Spokane River, which often has a diluting effect on the ground water. Also noted were the minor changes in specific conductance downgradient along the central part of the valley that occurred in spite of progressive recharge by percolation of water affected by various land uses along the way. This again indicates that water-carrying chemicals and substances, percolating downward from the land surface to the water table, are being diluted by the ground water; that is, the ground-water flow is of sufficient volume and rate to reduce any local man-induced increases in dissolved-solids content.

Water-quality data collected during the longer period of 1946–76 (Drost and Seitz, 1978) show that specific conductance of water samples from the Spokane aquifer was never as high as the maximum of 820 micromhos recorded in 1977. However, a dissolved-solids concentration of 539 milligrams per liter, approximately equal to a specific conductance of nearly 1,000 micromhos, was recorded at well 25/44–2Q1 on June 6, 1974. This was interpreted as resulting from percolation to the water table of some liquid wastes being dumped into a nearby gravel pit. This was the only dissolved-solids value that exceeded the criteria for drinking water during the 1946–78 period of water-quality sampling.

Chloride: How Salty Is the Water?

Dissolved chloride is not a major component of native water (natural water, unaffected by man) in the Spokane aquifer, and, therefore, its presence in significant concentrations generally can indicate the effects of much of man's land use activities. However, according to Vaccaro and Bolke (1983), the chloride con-

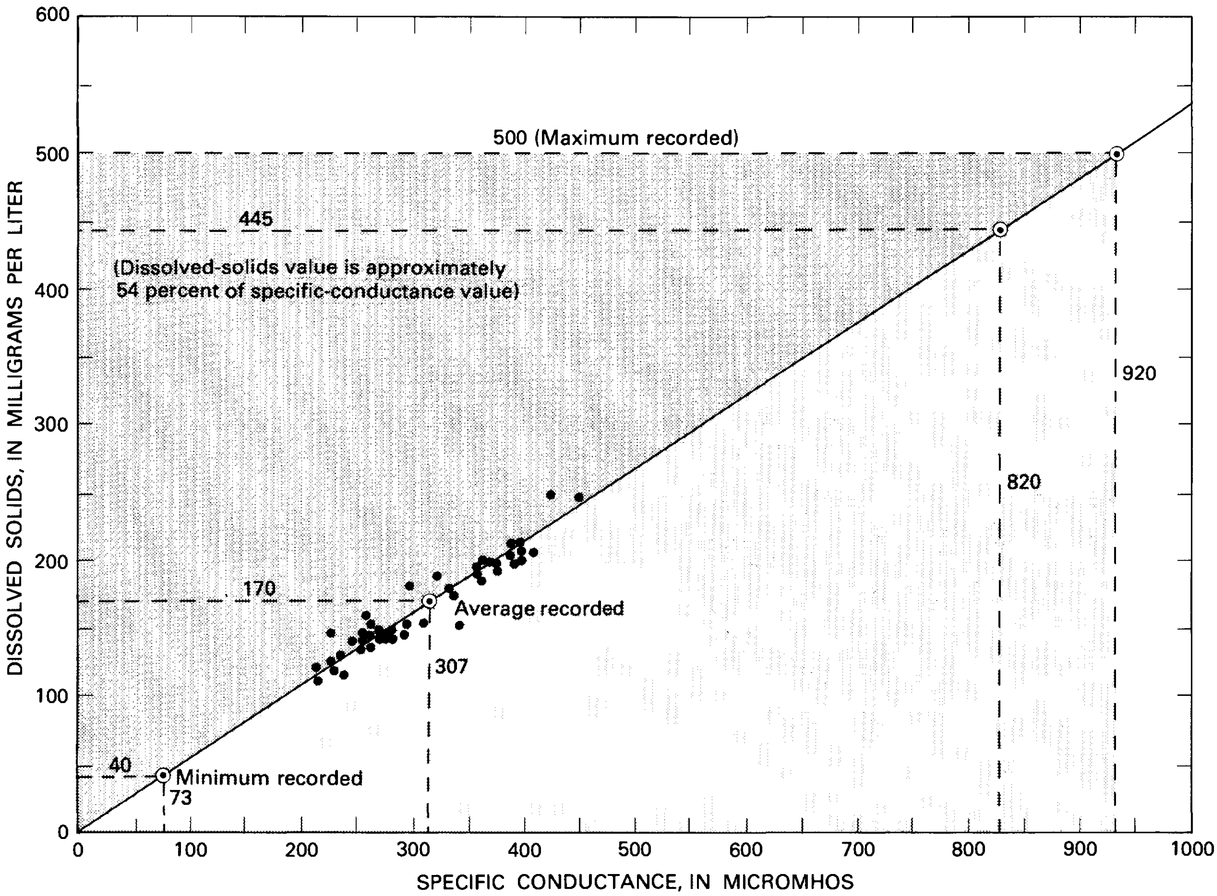
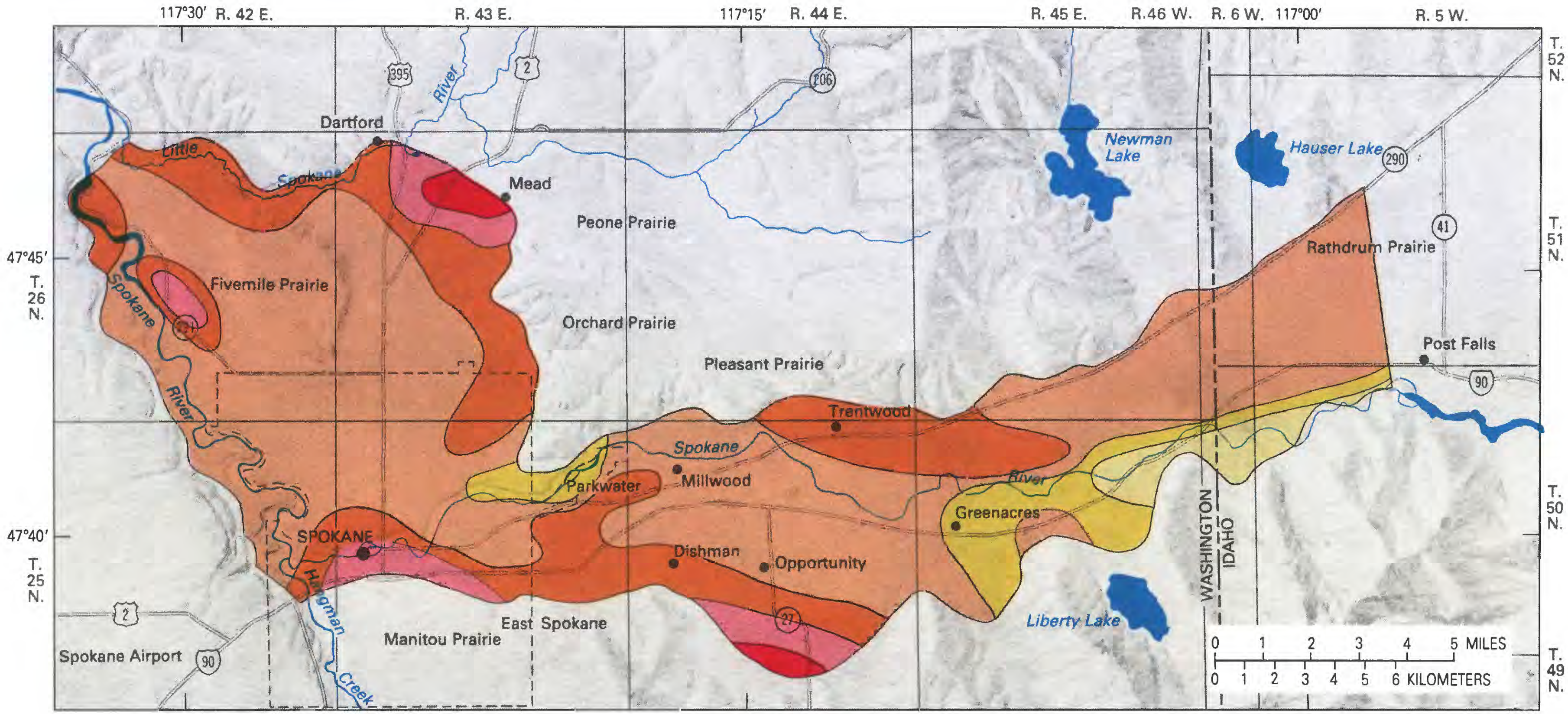


Figure 36. Approximate relation between values of dissolved solids and specific conductance in the Spokane aquifer. Values compared are those mentioned in text. Dots indicate measured compared values. (Modified from Vaccaro and Bolke, 1983).



EXPLANATION

—400— Line of equal specific conductance, in micromhos per centimeter at 25°Celsius

<100 | 100–200 | 200–300 | 300–400 | 400–500 | >500

Specific conductance, in micromhos per centimeter at 25°Celsius

Figure 37. Areal variations in average specific conductance of the Spokane aquifer, May 1977–May 1978. (From Vaccaro and Bolke, 1983.)

centrations noted during 1977-78 were low, from 0.4 to 24.0 milligrams per liter, with an average of 4.0 milligrams per liter, all well below the maximum of 250 milligrams per liter recommended for drinking water. The areal variations in average chloride concentration shown in figure 38 reveal the consistency of concentrations of 2 milligrams per liter or less throughout most of the aquifer. All the higher concentrations were found along the aquifer margins at some distance from the Spokane River. Ground-water inflows to the aquifer from peripheral areas had concentrations as high as 12 milligrams per liter in the Mead area.

The areal variations in "chloride loading" (the amount of chloride annually entering the Spokane aquifer from the overlying land) were calculated by Vaccaro and Bolke (1983) from the amounts and quality of water discharged over the land and at point sources. As shown in figure 39, and comparing it with figure 38, the transmissivity of the aquifer appears to be sufficiently high to allow enough flow to dilute and transport the material percolating from the land surface throughout most of the aquifer. Also, the ground-water flow should preclude significant long-term increases in chloride concentrations from the present land use activities.

