APPENDIX D

US GEOLOGICAL SURVEY STUDIES

Contents

Hydrogeology of the Unconsolidated Sediments, Water Quality, and Ground-Water/Surface-Water Exchanges in the Methow River Basin, Okanogan County, Washington

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ABSTRACT

The U.S. Geological Survey, in cooperation with Okanogan County, investigated the hydrogeology of the unconsolidated sedimentary deposits in the Methow River Basin, the quality of surface and ground waters, and the exchanges between ground water and surface water. Alluvium (Qa) and glaciofluvial sediments (Qga) deposited during the Quaternary period constitute the primary aquifer in the Methow River Basin, which is used as a source of water for domestic and public-water supplies and for maintaining streamflow during seasonal dry periods. The sediments form a nearly continuous unit along the valley bottom from above the Lost River to the confluence of the Methow and Columbia Rivers, covering more than 45 square miles of the basin's surface. There are no distinct units within the deposit that can be identified across or along the valley except for fragments of a possible lake bed near the town of Twisp. Ground-water levels in the unconsolidated aquifer are highest during the summer and lowest in the winter and early spring.

Ground water and surface water, sampled during June and September 2001, generally were of high quality. Only two samples from domestic and municipal wells indicated the possibility of ground-water contamination from nitrate and arsenic concentrations. In both cases, potential contamination was isolated to an individual well. No trends in water quality were apparent when comparing the results of this investigation with previous studies.

The flow of water between rivers and aquifers is important for regulating the availability of water resources for in-stream and out-of-stream uses in the Methow River Basin. Ground-water discharge from the unconsolidated aquifer to the Methow River from Lost River to Pateros ranged from an estimated 153,000 acre-ft in water year 2001 to 157,000 acre-ft in water year 2002. In contrast, ground-water discharge to the lower Twisp River from Newby Creek to near Twisp ranged from 4,700 acre-ft in water year 2001 to 9,200 acre-ft in water year 2002. The Methow and Twisp Rivers, among others in the basin, are major sources of recharge for the unconsolidated aquifer, particularly during high-flow periods in May and June. Aquifer recharge by both rivers increased with streamflow in water year 2002 compared to water year 2001 as indicated by daily losses of streamflow. Aquifer recharge by the Methow River from Lost River to Pateros was estimated to be 82,000 acre-ft in water year 2001 and 137,000 acre-ft in water year 2002. Aquifer recharge by the Twisp River from Newby Creek to near Twisp was estimated to be 2,000 acre-ft in water year 2001 and 6,400 acre-ft in water year 2002.

Seepage from unlined irrigation canals also recharges the unconsolidated aquifer during the late spring and summer and may contribute as much 38,000 acre-ft annually to aquifer recharge in the basin. Some portion of this ground water returns to rivers as indicated by a seasonal increase in ground-water discharge in the Methow River from Winthrop to Twisp and in the lower Twisp River during late summer and early autumn. Although the increase is likely due primarily to irrigation canal seepage, however, fluvial recharge during the summer also may have contributed to the increase. The increased rate of ground-water discharge decays by January in both reaches.

INTRODUCTION

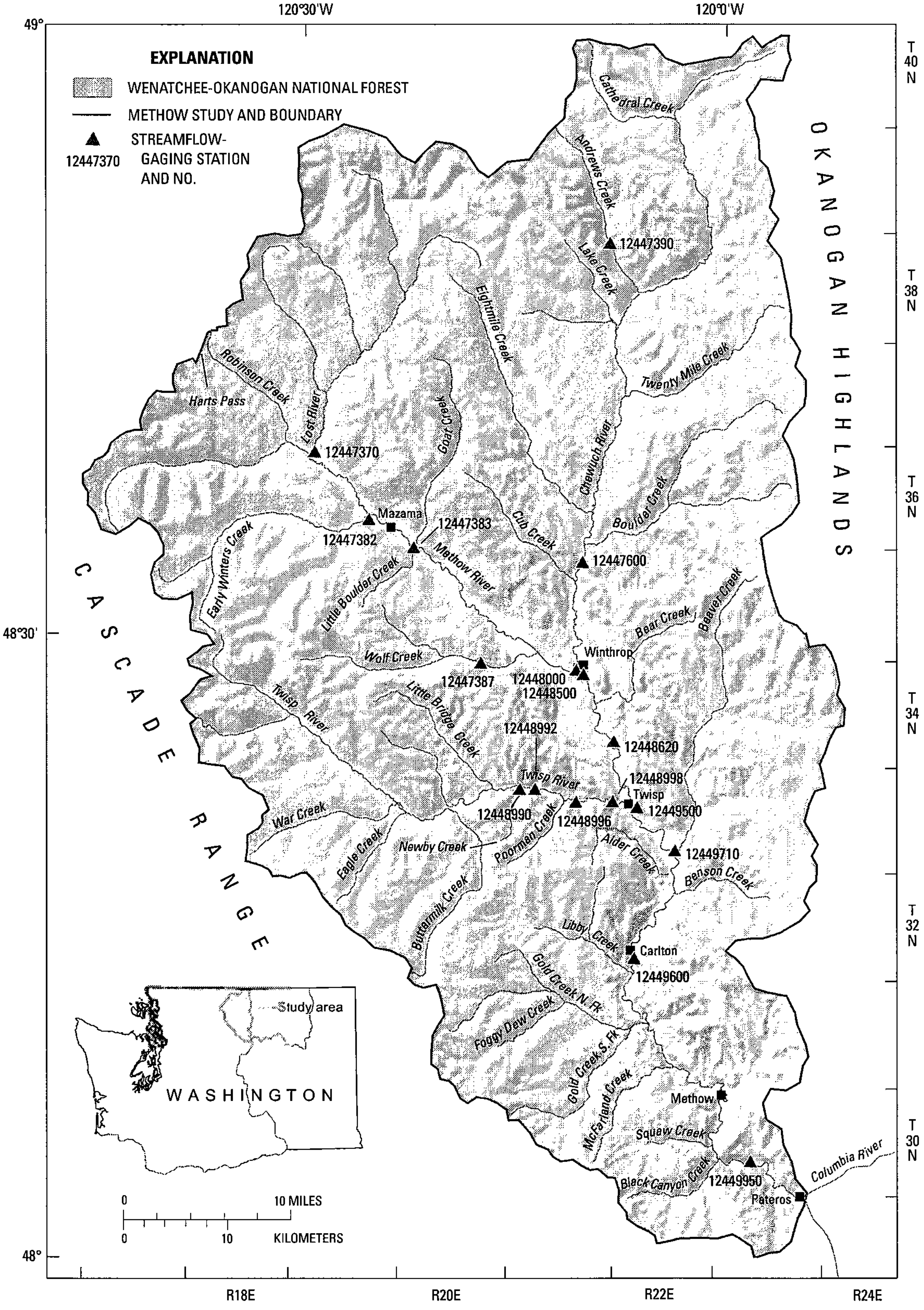
Water is an important resource to people and aquatic ecosystems in the Methow River Basin in north-central Washington State (fig. 1). Effective water-resources management for societal and ecological objectives begins with an understanding of the availability and quality of water, which varies by season and location in the basin. In 2000, the U.S. Geological Survey (USGS), in cooperation with Okanogan County and with support from the USGS Ground-Water Resources Program, began a study of three aspects of water resources in the Methow River Basin: the hydrogeology of unconsolidated sedimentary deposits, which serve as the primary ground-water resource for human uses and as the source of baseflow in rivers and streams; the quality of surface and ground waters; and the exchanges between ground water and surface water, which influence the availability of water for in-stream and out-of-stream uses. The three components of this investigation address recommendations developed by the Methow Valley Ground Water Management Advisory Committee (1994) for the development of water information in the basin. Moreover, the information will contribute to the scientific basis for water-resources management by the Methow Basin Planning Unit, established under the authority of Washington State Engrossed Substitute House Bill 2514.

Hydrologic processes in the Methow River Basin reflect the distinct seasons in the region's climate, characterized by cold winters with abundant snowfall at higher altitudes and warm, dry summers. During the spring and early summer, snowmelt recharges shallow aquifers and raises streamflow. By late summer, however, snow has melted from most of the basin and precipitation (either snow or rain) generally is scarce until autumn or winter. As a result, the availability of water resources is limited from late summer through winter. The limited availability of water resources in the Methow River Basin is most evident for rivers and streams in the late summer and early autumn, when surface water continues to be appropriated for agricultural and domestic uses but also provides habitat for spawning and rearing of endangered salmon (upper Columbia River Basin spring chinook).

The availability of ground-water resources is controlled by the occurrence of geologic formations that can store water (aquifers) and the flow of water into those formations (recharge). The availability of surface-water resources is controlled by the location of river and stream channels in the landscape, runoff of snowmelt and rainfall from hillslopes, and ground-water discharge from aquifers into the channels. Ground-water and surface-water resources are linked by the flow of water between rivers and aquifers such that both the quantity and quality of these resources depend on each other.

Purpose and Scope

This report describes the hydrogeology of unconsolidated sediments that fill the Methow River valley, the quality of ground and surface waters, and exchanges between ground and surface waters. The description of hydrogeologic units of the unconsolidated sediments is based on a review of well logs and other geologic investigations. The description of the unconsolidated units includes their extent and thickness, a discussion of confining material, and estimates of hydraulic conductivity. A map of ground-water levels in the unconsolidated sediments and seasonal fluctuations was constructed from water-level measurements made between November 2000 and July 2001. Water quality in the basin was assessed using ground-water and surface-water samples collected throughout the basin in June and September 2001 and analyzed for various constituents. Spatial and temporal patterns in exchanges between rivers and shallow unconsolidated aquifers were analyzed using streamflow measurements made in September 2001, February 2002, and September 2002, and surface-water discharge balances for water years 2001 and 2002. A water year begins on October 1 of the previous calendar year and ends on September 30.



Base from U.S. Geological Survey Digital Data, 1:100,000, 1985
Universal Transverse Mercator projection,
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Figure 1. Location of study area and streamflow-gaging stations in the Methow River Basin, Okanogan County, Washington.

Aquifer recharge due to seepage from irrigation canals in the basin was estimated from surface-water discharge balances for selected canals. Continuous monitoring of ground-water levels and a surface-water discharge balance were used to analyze the influence of aquifer recharge due to irrigation-canal seepage on streamflow in the lower Twisp River. The Modular Modeling System (MMS) was used to develop a water budget for the Methow River Basin for water years 1992-2001.

Acknowledgments

Many organizations contributed to and participated in the investigation including the Okanogan County Department of Water Resources, the Methow Basin Planning Unit, the Washington State Department of Ecology, the Washington Department of Fish and Wildlife, the U.S. Forest Service, and the U.S. Bureau of Reclamation. Their assistance is appreciated. The Twisp Valley Power and Irrigation Company (TVPI) allowed the U.S. Geological Survey to conduct detailed monitoring of their irrigation system and helped to get the involvement of landowners in the investigation. Marty Williams, manager of the TVPI Canal, contributed much of his time to help with the investigation. His willingness to participate in the investigation and his diligence to canal operations and reporting were invaluable. The participation of other irrigation companies and districts that provided access to their canals for discharge measurements also is greatly appreciated. Finally, this project could not have been possible without the support of hundreds of private landowners in the Methow River Basin who gave the U.S. Geological Survey access to their land and wells.

Description of Study Area

The Methow River drains 1,810 mi^2 in north-central Washington and is a tributary to the Columbia River (fig. 1). The Cascade Range forms the western boundary of the basin and the Okanogan Highlands form the eastern boundary. Land-surface altitudes range from 8,950 ft above NAVD 88 in the Cascade Range to 775 ft at the Methow River's confluence with the Columbia River. Major tributaries include the Lost River, Early Winters Creek, Wolf Creek, the Chewuch River, and the Twisp River. The population in the Methow River Basin was about 4,700 in 2000 (Washington State Office of Financial Management, 2002), with most people living in the valley. The largest towns are Twisp and Winthrop.

Most of the Methow River Basin and all its headwaters are in the Wenatchee-Okanogan National Forest. Land uses in the National Forest include recreation, grazing, and timber harvesting. Douglas fir (*Psuedotsuga menziesii*), lodgepole pine (*Pinus contorta*), and ponderosa pine (*Pinus ponderosa*) forests cover mid-altitude (2,000 to 5,000 ft) areas of the basin. Shrub-steppe communities with bitter brush (*Purshia tridentata*), big sagebrush (*Artemisia tridentata*), and bunchgrasses (such as *Agropyron inermi*) are common at altitudes less than 4,000 ft, and subalpine fir (*Abies lasiocarpa*), Pacific silver fir (*Abies amabilis*), mountain hemlock (*Tsuga mertensiana*), whitebark pine (*Pinus albicaulis*), and subalpine larch (*Larix lylli*) are common at altitudes greater than 3,000 ft. Deciduous trees including black cottonwood (*Populous trichocarpa*) and aspen (*Populus tremuloides*) occupy valley bottoms and riparian areas. Historically, fire was the dominant landscape process influencing the structure, composition, and extent of vegetation communities in the Methow River Basin (Knott and others, 1998).