The areas of greatest general chloride loading are south of Opportunity, east of Dishman, and north of Trentwood. The loadings near Opportunity and Dishman are the result of dense residential development, with homes having individual septic-tank discharges; loading in the Trentwood area reflects industrial activity and residences with septic-tank discharges. In general, the map showing areas of chloride loading (fig. 39) closely parallels a population-density map of the residential areas. Even within the sewered parts of the city of Spokane, a theoretical loading exists because of the spreading of water on the land surface. Agricultural land in the eastern part of the valley appears to contribute insignificant amounts of chloride to the aquifer.

Locally, chloride concentrations have increased, at least temporarily, as a result of man's activities. According to Drost and Seitz (1978), several cases of such increases involved local contamination (point-source loading) from industrial wastes. In late November 1954, for example, solid and liquid wastes from an aluminum-processing operation at Hillyard were dumped into a gravel pit about 170 feet above the water table. This resulted in a rapid increase in the chloride concentration in a well (26/43–34P1) about 1,000 feet to the north and downgradient from the gravel pit. Even though the dumping was stopped in February 1955 and much of the waste material was removed from the pit, the chloride concentration continued to increase, exceeding 1,000 milligrams per liter by June 1955. However, by March 1956, the concentration had decreased to 250 milligrams per liter, and, in May 1975, it was down to an acceptable 36 milligrams per liter.

A nearly identical situation occurred at an aluminum plant at Trentwood. The same type of liquid wastes had been dumped in a gravel pit with its bottom only about 20 feet above the water table. For 20 years, the effect on nearby wells was not noticeable, but, in 1964, a new gravel pit nearby became the site of a gravel-washing operation. The water was discharged over the accumulated wastes, and the resulting leaching of the wastes apparently was responsible for a salty taste in water from well 25/44–2Q1, about 1,000 feet from the old pit, and for a chloride concentration of 177 milligrams per liter in June 1964. Discharge of the liquid wastes subsequently was halted, and the chloride content of the well water decreased to 0.18 milligram per liter within 6 months.

Nitrate Nitrogen: Has the Water Been Polluted?

Figure 40 shows the general areal variations in nitrate nitrogen during 1977 and 1978 (Vaccaro and Bolke, 1983). As with specific conductance and chloride, the lowest values were recorded in the eastern and central parts of the valley. Higher concentrations were found in some marginal parts of the valley, at Spokane, and near Mead. At Mead, near the study area boundary, the criteria limit of 10 milligrams per liter was recorded.

Long-term records of nitrate concentrations, dating back as far as 1946 (Drost and Seitz, 1978), show a maximum concentration of 16 milligrams per liter in well 25/44–26L1 on November 4, 1970. This temporarily high nitrate concentration exceeded the recommended maximum of 10 milligrams per liter for drinking water.

QUALITY OF WATER IN THE SPOKANE RIVER

The quality of water in the Spokane River is important because the water is in direct contact with that in the aquifer and, therefore, has, to some extent, an influence on the quality of

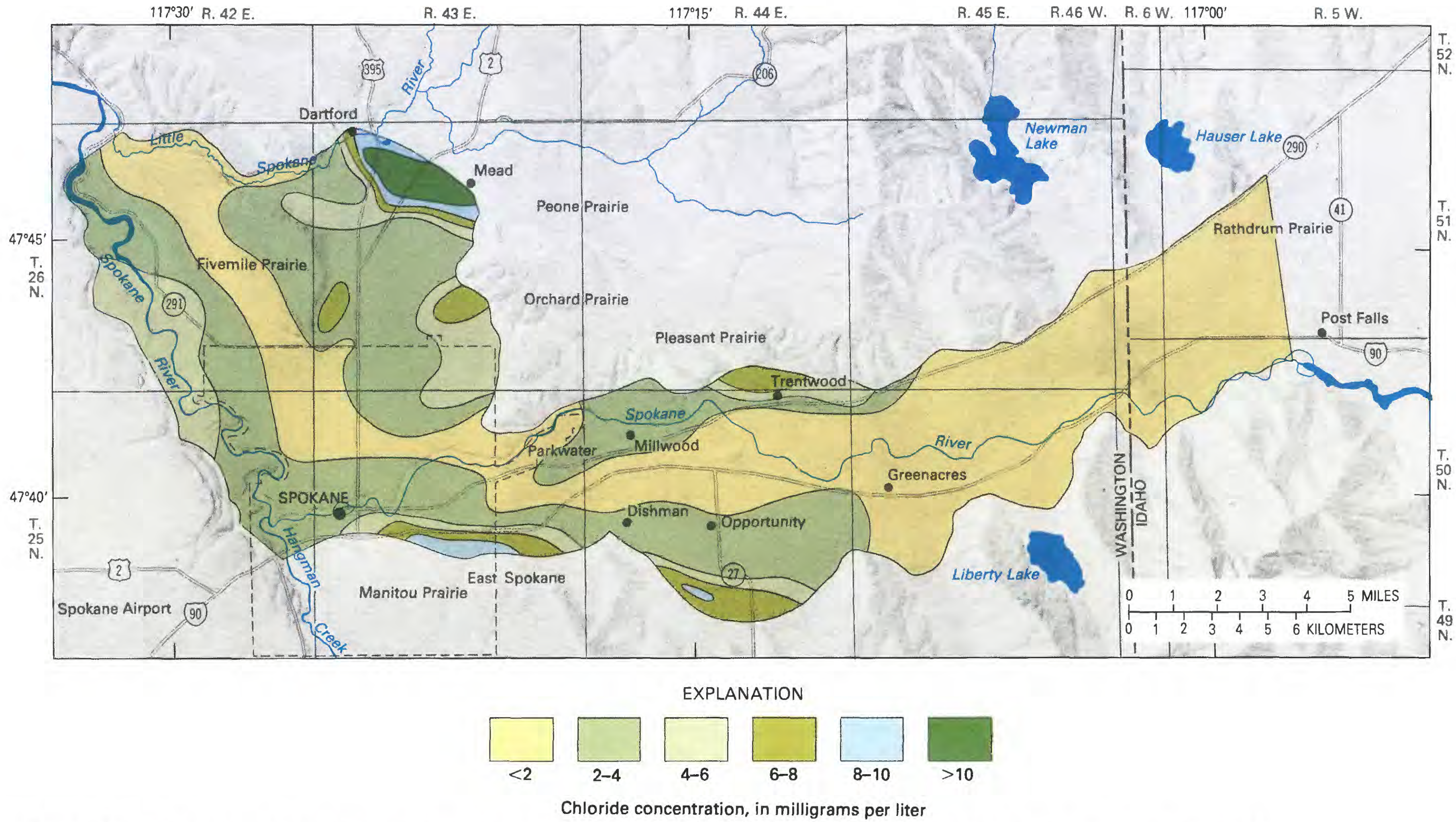


Figure 38. Areal variations in average chloride concentrations in the Spokane aquifer, May 1977–May 1978. (From Vaccaro and Bolke, 1983.)

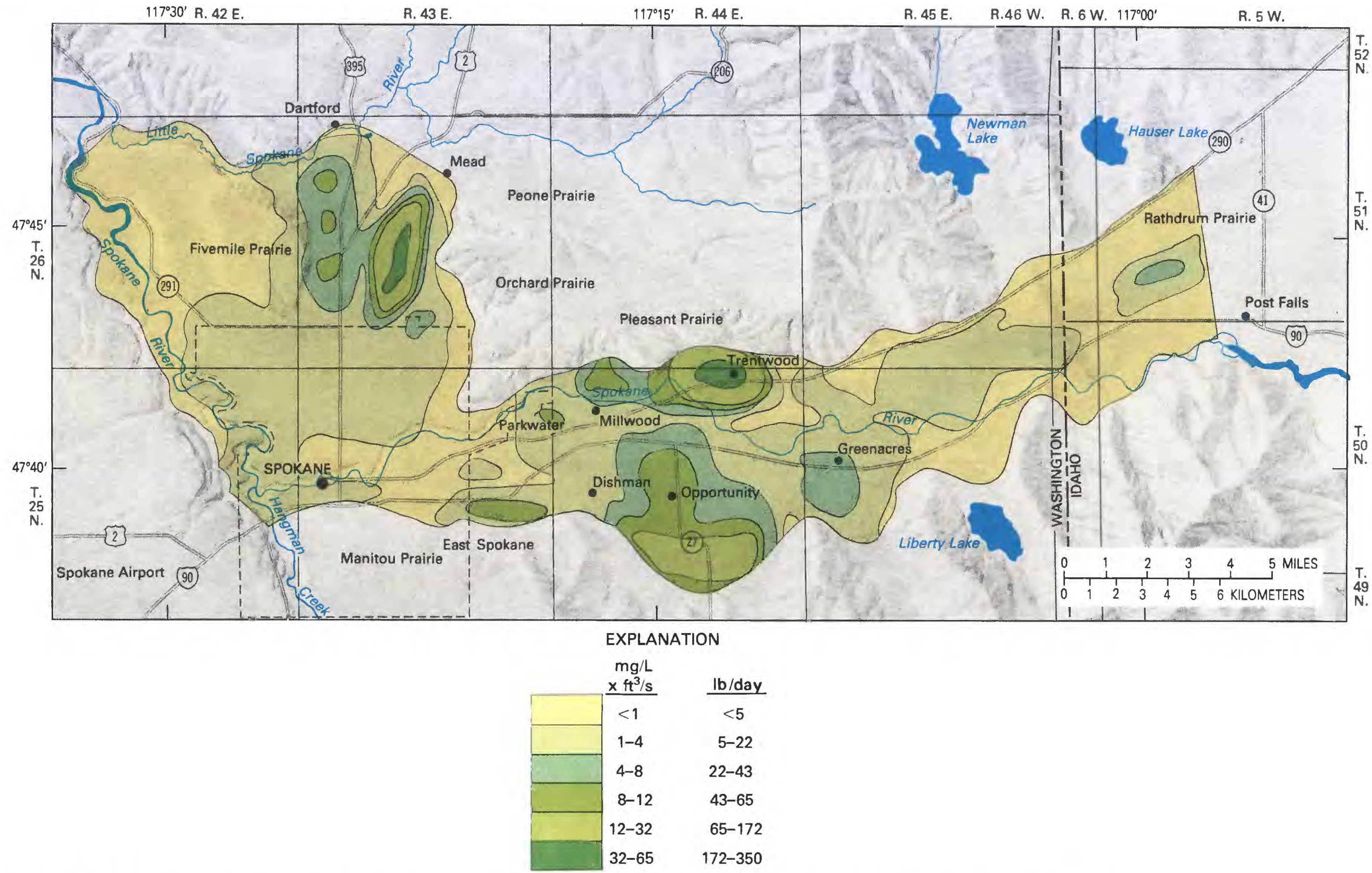


Figure 39. Areal variations in average chloride loading to the Spokane aquifer, May 1977–May 1978. (From Vaccaro and Bolke, 1983.)