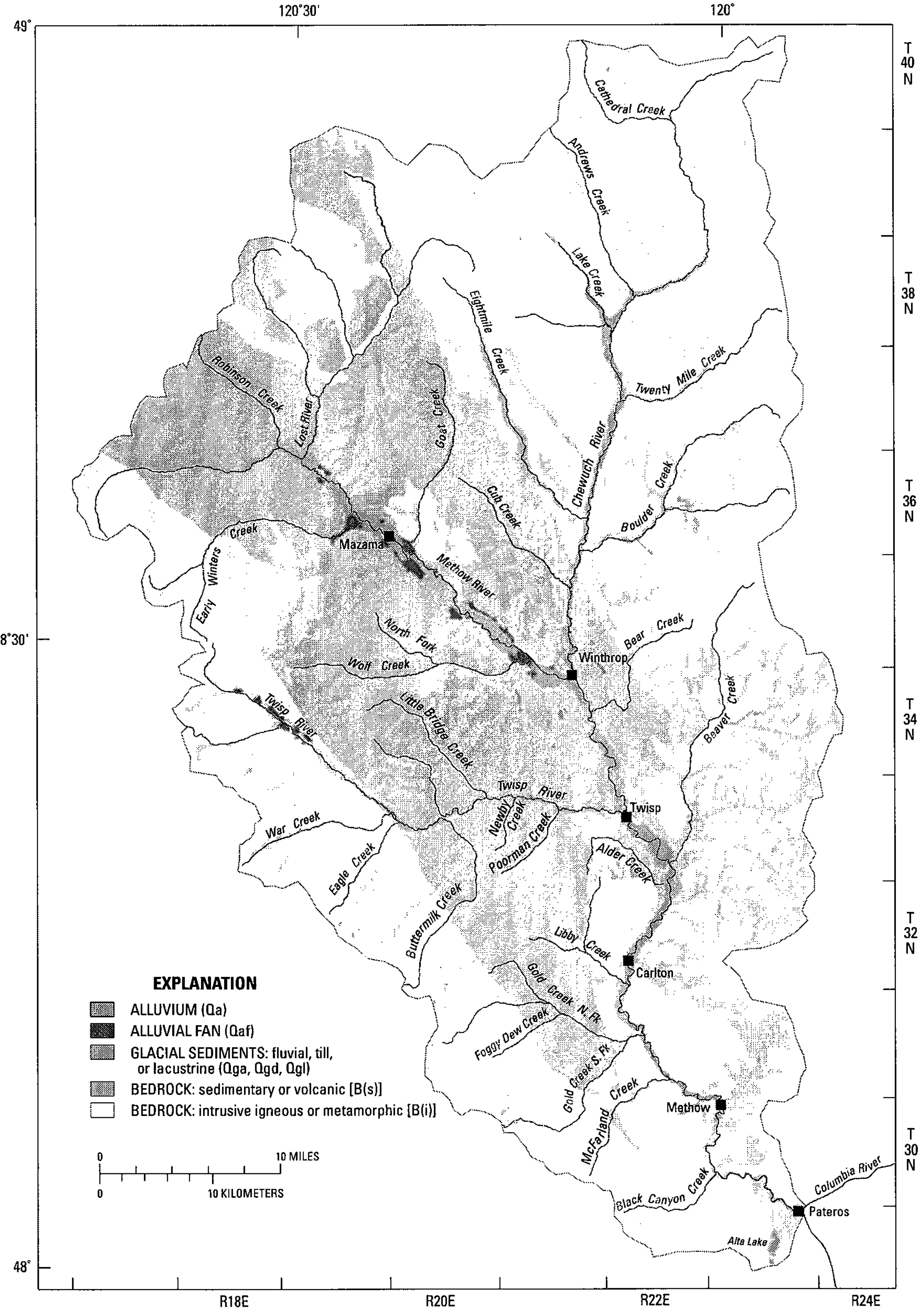
There is a steep precipitation gradient across the basin, with high-altitude areas on the western side of the basin receiving about 80 in. annually and areas in the lower river valley receiving 12 in. For water years 1984 to 2002, mean annual precipitation was 54 in. at Harts Pass, 22 in. at Mazama, and 14 in. at Winthrop. The basin receives most of its precipitation as snow during winter. Precipitation during November through February accounted for 57 percent of the total precipitation at Harts Pass, 60 percent of the total precipitation at Mazama, and 53 percent of the total precipitation at Winthrop (Natural Resource Conservation Service, 2003; Western Regional Climate Center, 2003a and 2003b).

A drought persisted over much of the Pacific Northwest during water year 2001, with below normal snowpack and streamflow throughout the region. Annual precipitation at Harts Pass, which generally represents snowpack conditions producing most of the runoff in the Methow River Basin, was 32 in. in water year 2001, compared to 65 in. in water year 2002 (National Resource Conservation Service, 2003). Likewise, annual precipitation at Mazama was 12 in. in water year 2001 compared to 22 in. in water year 2002 (Western Regional Climate Center, 2003a). Precipitation was less affected by the drought in the more arid parts of the basin. For example, annual precipitation at Winthrop was 8 in. in water year 2001 compared to 10 in. in water year 2002 (Western Regional Climate Center, 2003b).

Streamflow records from the Methow River near Pateros (12449950, fig. 1) for water years 1960-2002 illustrate seasonal hydrologic patterns in the basin. Mean annual discharge of the Methow River near Pateros was 1,550 ft^3/s, which is equivalent to annual runoff of 1.1 million acre-ft. Streamflow is unevenly distributed during the year, with high flows in late spring and early summer and low flows in late summer and winter. For example, the mean monthly discharge of the Methow River near Pateros was 4,932 ft^3/s for May and 5,915 ft^3/s for June, which, combined, account for nearly 60 percent of the mean annual discharge of the river. Mean monthly discharge of the Methow River near Pateros was 423 ft^3/s for January and 420 ft^3/s for February, although streamflow also is low in September, when the mean monthly discharge was 444 ft^3/s.

Geology

The Methow River Basin is underlain by bedrock that is exposed at the surface or only thinly covered by sediments almost everywhere except beneath the floors of the major valleys. The bedrock is of many different rock types of a wide range of ages. These rocks have been folded and faulted into a complex pattern (Walters and Nassar, 1974). Starting just south of Twisp and extending up the Methow River, the bedrock consists of sedimentary and volcanic rocks that have been downfaulted between large blocks of intrusive igneous and metamorphic rocks. The sedimentary and volcanic bedrock is exposed over a 15- to 20-mile-wide expanse that extends about 35 to 40 mi northwest to southeast (fig. 2). Downriver of the sedimentary and volcanic rocks, the bedrock underlying the river is primarily intrusive igneous and metamorphic. The basin has been described as a graben (Barksdale, 1975) or a rift-block valley (Waitt, 1972). Shales, siltstones, sandstones, conglomerates, breccias, and tuffs are the major sedimentary and volcanic rocks present in the basin. Both sedimentary and volcanic rocks span a range of ages from the Cretaceous Period (or possibly Jurassic) to the Tertiary Sub-Era (Barksdale, 1975). Most of the intrusive igneous and metamorphic rocks are granite, gneiss, marble, and schist. Intrusive igneous rocks range in age from the Cretaceous to the Oligocene Epoch, but the age of metamorphic rocks is not well known (Barksdale, 1975). The unconsolidated sediments that overlie the bedrock are mostly sands and gravels of glaciofluvial origin. Glacial till and glaciolacustrine silts and clays also are present, but are much less extensive than the sands and gravels. The unconsolidated sediments were deposited during the Pleistocene and Holocene Epochs.



Base from U.S. Geological Survey Digital Data, 1:100,000,1985
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Figure 2. Surficial geology of the Methow River Basin, Okanogan County, Washington. Geology was modified from Harris and Shuster (2000).

The basin was almost entirely covered by ice several times during the Pleistocene glaciations. Upland areas were eroded and ultimately mantled with relatively thin glacial deposits, while thick accumulations of sand and gravel, along with some tills, silts, and clays, were deposited along the lower slopes and bottoms of the major valleys (Walters and Nassar, 1974). Although the glacial deposits at the surface originated from the recent ice-sheet glaciation that covered most of the basin, there is clear erosional evidence of significant alpine glaciation prior to the ice sheets (Waitt, 1972). Alpine glaciation is responsible for the wide U-shaped cross-valley profiles of the Methow River valley upriver of Carlton and of the Twisp River valley upriver of Little Bridge Creek (Waitt, 1972). Beneath parts of these U-shaped valleys, alpine glaciation apparently eroded the bedrock many hundreds of feet below the level of the bedrock immediately downriver. Alluvial and alpine and ice-sheet glacial sediments later filled these deep sections.

HYDROGEOLOGY OF UNCONSOLIDATED SEDIMENTS

The spatial extent, depth, and lithology of the unconsolidated sediments form the hydrogeologic framework for the shallow ground-water system, which represents the primary ground-water resource in the Methow River Basin. The hydrogeologic framework was defined in the main river valley from Lost River to Pateros and in major tributary valleys based primarily on information from water-well reports filed with the Washington State Department of Ecology (Ecology). Ground-water levels in the unconsolidated sediments were measured in November 2000, March to April 2001, and June to August 2002.

Methods

Ground-water wells were the primary source of information used to define the hydrogeologic framework and the ground-water system of the unconsolidated sediments in the Methow River Basin. Geophysical data from previous investigations (Artim, 1975; EMCON Northwest, unpub. data, 1993) supplemented the data from the ground-water wells.

Well Inventory and Water-Level Measurements

Data from 488 wells were used to study the hydrogeology of the Methow River Basin (table 10, at back of report). Water-well reports for several thousand wells in the Methow River Basin were obtained from Ecology. These reports were reviewed and 463 wells were selected for a field inventory. Most of these wells were inventoried during late October through early December 2000. Data from an additional 25 wells used in previous studies (EMCON Northwest, unpub. data, 1993, and Montgomery Water Group, Inc., 2001) or in current (Okanogan County) or discontinued (Verne Donnet, written commun., 2002) water-level networks were incorporated into the database for this study. The selected wells are broadly distributed in the major river valleys (fig. 3) and open to both shallow and deep aquifers in both the unconsolidated sediments and in bedrock. A high priority was placed on locating wells that penetrated the bedrock surface, so that the thickness of the unconsolidated sediments in the study area could be determined.