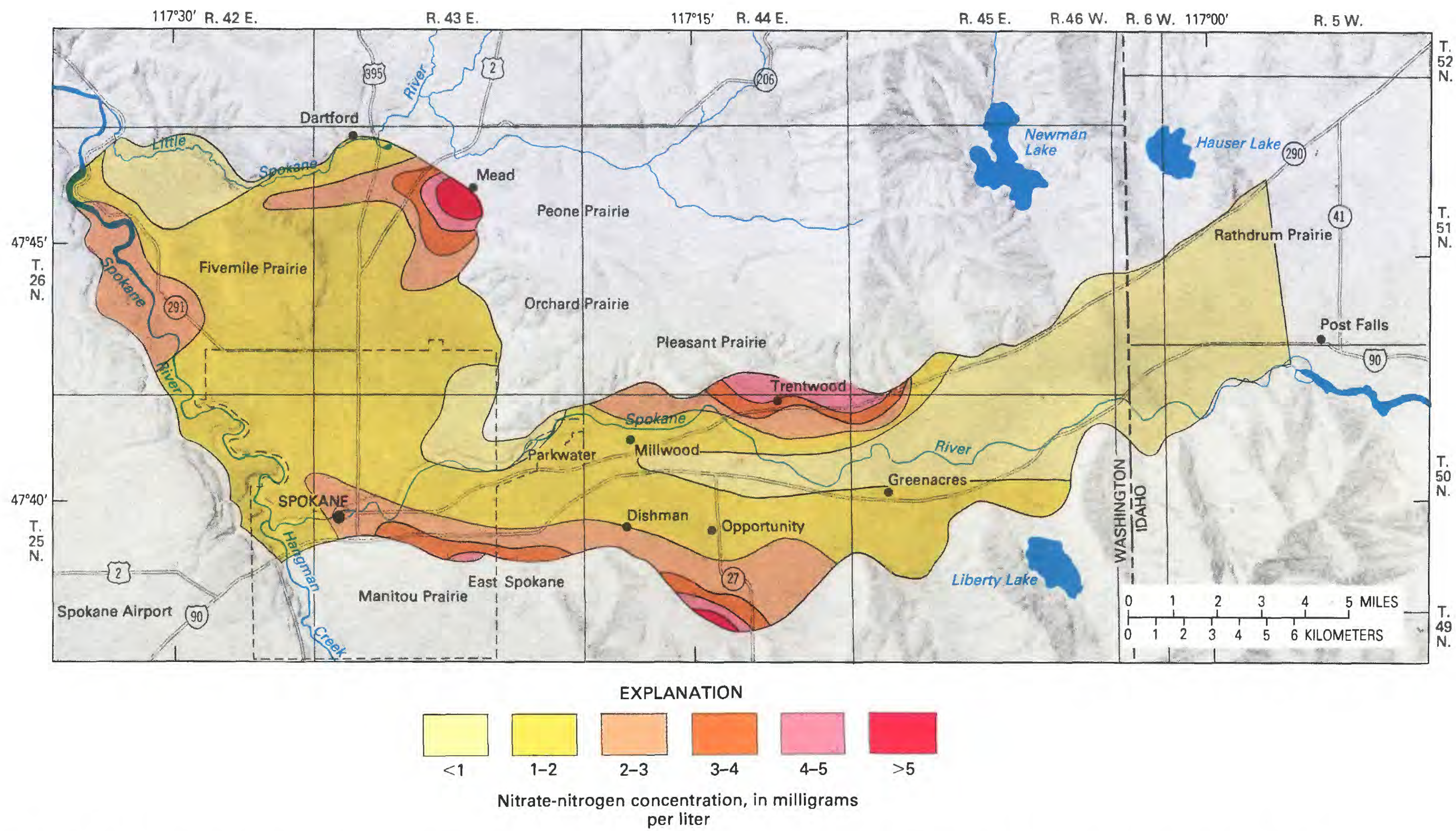


Figure 40. Areal variations in average nitrate nitrogen concentrations in the Spokane aquifer, May 1977–May 1978. (From Vaccaro and Bolke, 1983.)

ground water in the aquifer immediately adjacent to the river channel. The quality of the river water also is important mostly to people who utilize the river and its adjoining environment for homesites and recreation and for general esthetic enjoyment. As noted earlier, use of water directly from the river is limited mostly to irrigation in the eastern, rural parts of the valley and to nonconsumptive hydroelectric power generation; only minor amounts are diverted for industrial purposes. To date, river water has not been diverted for public drinking-water supplies, and such use is not anticipated in the foreseeable future.

Determination of the quality of the river water is based on analyses of various constituents in water collected from selected streamflow-gaging sites (fig. 14) at various times and intervals. The most complete sets of data were collected during the 1975-78 water years from sampling site 1 near Post Falls, Idaho, and site 7 at Riverside State Park, Washington. Analysis of the data from these two sites has provided the best available characterization of water entering and leaving the study area. The principal constituents examined included dissolved oxygen, dissolved solids, chloride, nitrate nitrogen, Kjeldahl nitrogen (ammonia nitrogen plus organic nitrogen), and phosphorus. These constituents are among those that might indicate water-quality changes resulting from man's activities along the river—such as the discharge to the river of industrial wastewater and treated municipal sewered water—and inflows along the channel of ground water that generally have higher concentrations of certain constituents.

Maximum concentrations of all examined constituents except dissolved oxygen generally occur during periods of low streamflow, when less water is available to dilute the concentrations. For this reason, determinations were made of constituent concentrations during, or near, days of minimum recorded river discharges.

Principal Constituents

As shown graphically in figures 41 to 43, downstream increases between Post Falls, Idaho, and Riverside State Park, Washington, were noticeable in nearly all the analyzed constituents during the period 1975-78. As was expected, concentrations of dissolved solids, chloride, nitrate nitrogen, Kjeldahl nitrogen, and phosphorus increased between the two sampling sites, indicating the net inflow into the river of more highly mineralized ground water. More significant, however, are the downstream increases in these constituents during the spring runoff period of March through May. These increases probably reflect some occasional large discharges from the municipal sewage-treatment plant upstream from the Riverside State Park sampling site, when the sewage system becomes overloaded by storm runoff water. The higher concentrations of chloride in February 1976 and April 1977 and of ammonia and organic nitrogen in May 1975 noted at Post Falls may reflect the discharge to the river of surface-runoff water carrying dissolved constituents from fertilizers spread on the agricultural lands upvalley.

In contrast to increased concentrations of the above-mentioned constituents with decreased streamflow, dissolved oxygen decreased between Post Falls and Riverside State Park during periods of low streamflow (fig. 43). This is to be expected because (1) low streamflow occurs during the warmer months of the year, and oxygen solubility and content decrease as water temperature rises and (2) a large part of the water in the river at Riverside State Park is that discharged from the Spokane Sewage Treatment Plant. The oxygen content of this water has been depleted severely by bacterial action during treatment.

An analysis also was made of downstream changes in selected water-quality characteristics during the period of low streamflow in summer. It is at this time that the river water has larger proportions of ground water, with its generally higher concentrations of certain dissolved minerals. The availability of water-quality data from seven sites along the river during the period July–September 1973 allowed for the evaluation of downstream variations, which are shown in figure 44.

Of the five properties analyzed, only nitrate nitrogen and total coliform bacteria showed generally steady downvalley increases. Nitrate nitrogen increased from 0.08 milligram per liter at the Stateline Bridge (site 2) to 0.75 milligram per liter below Nine Mile Dam (site 10), and total coliform bacteria increased from less than 20 colonies per 100 milliliters at the Stateline Bridge to 6,000 colonies below the dam. In addition, coliform bacteria was in concentrations greater than 40,000 colonies below the sewage-effluent discharges at the sewage-treatment plant. Increases in coliform bacteria and nitrate nitrogen (and also phosphorus, as mentioned below) are significant because of their potential for causing the growth of algae in the river. This would be particularly true where the flow decreases and the water becomes impounded, as in the reservoir behind Nine Mile Dam and at Long Lake (below the study area, fig. 2).

These substances also increased significantly below points of sewage-effluent discharge. Total phosphorus increased from 0.08 milligram per liter at the Stateline Bridge (site 2) to 0.24 milligram per liter at the Trent Bridge (site 3), then decreased to 0.02 milligram per liter at the Fort Wright Bridge (site 8) before again increasing considerably below the sewage-treatment plant to 0.33 milligram per liter as recorded at Riverside State Park. Total Kjeldahl nitrogen also showed similarly noticeable increases below points of sewage-effluent discharges, from 0.67 milligram per liter at Stateline Bridge to 0.90 milligram per liter at the Trent Bridge to 2.3 milligrams per liter at Riverside State Park, with minor decreases observed at sites in between.