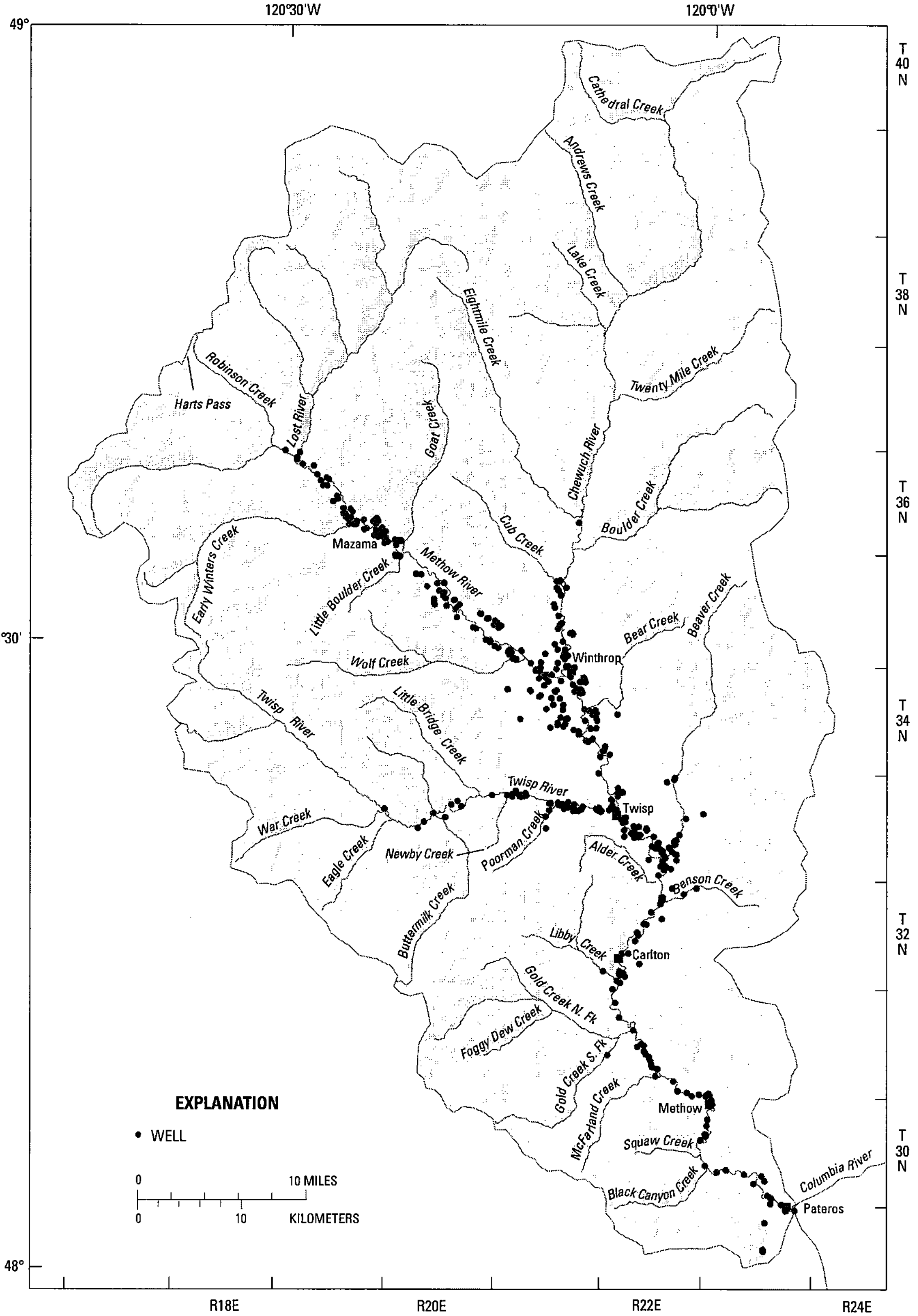

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Figure 3. Location of wells used to study the hydrogeology, quality of water, and ground-water/surface-water exchange in the Methow River Basin, Okanogan County, Washington.

Wells in Washington are assigned a local number that identifies the township, range, section, and 40-acre tract. For example, 33N/21E-09C01 (fig. 4) indicates that the well is in township 33 north (N) and Range 21 east (E) of the Willamette base line and meridian. The numbers immediately following the hyphen indicate the section (09) within the township; the letter following the section identifies the 40-acre tract within the section. The two-digit sequence number following the letter (01) indicates that the well was the first one inventoried by the USGS in that tract. The letter D and a number following a sequence number indicate that the well has been deepened and how many times; for instance, D1 indicates the well has been deepened once. The letters A or B after the sequence number indicates that piezometers are nested in the well, with successive numbers or letters assigned to each piezometer in the well.

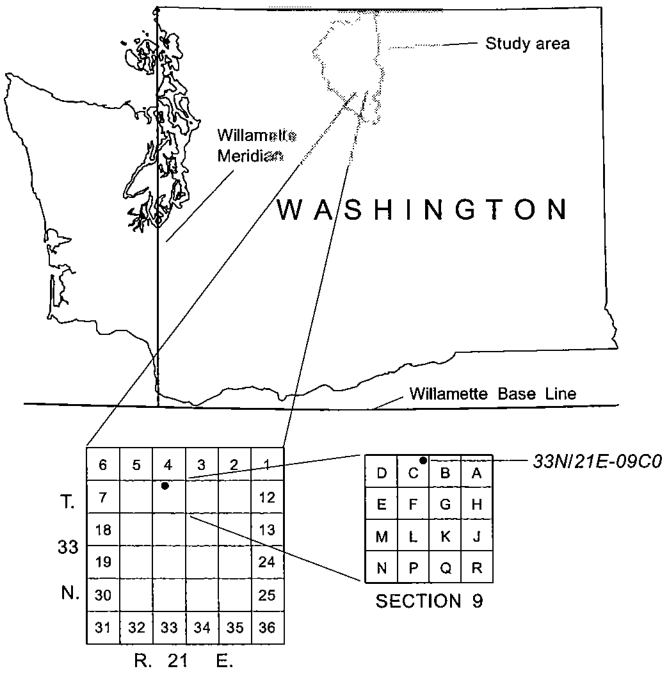


Figure 4. Well-numbering system used in Washington.

The field inventory consisted of locating wells for which lithologic logs and well-construction information were available. After a well was located in the field and permission given by the owner, the water level in the well was measured and the coordinates (latitude, longitude) of its location were determined. Water levels were measured as depth below land surface using either a graduated steel tape or a calibrated electric tape accurate to the nearest 0.01 ft. Water levels were measured at least twice, several minutes apart, to verify the measurement and determine if the water level was static or was affected by recent pumping or pumping of a nearby well. After the initial field inventory, many of the wells were revisited, either for additional water-level measurements or to collect samples for water-quality analysis.

Latitude and longitude of a well were determined using hand-held Global Positioning System (GPS) receivers. The accuracy of these latitudes and longitudes probably is within 0.5 second. Land-surface altitudes were determined by plotting the wells, using the latitude/longitudes from the GPS receivers, on 1:24,000-scale topographic maps and interpolating the altitudes from the contours (generally to within one-half the contour interval). The contour interval in most of the study area was 40 ft, and some areas had supplemental 20-foot contours.

More precise latitudes, longitudes, and land-surface altitudes (NAVD 88) were determined for a subset of 133 wells using a differential GPS from June 18 to June 21, 2001. Two GPS receivers (reference stations) were placed at fixed locations for at least 8 hours each day. Four other GPS receivers were placed at wells within 6 mi of a reference station for at least 20 minutes per well. The transient deviations in the base station coordinates for any given period were used to correct the coordinates of wells. The accuracy of these latitudes and longitudes is within 0.1 second. The accuracy of the land-surface altitudes is within 1 ft, and probably within 0.2 ft in most instances.

Water-surface altitude was calculated for each water-level measurement as the difference between the land-surface altitude at the well and the depth to the water surface. The water surface in an open well is referred to as the potentiometric surface of the aquifer. The altitude of the potentiometric surface is equal to the sum of the altitude of water at the open interval of the well casing and the pressure of the water at the open interval divided by its specific weight (the pressure head). If an aquifer is confined (above) by a low-permeability layer, water may be under higher pressure than the atmosphere and the potentiometric surface altitude of water measured in an open well would be higher than the altitude of the top of the saturated aquifer.