Coliform Bacteria

Analysis was made of total coliform bacteria in water sampled at five sites on the Spokane River between the Stateline Bridge and Nine Mile Dam. Although the analysis was based on samples collected at irregular intervals during the period 1968–77, the maximum recorded coliform counts—reported as number of colonies per 100 milliliters of water—was more than five times higher at Nine Mile Dam (21,500 counts) than at the Stateline Bridge (4,000 counts; fig. 45). Fecal-coliform bacteria generally constituted 3–8 percent of the total coliform bacteria in the counts.

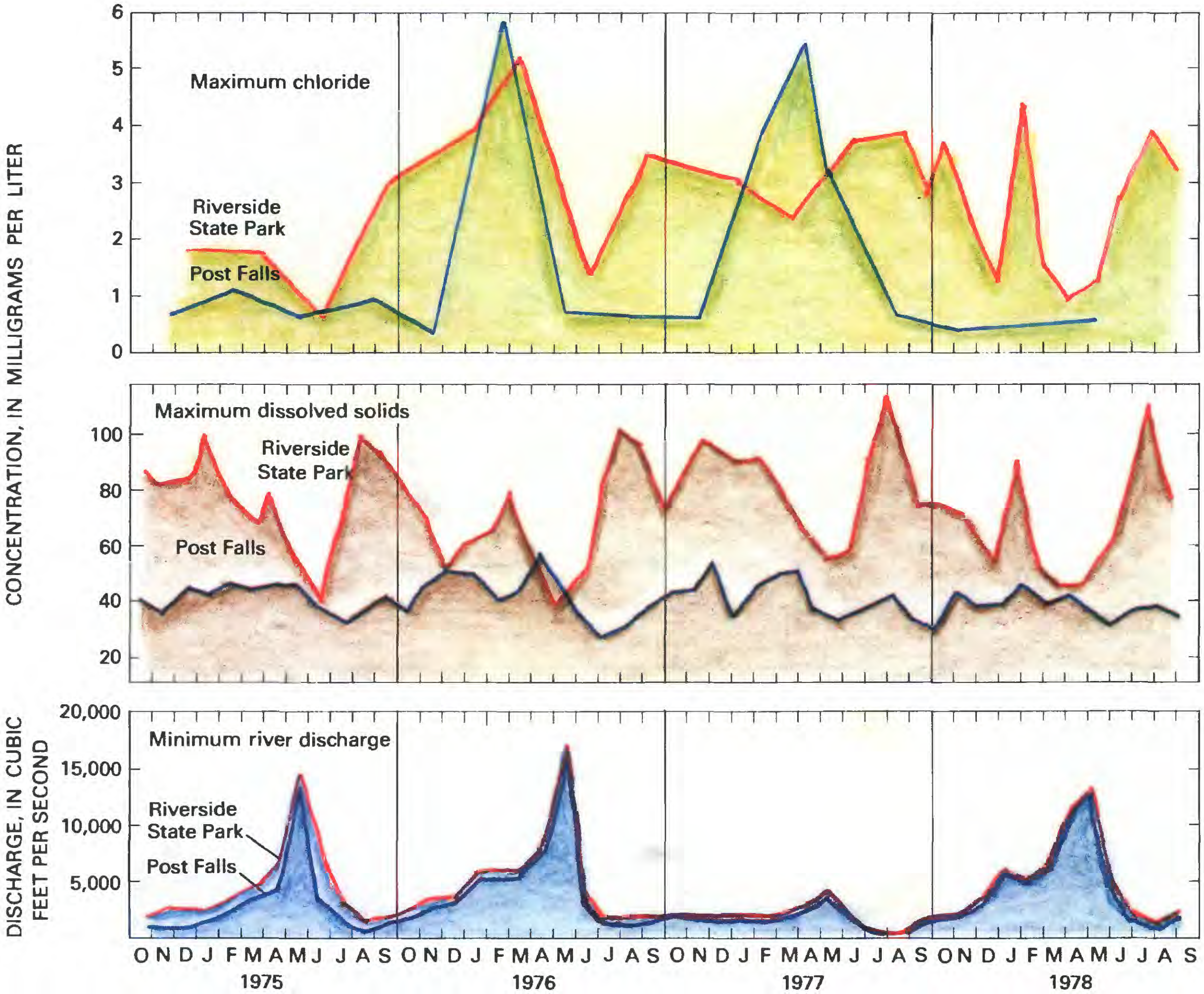


Figure 41. Maximum concentrations of dissolved solids and chloride in the Spokane River and minimum discharges of the Spokane River near Post Falls, Idaho, and Riverside State Park, Washington, as recorded monthly during the 1975–78 water years. (Data from annual summaries of the U.S. Geological Survey, 1976–79.)

In September 1972, many water samples were collected from the Spokane River and from one municipal (Spokane) and five industrial sewage-treatment plants that discharge effluent to the river. The five industrial plants yielded effluent with average total coliform bacteria counts ranging from less than 10 to 550 colonies per 100 milliliters. The Spokane Sewage Treatment Plant yielded effluent with about 19,200 colonies per 100 milliliters, far in excess of the long-term mean at this site.

GROUND-WATER QUALITY: CAN IT BE PROTECTED?

Streams, lakes, and ground water are natural resources that are considered to be part of the public domain. As such, their availability and quality are a public trust, to be managed by representatives of tne public to assure protection of the water and preservation of its natural quality for the benefit of present and future generations.

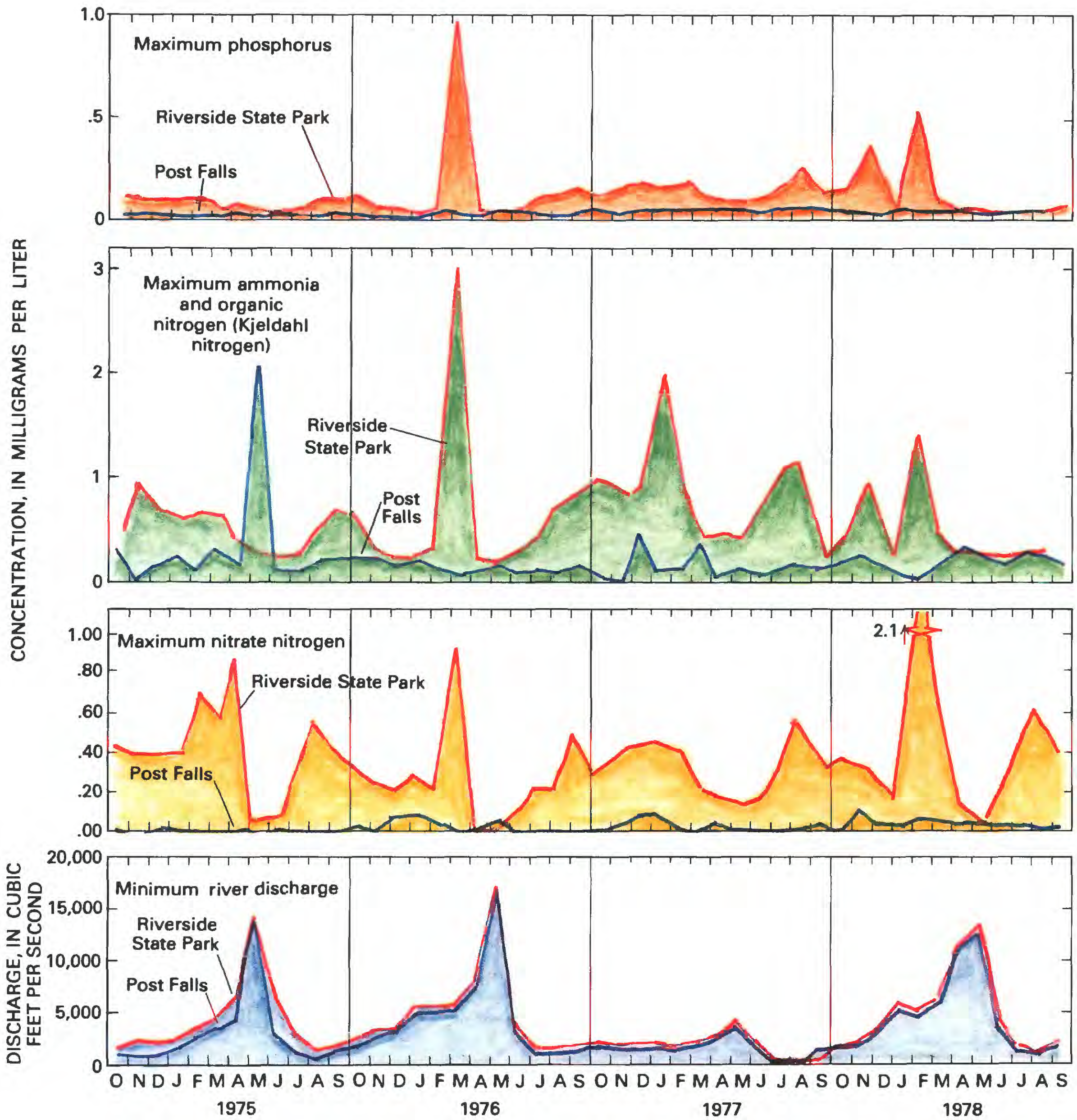


Figure 42. Maximum concentrations of phosphorus, Kjeldahl nitrogen, and nitrate nitrogen in the Spokane River and minimum discharges of the Spokane River near Post Falls, Idaho, and Riverside State Park, Washington, as recorded monthly during the 1975–78 water years. (Data from annual summaries of the U.S. Geological Survey, 1976–79.)

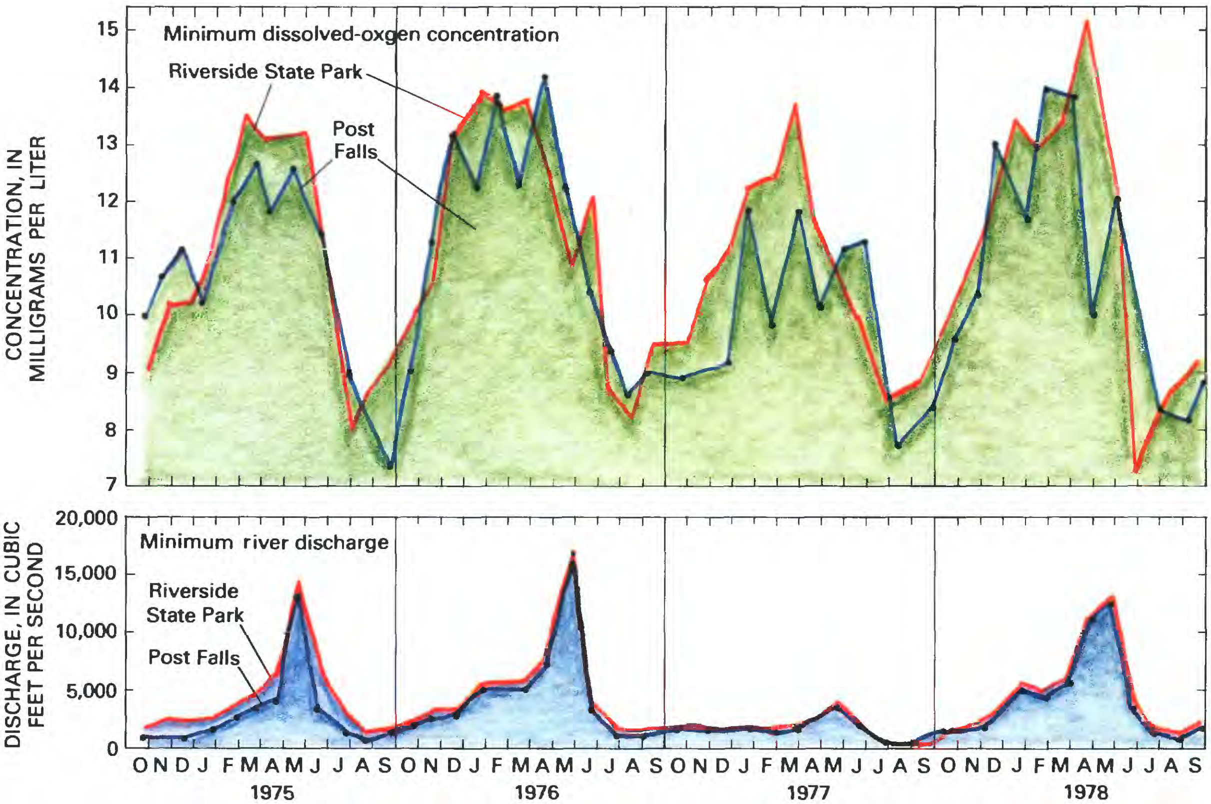


Figure 43. Minimum concentrations of dissolved oxygen and minimum discharges of the Spokane River near Post Falls, Idaho, and Riverside State Park, Washington, as recorded monthly during 1975–78 water years. (Data from annual summaries of the U.S. Geological Survey, 1976–79.)

Until recently, most water-pollution concerns and controls have dealt with the water of lakes and streams—where quality degradation is most obvious to the eye and where controls are more direct. On the other hand, water beneath the ground was considered pristine and naturally protected from man's activities by virtue of its burial within the earth. However, man is becoming increasingly aware that ground water is vulnerable to pollution and that serious problems have occurred in the past, particularly in industrialized areas of the Eastern United States, where toxic chemicals have been found in drinking-water supplies. Because ground water is used widely for drinking water, it is important that man be alerted to the hazards of pollution and be prepared to avert water-quality degradation before it happens.

A sustained increase in widespread pollution of the Spokane aquifer appears unlikely. Short-term increases in some pollutants in the aquifer have occurred in the past, and the potential always exists for them to occur in the future. This is especially true because the very high permeabilities in the unsaturated zone of the aquifer allow for rapid vertical movement of water and wastes to the water table with very few beneficial effects of chemical and bacterial reactions and absorption processes. Long-term localized increases in some chemical constituents also can occur when the source of the pollutant(s), such as a landfill or a waste-storage area, is permanent or large. Short- and long-term localized increases in the concentrations of some chemical constituents also can occur if the chemical source is close to the Spokane River. This would be due to the hydraulic connection between the river and the aquifer, which allows for rapid conveyance of water between the two water bodies.

Because protection of the ground-water quality in the Spokane aquifer is the foremost consideration in land use planning in the Spokane Valley, measures are being taken to eliminate any hazards that could lead to aquifer contamination. With man's present knowledge of the direction and rate of ground-water movement beneath different parts of the valley, assessments are possible of the potential for pollution by (1) calculating the amount (concentration) and type(s) of pollutants being discharged into the soil zone, (2) determining the depth to the water table and the rate of percolation of the potential pollutants, and (3) determining the nature and the rate of decay of the material and (or) rate of dilution, transportation, and dispersal in the ground water.

Many inorganic and most synthetic substances that move through the earth materials remain relatively unchanged except for some chemical, bacterial, and absorption processes. Contamination associated with human and animal wastes often is reduced to acceptable limits by bacterial processes within the soil if the depth to water is sufficient or the percolation rate is slow. Water-quality samples taken from the Spokane aquifer and analyzed for coliform bacteria show that this is generally true for the aquifer. Once the contaminant reaches the water table, however, these processes are no longer effective, and dilution, transport, and dispersal processes become important. Therefore, the type of contaminant and the depth and rate of percolation to the water table are critical factors in determining the potential for contamination.

As noted earlier, the geologic materials forming and overlying the Spokane aquifer are coarse, and the percolation (vertical movement) of pollutants through them is correspondingly rapid. However, because evidence of widespread ground-water contamination to date is lacking, the pollutants probably either are insignificant in amount and concentration or are rapidly diluted, transported, and dispersed in the aquifer.

Nonetheless, the increasing development in the Spokane area portends an associated conjunctive increase in water use, transportation of chemical materials, and waste storage and disposal. Thus, protection of the water quality of the aquifer will become more important and increasingly complex in the future. Protection of the quality of water in the public's interest will depend on such things as the proper management of the transportation of chemical materials and waste storage and disposal, and the development of reasonable plans for the prevention and mitigation of accidental spills of contaminants.

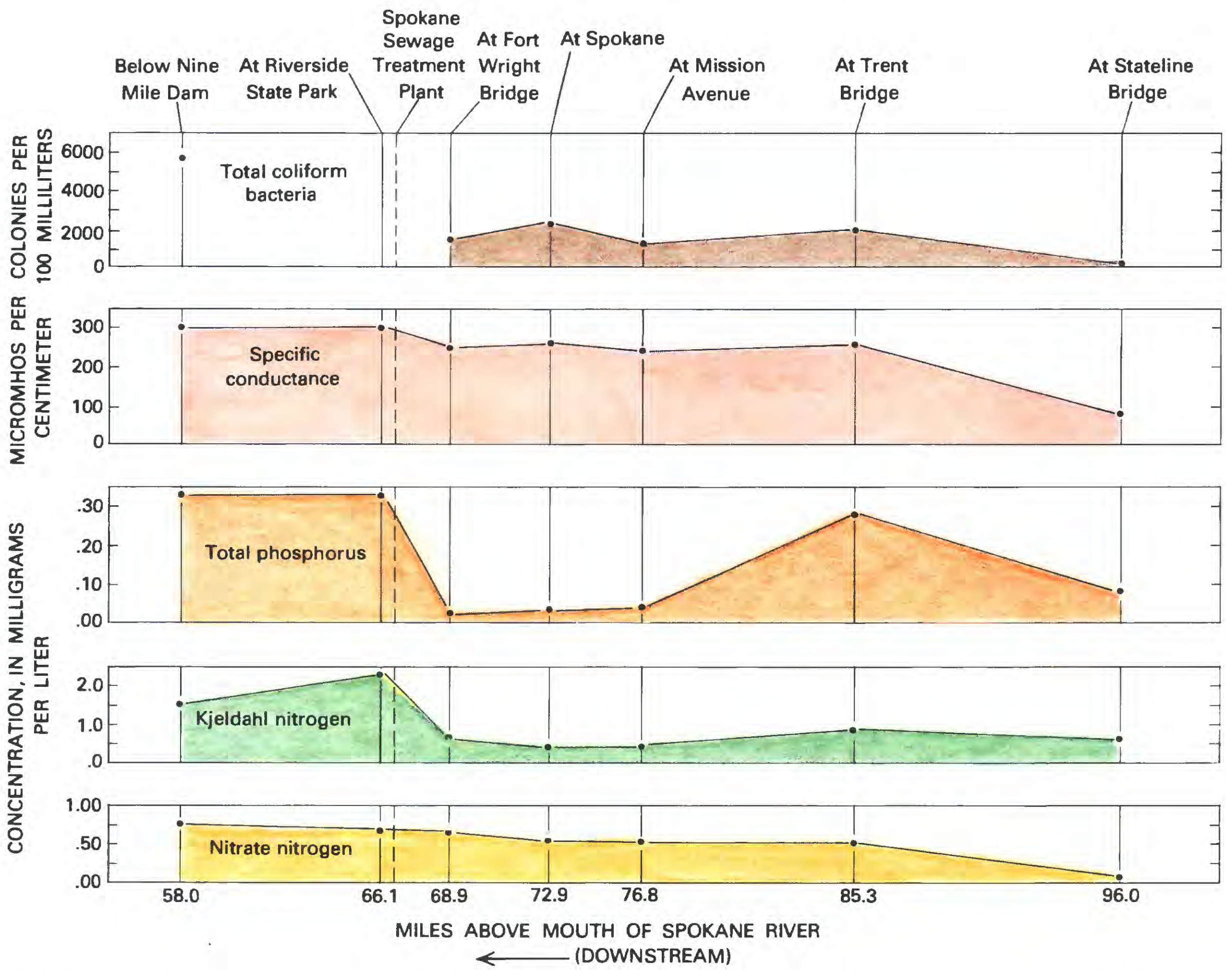


Figure 44. Downstream changes in the highest values of selected water-quality characteristics of the Spokane River during the low-streamflow period of July–September 1973. (Data from U.S. Geological Survey, 1974.)