Static water-surface altitudes (NAVD 88) with a precision within 1 ft, measured from June through August 2001, were used to construct a map of the potentiometric surface of ground water in the unconsolidated deposits of the Methow River Basin. Construction of the map generally followed procedures outlined by Technical Memorandum No. 2002.06 (U.S. Geological Survey, Office of Information, written commun., accessed November 1, 2002, at URL http://water.usgs.gov/publishing/Memos/memo2002_06.html). Along rivers and streams, the altitude of the ground-water surface was assumed to be equal to the land-surface altitude. A digital elevation model (DEM) of the land surface (U.S. Geological Survey, 2003) was used to locate points where the potentiometric contours cross rivers and streams. Surface-water levels were known to within 1 ft at 14 locations that have continuous stage records. Mean surface-water levels at these sites for June 2001 confirmed that the DEM generally was representative of summer water-surface levels for the Methow River. After the initial potentiometric contours were digitized, they were checked for consistency with water levels from wells where altitudes were less precise than 1 ft.

Hydrogeologic Interpretation

The hydrogeologic units in the Methow River Basin were determined using a variety of geologic data, including surficial geologic maps (Artim, 1975; Harris and Schuster, 2000), the lithologic logs from water-well reports and geophysical logs (seismic reflection and vertical electric resistivity) from previous investigations (Artim, 1975; EMCON Northwest, unpub. data, 1993).

The surficial geologic map by Harris and Schuster (2000) is a composite of many different mapping investigations by numerous investigators. The nature and extent of the mapping of the unconsolidated sediments varied widely among these investigations. Some of the composite maps indicate unconsolidated sediments only where these sediments are thick and areally extensive, and indicate bedrock at the surface where the sediments are thin or of minor areal extent. On some maps, the unconsolidated sediments were divided into several units (for example, "glacial drift" and "alluvium"), and on others they were lumped into a single unit ("sedimentary deposits"). The unconsolidated sediments were mapped by Harris and Schuster (2000) in some detail east of Twisp and Winthrop (fig. 2), but were mapped in much less detail in other areas of the basin. Additional areas of unconsolidated sediments were added to figure 2 based on additional information from lithologic logs, field observations, topography, and descriptions of depositional features by Waitt (1972).

Hydrogeologic interpretations were made for all study wells with available lithologic logs (table 11, at back of report). Well-construction information supplied by well drillers and water levels measured during the inventory were used to determine the nature of the water-bearing units in each well and label the well as confined or unconfined (table 12, at back of report).

Hydraulic Conductivity

Water production from a well is often tested at the time of drilling. The pumping rate, drawdown of water level, and pumping time of a specific-capacity test can be used to calculate hydraulic conductivity. Of all the wells inventoried for this investigation, only 36 had adequate test results for analysis. The test results were analyzed using the modified Theis equation for drawdown of a confined aquifer (Jacob, 1947) and were corrected for wells that partially penetrate the aquifer (Jacob, 1950). Assumptions underlying the analysis include horizontal ground-water flow; an infinite, homogeneous, and isotropic aquifer; and constant transmissivity. The analysis used a storage coefficient of 0.1 for the 26 wells in unconfined aquifers, and the analysis used two values of the storage coefficient (0.01 and 0.001) for the 10 wells in confined aquifers to test the sensitivity of the results for the likely range of values for the storage coefficient.

Hydrogeologic Units

The most significant part of the ground-water reservoir, in terms of volume and proximity to rivers and the human population in the Methow River Basin, is in the unconsolidated sediments along the bottoms and lower slopes of the major valleys. These unconsolidated sediments are composed mostly of sand and gravel and range in thickness from a few feet to more than a thousand feet. Wells open to these materials typically will yield more than 100 gal/min. Layers of silt, clay, or glacial till are present within the sands and gravels and act locally as confining beds. The bedrock underlying the unconsolidated sediments or exposed at the land surface typically is a poor producer of ground water. Single-home domestic supplies can be obtained from the bedrock in some locations, but often require wells that penetrate and are open to several hundred feet of the bedrock.

Geologic identification and mapping of the unconsolidated sediments in the Methow River valley have not been done in any detail. Given the state of mapping and the nature of the available data (primarily water-well reports), it is not possible to identify and correlate individual layers over any great distance. Therefore, identification of the unconsolidated sediments was done primarily on a lithologic basis, resulting in the following set of units.

- **Recent alluvium (Qa)**. Mostly sand or sand and gravel with minor amounts of silt and clay, deposited by alluvial processes. Primarily forms aquifers. Probably of Holocene age.
- **Alluvial fan (Qaf)**. Mostly sand and gravel, some boulders, with minor amounts of silt and clay, deposited by alluvial and colluvial (landslide) processes. Primarily forms aquifers. Probably of Pleistocene-Holocene age.
- **Glaciofluvial sediments (Qga).** Mostly sand and gravel, some coarse sands, some cobbles, deposited by glaciofluvial processes. Primarily forms aquifers. Probably of Pleistocene age.
- **Glacial till (Qgd)**. Unsorted, unstratified mixture of fine- to coarse-grained sediments, compacted or uncompacted, deposited by glacial processes. Primarily forms confining units. Probably of Pleistocene age.
- **Glaciolacustrine sediments (Qgl).** Mostly silt and clay, with minor amounts of fine sand, deposited by glaciofluvial processes. Primarily forms confining units. Probably of Pleistocene age.

The glacially derived units (Qga, Qgd, and Qgl) are often repeated several times in the lithologic logs, and three or four different Qga, Qgd, or Qgl units may appear in the same log (table 11).

The thickest unconsolidated sediments are found in the Methow River valley upstream of Winthrop (pl. 1). Most of this part of the valley is underlain by at least 500 ft of unconsolidated sediments and in some locations by more than 1,000 ft. The interpretation of unconsolidated sediment thickness in this study differs from an earlier interpretation (EMCON Northwest, unpub. data, 1993) that proposed the existence of a bedrock "barrier" extending across the entire valley, based on a seismic profile between wells E-1, with bedrock at a depth of 550 ft, and E-2, with bedrock at a depth of 1,050 ft (pl. 1). Bedrock is more likely shallower at well E-1 because that well is closer to the valley wall than well E-2, rather than because a shallow bedrock surface extends across the valley.

Downstream of well E-1, the bedrock surface is at greater depth, for example greater than 820 ft at well E-14, which is not consistent with an upstream bedrock barrier.

Downstream of Winthrop, the unconsolidated sediments beneath the Methow River generally are less than 200 ft thick, except in the reach from Twisp to Benson Creek, where thicknesses can approach 300 ft. In a buried valley segment near the mouth of the Methow River beneath Alta Lake (Waitt, 1972), thickness of the unconsolidated sediments is estimated to exceed 500 ft.

The unconsolidated sediments beneath the main Methow River valley are dominated by coarse-grained materials, mostly sand and gravel. These coarse-grained materials are highly transmissive and, where saturated, are the most productive aquifers in the basin. These materials include Quaternary alluvium (Qa) deposited recently (Holocene) by rivers or glaciofluvial sediments (Qga) deposited earlier by glaciers and rivers.

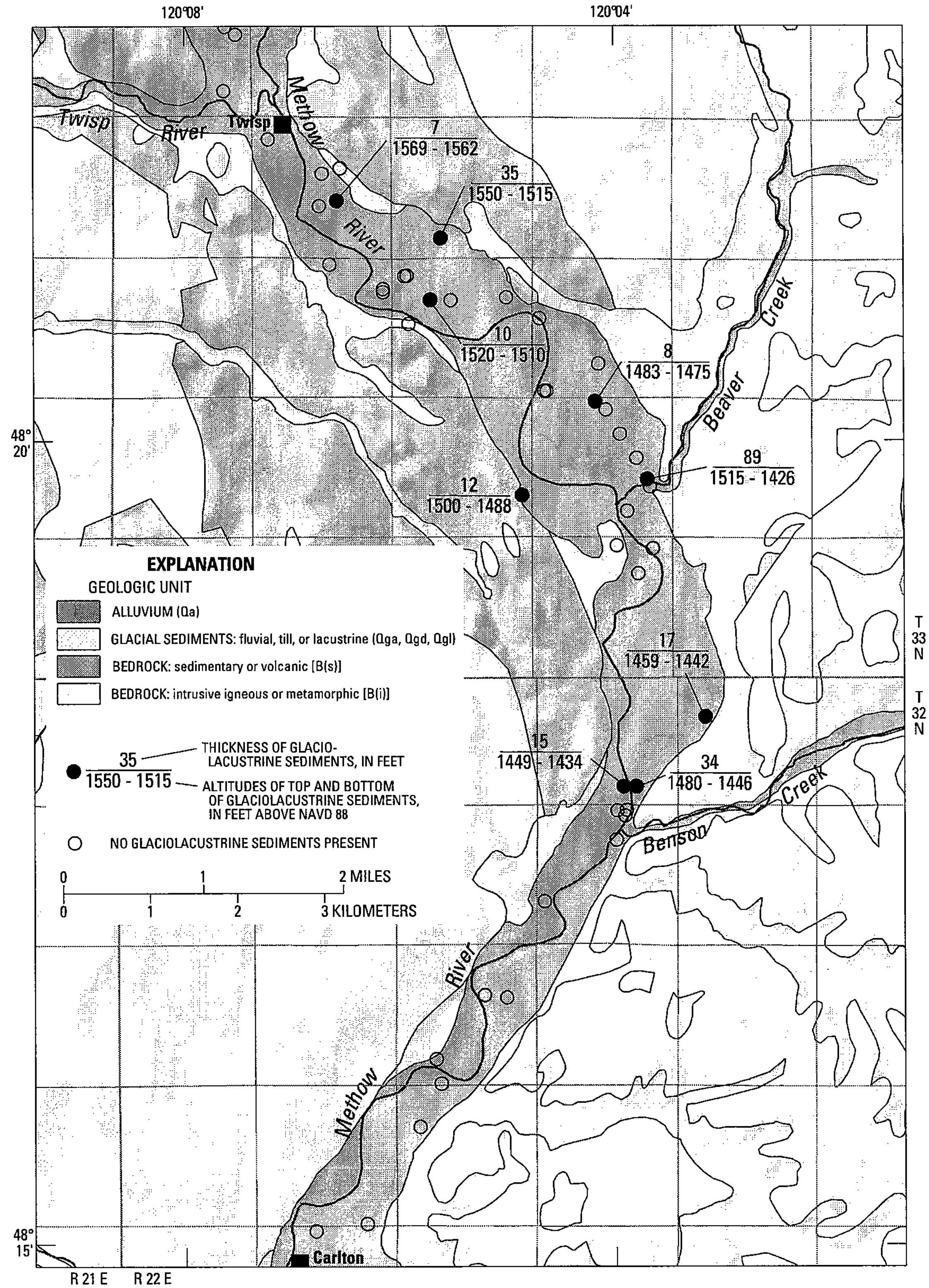
Relatively minor amounts of silts and clays (Qgl) and till (Qgd) occur within the mass of coarse-grained unconsolidated deposits. The fine-grained deposits are relatively poorly transmissive and locally act as confining units. Beneath some parts of the main Methow River valley, these confining units are nearly nonexistent: during the drilling of a 527-foot test well near Mazama (36N/19E-25J02A), only 20 ft of confining materials was encountered, from a depth of 222 to 242 ft.

In the Twin Lakes area just south of Winthrop, where a kame moraine (unstratified drift deposited by glacial meltwater) occupies most of the river valley (Waitt, 1972), a relatively large percentage of the sediments is confining material. Many of the wells on the kame moraine were drilled through thick silts, clays, and tills that frequently make up 50 percent or more of the materials encountered.

The existing data indicate that the confining units are of limited lateral extent, although originally they may have been more continuous. The remnants of what may have been a continuous glaciolacustrine deposit from a possible glacial lake can be seen as blue or gray clays in logs from a few of the wells between Twisp and Carlton (fig. 5).

The unconsolidated sediments directly beneath the main Methow River valley form the most productive aquifers where the ground water is closely connected to the flow in the Methow River. Additional unconsolidated sediments occur along the main valley side slopes, in tributary valleys, and in some upland areas. These sediments differ from the main valley sediments, generally containing much larger percentages of non-aquifer materials, typically finer grained and compacted sediments. An example is at well 35N/20E-24N01, which is located along the southwestern slope of the Methow River valley upriver from Winthrop. This well was drilled through 365 ft of glacial deposits, 338 ft of which were silts, clays, and tills.

Hydraulic conductivities were calculated from specific-capacity tests from 36 wells with open intervals in glaciofluvial deposits (Qga). The storage coefficient, which must be specified to calculate hydraulic conductivity from a specific-capacity test, was not known for Qga, so a storage coefficient of 0.1 was used to calculate hydraulic conductivity where the unit is unconfined. Hydraulic conductivity calculated from the specific-capacity tests from 26 wells completed in the unconfined unit ranged from 20 to 3,500 ft/d with a median of 430 ft/d. The storage coefficient may vary over a few orders of magnitude for a confined aquifer. Hydraulic conductivity calculated from the specific-capacity tests from 10 wells completed in the confined unit ranged from 50 to 2,600 ft/d with a median of 460 ft/d, assuming the storage coefficient was 0.01. When the storage coefficient was changed to 0.0001, the hydraulic conductivity of the unit ranged from 70 to 3,500 ft/d with a median of 620 ft/d. The calculated hydraulic conductivities are consistent with published values for clean sand and fine gravel (Freeze and Cherry, 1979). Hydraulic conductivities were not calculated for other units because there were no specific-capacity tests for wells in those units.