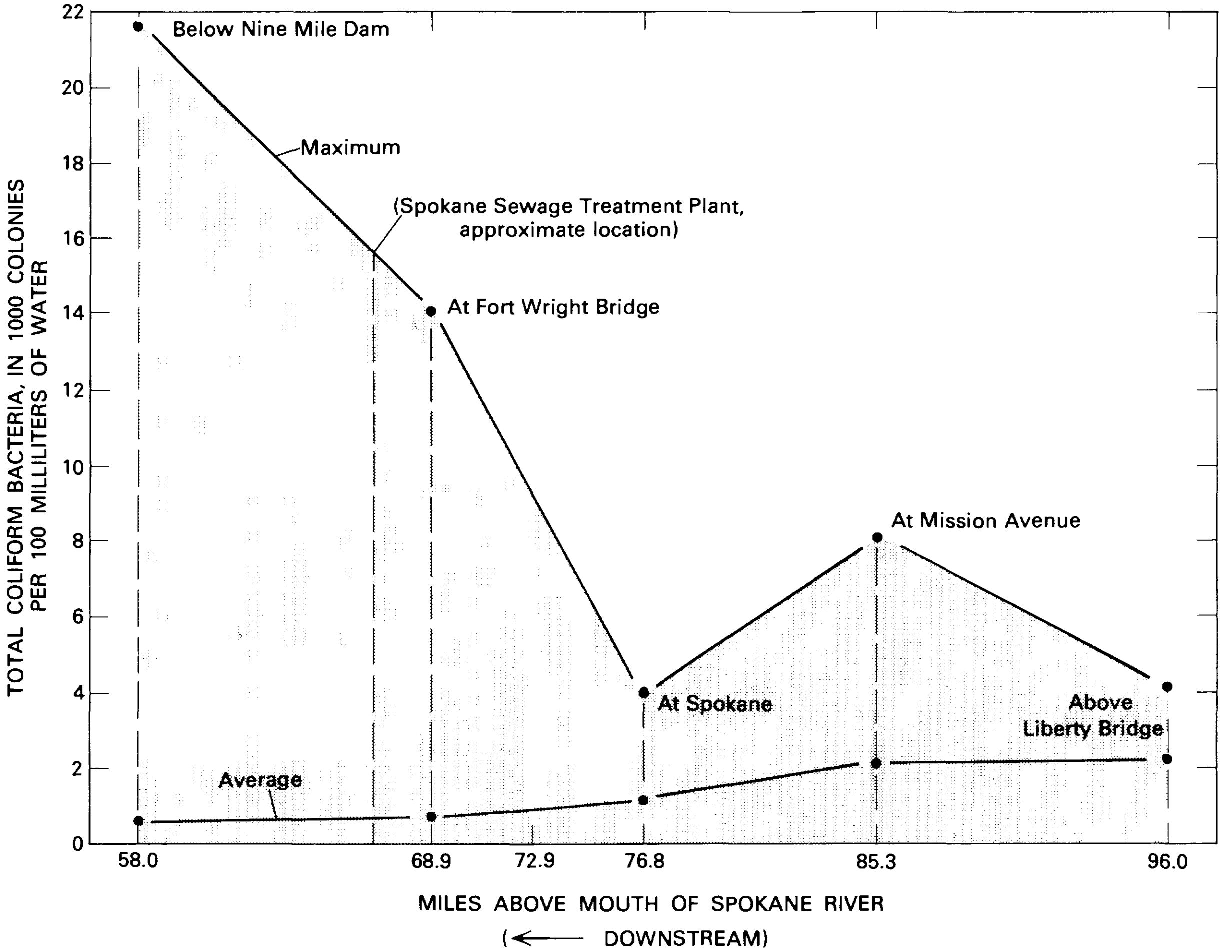


Figure 45. Average and maximum concentrations of total coliform bacteria at selected sampling sites in the Spokane River, 1968–72. (Data from Drost and Seitz, 1978.)

Ground-Water Modeling: A Water-Management Tool

Studies of the occurrence, availability, and quality of ground water in the Spokane aquifer over past decades have resulted in compilation of considerable amounts of certain types of basic data (measurable information). These include depths and diameters of wells, casings, and screens; depths to water (and altitude of the water table), pumping yields of wells, and amounts and rates of water-level drawdowns and recoveries in wells; and seasonal and year-to-year water-level changes, related records of precipitation and of discharges of the Spokane and the Little Spokane Rivers, uses of ground water, and results of chemical and bacteriological (sanitary) analyses of ground water. In turn, these basic data have allowed, to some extent, computation of values not directly measurable, such as permeability and transmissivity, which indicate the nature and rate of ground-water flow within the aquifer and, thereby, help to define the characteristics of dilution, transportation, and dispersion of chemical and biological materials entering the aquifer.

With an increasing understanding of the hydraulic and water-quality characteristics of an aquifer over long periods of time, man has been able to determine changes and fluctuations resulting from natural causes in the watershed and those induced by man's activities on the land surface. These determinations of the cause-and-effect relations of the past have provided the basis for anticipating similar changes in the future and for predicting changes due to modifications of man's activities.

In the past, the understanding and predictions of changes in various characteristics of an aquifer required laborious mathematical calculations to arrive at the desired information. The process was slow, and sometimes the questioned changes occurred before the calculations were completed. In addition, complexities of aquifer geometry and boundary conditions often restricted the use of mathematical calculations to only the most simple, or simplified, field problems. It was, therefore, a significant breakthrough in hydrologic studies when, in the late 1950's, ground-water systems were first simulated by electric analog models. Since then, the blending of mathematics and computer ground-water science has resulted in the use of digital models of systems for aiding water managers in the analysis of many ground-water problems, for laying the groundwork before field investigation, for verification of the aquifer hydraulics after the fieldwork, and for predicting future conditions in the system, including water quality.

As described by Mercer and Faust (1981), a mathematical model of the ground-water system consists of the equations that describe ground-water flow subject to certain boundary conditions. The digital model is basically a set of equations that, subject to certain assumptions, describe the physical processes occurring in the aquifer. The equations include representations of the various geohydrologic characteristics of the aquifer. Although a digital model itself obviously lacks the detailed reality of the real ground-water system, its behavior approximates that of the system. Its limitations are dependent, among other things, upon the amount and accuracy of the data available for its construction and verification.

On the basis of data compiled from several previous studies, but mostly covering the period of February 1977–May 1978 (Bolke and Vaccaro, 1979), two ground-water models of the Spokane aquifer were developed. The first model describes the aquifer's ground-water-flow (hydraulic) characteristics (Bolke and Vaccaro, 1981). The second model, which is based on the first model, describes the aquifer's water-quality characteristics (Vaccaro and Bolke, 1983). The two models simulate the interaction between the Spokane and the Little Spokane Rivers and the aquifer and processes occurring on the land surface that affect the aquifer.

The ground-water-flow model developed for the Spokane aquifer is typical of digital models that simulate ground-water-flow systems. The model's basic components include elements (the "boxes" shown in fig. 46) arranged in rows and columns. The elements vary in size and shape throughout the model area depending on the degree of detail needed for the computed solution of water levels to closely approximate observed values. Factors such as hydrologic boundaries to the stream-aquifer system, available data, and the present and anticipated water-level surface are considered when designing the "mesh" of elements; for example, a higher degree of detail is required where hydraulic gradients change over short distances in the model, such as near a pumping well. Fewer elements are required where hydraulic gradients are relatively flat and are not anticipated to change appreciably in time. At the corner of every element is a node, where the solution of head to the ground-water-flow equations are solved by the digital model.

Each element in the ground-water flow model of the Spokane aquifer has certain values associated with it that represent the average of the values calculated or estimated from the geohydrologic data obtained from all pertinent information in that element area. An element would often have values for aquifer thickness or transmissivity, specific yield, and depth to water assigned to it. Thus, the computed solution of hydraulic head at each node defines a plane of the water-level surface in the corresponding elements, which provide the basis for calculating the direction, rate, and amount of ground-water flow through the entire model area. Also included in the ground-water-flow model are values for streamflow and elevations of stream surface and of streambed. These data are used to help estimate the interaction of the rivers and aquifer at each river node shown in figure 46. The interactions at each river node then are put into the equations for the nodes of those elements of the ground-water model that include the river nodes.

Often, an important function of a ground-water-flow model is the prediction of future changes in the aquifer. By making modifications in the data put into the computer, for example, we can make predictions about such factors as changes in water levels. By changing one or more of the values for inflow (recharge by precipitation, seepage from the river, and ground-water underflow), we can calculate the effects of these changes on the water level in an element and over the complete modeled area.

The ground-water-flow model simulates movement of water within the Spokane aquifer as well as between the aquifer and its boundaries and between the aquifer and the Spokane and the Little Spokane Rivers and Hangman Creek. Data used in the model construction and verification and (or) model operation included water-level measurements made in 142 wells at seven time intervals, records of pumpage from 135 wells used for irri-

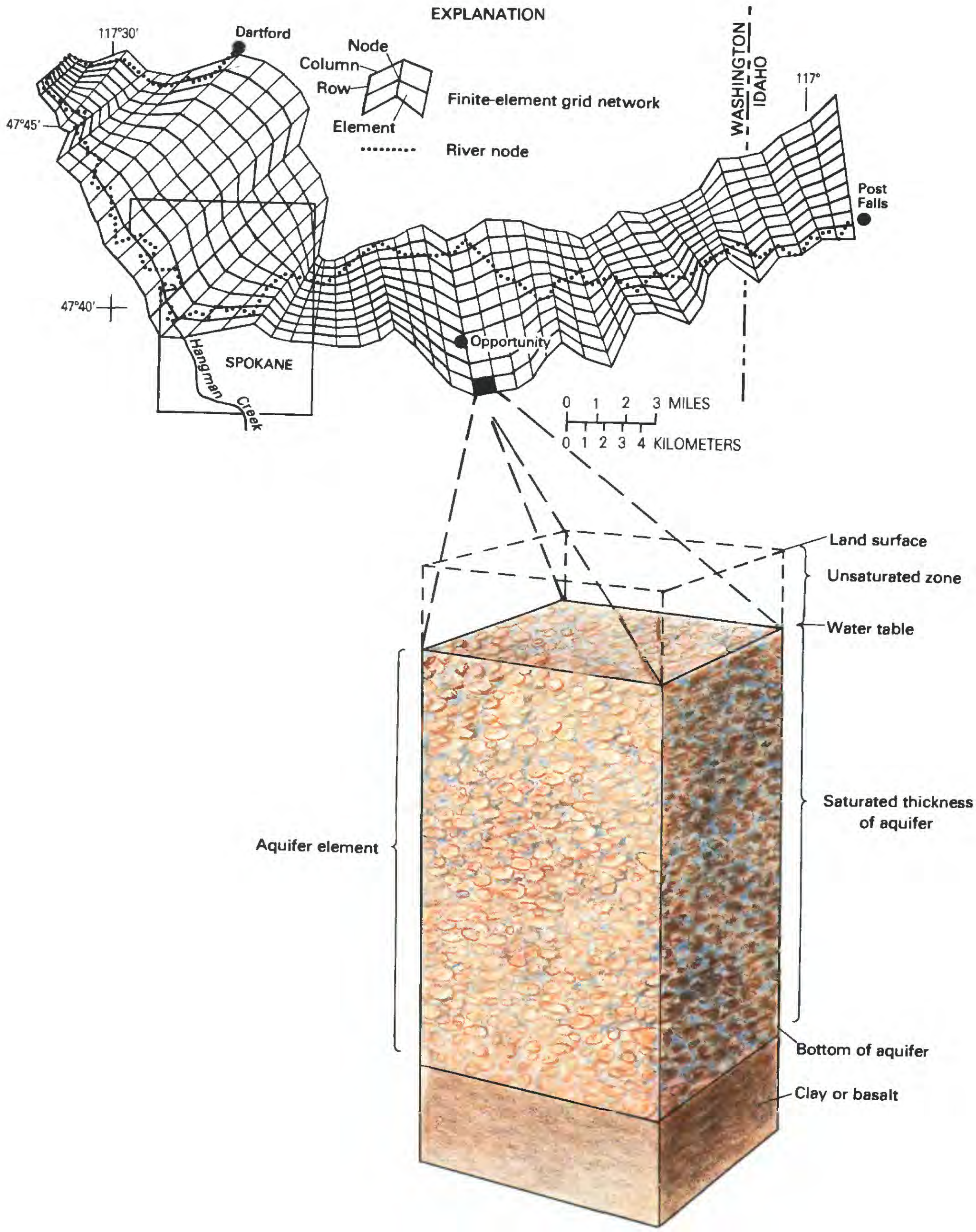


Figure 46. Elements of the Spokane aquifer ground-water flow model, with details of one element.

gation and industrial and public supplies, and records of the streamflow of the Spokane and the Little Spokane Rivers and Hangman Creek. The model was used to show the effects of a projected increase in ground-water withdrawals (pumpage) on the water levels in the aquifer and on the flows of the Spokane and the Little Spokane Rivers. By doubling the 1977 pumping rates, a more significant effect on the flow of the Spokane River than on the change in water levels in the aquifer was predicted, reflecting the high transmissivity of the aquifer. This model also can be used to show the effects on the Spokane aquifer of changes in other parts of the hydrologic system, such as precipitation, streamflow, and ground-water underflow between the Spokane Valley and adjoining areas.

The water-quality model also can provide predictions of water-quality changes if the concentrations of certain constituents entering the modeled area are changed. Such information provides a basis for determining the potential changes in water quality that might result from increases or decreases in contamination from various sources.

The water-quality model was used to determine the impact on chloride concentrations in the aquifer resulting from septic-tank and irrigation-water discharges (percolation). The results showed that the impact was insignificant—the increase in chloride concentrations ranged from less than 1 milligram per liter in 80 percent of the aquifer to about 3 milligrams per liter in some peripheral areas. Again, this indicates the high transmissivity of the aquifer and the corresponding rapid diluting effect of the ground water. The water-quality model also can be used to test other types of water-quality stresses imposed on the aquifer in different areas under various water-management plans and land use categories, such as urban and suburban, sewered and unsewered, agricultural and industrial lands.

For detailed, technical descriptions of the development and use of the two models, the reader is referred to the reports by Bolke and Vaccaro (1981) and Vaccaro and Bolke (1983). An excellent general discussion of ground-water modeling and of the various types of models, with their use and limitations, is provided in a report published by the National Water-Well Association (Mercer and Faust, 1981).

Metric Conversion Factors

Multiply	*By*	*To obtain*
inch	25.4	millimeter (mm)
	2.540	centimeter (cm)
	0.0254	meter (m)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.59	square kilometer (km^2)
acre	4047.0	square meter (m^2)
acre-foot (acre-ft)	1233.0	cubic meter (m^3)
	0.001233	cubic hectometer (hm^3)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	28.32	liter per second (L/s)
cubic mile (mi^3)	4.10	cubic kilometer (km^3)
foot squared per second (ft^2/s)	0.0929	meter squared per second (m^2/s)
micromho per centimeter at 25 degrees Celsius (μmho/cm at 25°C)	1.0	microsiemens per centimeter at 25 degrees Celsius (μs/cm at 25°C)
degree Fahrenheit (°F)	0.5666	degree Celsius (°C) after subtracting 32

Glossary of Technical Terms

Acre-foot The volume of a 1-acre area, 1 foot thick (43,560 cubic feet).

Aquifer Water-saturated rock material capable of yielding water to wells and springs.

Artesian In an artesian aquifer, water is confined beneath an overlying stratum of a lesser permeability under greater-than-atmospheric pressure which causes the water in a well to rise above the top of the aquifer tapped. If the water rises above the top of the well, then it is a flowing artesian well. Synonymous with "confined."

Atmospheric pressure The force per unit area exerted by the atmosphere, usually expressed in pounds per square inch.

Basalt A generally dark, fine-grained, extrusive igneous rock.

Bedrock The solid rock underlying, or protruding through, unconsolidated rock or soil materials.

Chloride loading Addition of chloride ion to an aquifer, as through contamination from outside (surface) sources.

Concentration The relative content of one component in another.

Cone of depression The shape of the water table around a well that forms as a result of lowering the water level in the well by pumping.

Consolidated rock Firm and coherent earth materials such as igneous, metamorphic, and cemented sedimentary rocks.

Contour Line connecting points of equal value, as land-surface elevations.

Degradation Loss in quality, as in the contamination of ground water or surface water by human activities on the land surface.

Digital model (Mathematical model) The numerical equations used to simulate a real system or physical feature.

Discharge Loss or flowing out of water (or other substance).

Dispersivity The quality of scattering or distribution of material.

Drawdown The lowering of the water level in a well by pumping.

Effluent Flowing out of; an effluent stream (also called a gaining stream) or reach of a stream is one into which ground water flows; that is, it receives water from the zone of saturation.

Electric analog model An electrical apparatus that has been constructed to represent (model) ground-water flow on the basis of the analogy between the flow of an electric current, expressed by Ohm's law, and the flow of ground water, expressed by Darcy's law.

Erosion Mechanical wearing away of the land by wind, water, and moving ice.

Evaporitic rocks Sedimentary rocks resulting from deposition from aqueous solutions as a result of extensive or total evaporation of the solvent.

Evapotranspiration Loss of water from land area by evaporation from the soil and by transpiration from vegetation.

Fecal-coliform bacteria Bacteria that are present in the intestinal tract or feces of warm-blooded animals.

Frequency The number of times that a periodic function repeats the same sequence of values during a unit variation of the independent variable.

Gradient The rate of regular or graded ascent or descent (of a slope).

Ground water Water occurring within the saturated zone in rock materials.

Ground-water model Simulation of a ground-water system.

Ground-water-flow model Simulation of the rate of flow of ground water, as in a digital model.

Headwater Uppermost part of a river drainage basin.

Igneous rock Cooled and solidified rock formed from molten rock.

Inflow Flow in or addition of water into an aquifer.

Interstice Opening, void, or pore, as within a rock material.

Lobe Projection of a glacial margin beyond the main body of ice.

Magnitude Characteristic of size, quantity, amount.

Mathematical model System of algebraic equations that describe continuous variables over the region.

Micromho One-millionth of a mho, the unit of conductance—a measure of a material's ability to conduct electricity.

Metamorphic rock Sedimentary or igneous rock altered by heat and pressure to attain a denser and generally more crystalline character.

Milligrams per liter A unit of measure used to define the concentration of certain elements in one liter of a water sample: 1 milligram is one-millionth of a liter. Synonymous with "parts per million."

Moraine Glacial rock debris deposited by a glacier along its margins (lateral moraine) and at its terminus (terminal moraine) or by melting of the glacier (ground moraine).

Node Point in a model.

Outwash Rock material deposited by glacial meltwater streams, generally across a plain (outwash plain) below the terminus of an advancing or receding glacier.

Percolation The seepage of water from an unsaturated zone to a saturated zone.

Perennial stream A stream that flows throughout the year.

Permeability The relative ease with which water flows through a rock unit. Synonymous with "hydraulic conductivity."

Point-source pollution Contamination resulting from a localized discharge of chemical or biological substances, such as at a site for the discharge of industrial or municipal wastes.

Pollutant Organic or inorganic, chemical or biological substance capable of polluting the air, liquid, or solid into which it is injected.

Recharge The process by which water is added to an aquifer, such as by percolation of precipitation or leakage from surface-water bodies and from overlying and underlying aquifers.

Sedimentary rock Rock formed by deposition of rock particles or organic material by ice, water, or wind and subsequent solidification through cementation or compression.

Seismic study Geophysical prospecting using the generation, reflection, refraction, detection, and analysis of elastic waves in the earth.

Specific conductance Ability of water (a liquid) to transmit electrical current.

Specific yield Ratio (percentage) of (1) volume of water in a saturated rock material that it will yield by gravity to (2) its own volume.

Stage (hydraulic) Elevation of water surface above any chosen datum plane; gage height.

Surface water Body of water on the land surface, as a stream or lake.

Topography The relief features or surface configuration of an area.

Total coliform bacteria Bacteria count that includes all forms of coliform bacteria.

Transmissivity Rate of flow of water through a unit width of an aquifer under a unit hydraulic gradient.

Transpiration Process by which water vapor passes through special cells in the leaf surface of living plants and enters the atmosphere.

Unconfined aquifer An aquifer whose upper boundary or surface is the water table. Synonymous with "water-table aquifer".

Unconsolidated materials Loose materials not held together by cementation of the individual agents.

Underflow Flowing under, such as ground-water flowing from beneath one area to beneath an adjacent area.

Water level Level of water in a well usually reported relative to land surface.

Water table The surface of the saturated zone in an unconfined aquifer along which the pressure is equivalent to atmospheric pressure.

Watershed Area contained within a drainage divide; drainage area.

Water year The 12-month period beginning with October 1 and ending with September 30.

Withdrawal Taking out of (removal of) water from an aquifer or surface-water body.

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Appendixes

APPENDIX A.

WHERE ADDITIONAL INFORMATION ON GROUND WATER CAN BE OBTAINED

Many interested citizens are not familiar with the availability of a large number of reports that deal with ground water in Washington. The reports have been prepared to provide results of studies of the occurrence of ground water in various parts of the State and in various geologic materials. In general, they discuss the movement of the water, areas of recharge and discharge, yields of wells, and the chemical and sanitary quality of the water. Some reports discuss generally the ground-water resources by county or topographic basin, and other reports discuss more localized areas where ground-water availability or quality have become problems of particular concern.

The studies generally are made under cooperative funding by two or more agencies. Most of the cooperative programs have included the U.S. Geological Survey and the State of Washington Department of Ecology (and its predecessor agencies, the Department of Water Resources and the Division of Water Resources); however, many other Federal, State, and local agencies have been involved, including the State Departments of Fisheries, Game, Transportation (formerly Highways), and Natural Resources; county and municipal agencies; and Indian tribal governments. A list of publications covering ground-water resources of various areas of the State of Washington may be obtained by writing to the following agencies:

Washington Department of Ecology
Olympia, Washington 98504

and

U.S. Geological Survey
Water Resources Division
1201 Pacific Avenue, Suite 600
Tacoma, Washington 98402

Information on publications covering ground- and surface-water resources generally and in various other parts of the United States may be obtained by writing to the following address:

Hydrologic Information Unit
U.S. Geological Survey
420 National Center
Reston, Virginia 22092

APPENDIX B.

WATER LAW IN THE STATE OF WASHINGTON

Article XXI of the Washington State Constitution declares that the use of water for irrigation, mining, and manufacturing is a public use. The procedure for appropriating these public waters was provided by the State legislature under Chapter CXLII, Session Laws of 1891. Under this statute, rights to the use of the surface waters of the State could be acquired by posting a notice in writing at a conspicuous place at the point of intended diversion and filing a copy of the notice with the county auditor of the county in which the notice was posted. Through compliance with the specific provisions of this act and the development and use of the waters, rights were established with a date of priority which related to the date of posting of the notice. However, this procedure proved to be inadequate because no supervisory agency had been created to assure compliance with the provisions of the act. Numerous filings were made whereby the notice was posted at the intended point of diversion and a copy was filed with the local auditor but no actual diversion was made. Thus, the appropriation was never finalized and the actual right never established. Due to the lack of records, considerable investigation and litigation would have been needed to ascertain which filings had been perfected.

Through the years, many conflicts arose over rights to the use of public waters. In 1913, the governor was petitioned to compile a water code for the State. As a result, a commission was formed which drafted a code of 44 sections which was passed into law by the legislature as Chapter 117, Laws of 1917.

Chapter 117 became effective June 6, 1917, and has become known as the Surface Water Code. This code extended the concept of rights by appropriation by declaring, "Subject to existing rights, all waters within the State belong to the public and any right thereto, or to the use thereof, shall be hereinafter acquired only by appropriation for a beneficial use." The code provided that, for more than one appropriation, the first in time shall be the first in right. Further, it declared that nothing in the act shall lessen, enlarge, or modify the rights of riparian owners existing as of June 6, 1917, or any right however acquired, existing as of that date. The act created the office of Hydraulic Engineer to administer these laws. The basic concept of the laws has not been changed through the 66 years of their existence. Administration of the Surface Water Code is now under the jurisdiction of the Department of Ecology.

Because the code recognized rights which existed at the time the 1917 Surface Water Code became effective, a procedure was established to determine the validity, extent, and priority of rights claimed before 1917. This procedure involves the adjudication of all rights on a certain stream or water course through the superior court of the county in which the major part of the stream is located. The Department of Ecology appoints an adjudication referee whose job it is to conduct public hearings and to receive evidence for the court. Upon conclusion of the hearing, a report is prepared by the referee. The report presents a schedule of rights, which sets forth the priority and extent of the rights of each claimant. If adopted by the court, this report then becomes a decree in the case, and title to all rights on the stream are determined.

For an appropriation initiated after June 6, 1917, the code provides that an application must be made for a permit to make the appropriation and that no use or diversion of water shall be made until a permit has been issued. The date and time the application is received in the Department of Ecology establishes the priority of the application. After office review of the application, publication of a legal notice is required once a week for two consecutive weeks in a newspaper of general circulation published in the county, or counties, in which the source of water is located. Notice of the application also is forwarded to the State Department of Fisheries and the State Department of Game for their consideration of the effects of the proposed water right on streams and lakes in the area. A field investigation is conducted by the Department of Ecology to determine what water, if any, is available for appropriation and to what beneficial use, or uses, it can be applied. After a full review of the application, written findings of fact are prepared concerning all aspects of the application. If it is found that water is available for appropriation from the proposed source of supply and that the proposed use will not conflict with existing rights and will not prove to be detrimental to the public interest, with due regard to the highest feasible development of the use of the waters, the application may be approved.

Approval of the application and issuance of the permit constitute authority to begin construction leading to actual beneficial use of the water. When the water has been put to full beneficial use, the permittee may acquire a certificate of water right. This certificate is recorded in the local county auditor's office and the Department of Ecology and becomes a perfected water right. The certificate of water right is issued only for the quantity of water actually used and for the purposes for which the water has been beneficially applied within the maximum limits set by the permit.

Development and use of public ground waters of the State took place at a slower rate than the surface waters. Therefore, the need for regulatory control evolved at a later date. With improvement of drilling techniques and the expansion of the industrial, municipal, and irrigation requirements of the State, the need for laws relating to the appropriation and use of ground water became necessary. In 1945, the Association of Washington Cities sponsored and assisted in drafting legislation which is now referred to as the Washington State Ground Water Code.

The ground-water laws supplement the Surface Water Code and are enacted for the purpose of extending the application of the surface-water statutes to the appropriation of ground waters for beneficial use. The laws are administered by the Department of Ecology, and the appropriation procedure is essentially the same. Basically, the law provides that no withdrawal of public ground waters and no wells or works for such withdrawal shall be constructed unless an application to appropriate those waters has been made and a permit has been issued. A permit is not required for any withdrawal of public ground waters for stock-water purposes, for watering of a lawn or of a noncommercial garden not exceeding one-half acre in area, for single or group domestic uses, or for an industrial purpose where the amount of withdrawal does not exceed 5,000 gallons per day. However, applications may be submitted for these purposes if any person or agency wishes to record the well and its use.

In much the same manner as the Surface-Water Code, the ground-water code recognized existing rights established by development and use of ground waters before the effective date of the code, June 6, 1945. The ground-water code differs in that a declaratory period is provided whereby wells developed before 1945 could be recorded. The code provided that any person claiming a vested right for the withdrawal of public ground waters by virtue of prior beneficial use could, within 3 years after June 6, 1945, receive a certificate of ground-water right to that effect upon declaration by the claimant. This declaratory period was subsequently extended for a period of 2 years.

For specific water-right information concerning the Spokane aquifer, the reader should contact the Department of Ecology at the following address:

Eastern Regional Office
East 103 Indiana
Spokane, Washington 99207

APPENDIX C.

WELL- AND LOCATION-NUMBERING SYSTEM

Wells and locations mentioned in this report are identified by numbers that indicate their locations by township, range, section, and 40-acre subdivision of a section; for example, in the number 25/44–23D1, the part preceding the hyphen indicates, successively, the township and range (T. 25 N., R. 44 E.) north and east of the Willamette base line and meridian. Because most of the study area is in Washington State and lies entirely north and east of the base line and meridian, the letters indicating the directions north and east are omitted. The first number following the hyphen indicates the section (sec. 23), and the letter "D" gives the 40-acre subdivision of the section, as shown in the figure below. The number "1" indicates that this well is the first one inventoried within the subdivision. The locations of other features mentioned, including photographic viewpoints, are similarly numbered but without the sequential number. (One photograph taken in Idaho is identified by a different meridian sequence that includes the letter "W" designated for west.)