Base from U.S. Geological Survey Digital Data, 1:100,000, 1985
Universal Transverse Mercator projection,
Zone 10, Datum NAD83

Figure 5. Thickness and altitude of the top and bottom of glaciolacustrine deposits in selected wells between Twisp and Carlton in the Methow River Basin, Okanogan County, Washington.

The deposits may be remnants of a once-continuous deposit.

Water Levels in the Unconsolidated Aquifer

Unconsolidated sedimentary deposits in the Methow River valley extend continuously from above Lost River to around Black Canyon Creek, where bedrock is exposed along the river channel. Alluvial and glaciofluvial deposits (Qa and Qga) along the Lost, Chewuch, and Twisp Rivers and Beaver, Benson, and Libby Creeks are contiguous with alluvial and glaciofluvial deposits along the mainstem of the Methow River. These deposits form an unconsolidated aquifer, which exchanges water with the Methow River and its tributaries.

Ground-water levels were measured during a regional drought in water year 2001. Ground water generally was close to the land surface in the unconsolidated aquifer from November 2000 through August 2001 (table 13, at back of report). The median value for static depth to ground water in 184 wells from June through August 2001 was 27 ft below land surface, with a range from 1.2 to 218 ft. Generalized altitudes of the potentiometric surface for the unconsolidated aquifer (Qa and Qga) and, in some cases, alluvial fans (Qaf) during the summer of 2001 are shown on plate 1.

Ground-water levels generally are even across the valley, with higher levels along the valley walls. For an aquifer where the hydraulic conductivity is isotropic (equal in all directions), the direction of ground-water flow is perpendicular to the potentiometric contours. Assuming isotropic conditions, ground-water flow generally is oriented down valley with some inflow from the surrounding terraces and alluvial fans. Ground water flows into the Methow River where potentiometric contours are concave downstream and the river recharges the aquifer where potentiometric contours are convex downstream. Ground water discharges to the Methow River upstream of Wolf Creek, at the Twin Lakes terrace, and at some tributary junctions, particularly Beaver Creek.

The steepest hydraulic gradient in the main valley was 0.9 percent, from the Lost River to Early Winters Creek. The hydraulic gradient decreased downstream to Winthrop, where it was 0.5 percent and remained fairly constant to Beaver Creek. The lowest hydraulic gradient was 0.3 percent, from Beaver Creek to Libby Creek. Downstream of Libby Creek, the hydraulic gradient of ground water increased, reaching a maximum of 0.6 percent in the narrow canyon upstream of Pateros.

The altitudes of the potentiometric surface on plate 1 generally are consistent with Artim (1975), who mapped ground-water levels from Mazama to Winthrop, although the potentiometric contours on plate 1 are convergent from Weeman Bridge to Wolf Creek rather than straight across the valley as in Artim (1975).

The vertical component of ground-water flow is not known because wells in the unconsolidated aquifer generally were shallow and neighboring wells typically penetrated to similar depths. Vertical hydraulic gradients were inferred from water levels in neighboring shallow and deep wells north of Twin Lakes, where ground water may flow upward from a deep bedrock aquifer into the overlying unconsolidated glacial terrace. Assuming ground water is in equilibrium with the altitude of Beaver Creek, ground water in the alluvial deposits may flow downward into older unconsolidated material. In highly permeable material such as alluvium, vertical ground-water flow is likely to be greatest at sources of active recharge, at seepage faces, and at discontinuities in impermeable layers that allow ground water to flow vertically between regions with different potentiometric heads. Ground-water flow also is likely to have a large vertical component where the altitude of the underlying confining bed varies in the direction of horizontal flow. For example, the altitude of the bottom of the unconsolidated sediments appears to increase from Mazama to Winthrop. As a result, ground-water flow in this region is likely to have a large vertical (upward) component.

Seasonal fluctuations were analyzed using ground-water levels from 93 wells in which static water levels had been measured in autumn (November 2000), spring (March-April 2001), and summer (June-August 2001). Of the three seasons in water year 2001 when ground-water levels were measured, water levels generally were lowest in the spring (March and April 2001) and highest in the summer (June-August 2001), although there were many wells that deviated from this pattern. Water levels generally declined from autumn to spring, with a median change in water level of -0.4 ft (range of -17 to 31 ft) from autumn to spring. Water levels generally rose from spring to summer, with a median change of 1.0 ft (range of -23 to 27 ft). The seasonal fluctuations in ground-water levels were locally consistent among neighboring wells but varied along the valley (table 1, pl. 1). The largest rises in water levels from spring to summer were in the upper valley, upstream of Weeman Bridge. Other areas with large rises include around Bear Creek on the east side of the Methow River, the large terrace north of the Twisp River, and the northeast side of the Methow River from Twisp to Beaver Creek. Wells with declining water levels from spring to summer were isolated and generally were located on terraces above rivers.

Table 1. Changes in static water levels and number of wells in the unconsolidated sediments of the Methow River Basin, Okanogan County, Washington, spring to summer 2001

Change in water level	Number of wells
Decline greater than 1.0 foot	8
Decline of 1.0 foot to rise of 1.0 foot	37
Rise of 1.0 to 2.0 feet	18
Rise of 2.0 to 10 feet	21
Rise greater than 10 feet	9

WATER QUALITY

The quality of surface and ground waters in the Methow River Basin was assessed by synoptic (one-time) sampling during 2001 from 19 surface-water sites and 89 ground-water wells. The samples were analyzed for common water-quality parameters (temperature, pH, specific conductance, dissolved oxygen), nitrate, chloride, arsenic, and lead as indicators of anthropogenic contamination, and common ions to characterize the source of water. Previous studies were reviewed to provide information on water quality in the basins at other times.

Previous Studies

Water-quality studies in the Methow River Basin have been limited mostly to synoptic water-quality sampling of one or more surface- or ground-water sites (Raforth and others, 2000; HWA Geosciences, 2001; Raforth and others, 2002). The USGS and the Washington State Department of Ecology (Ecology) have sampled surface-water quality periodically at seven sites (table 2). Andrews Creek near Mazama is one of 50 stations in the USGS Hydrologic Benchmark Network (HBN) chosen to provide long-term measurements of streamflow and water quality in areas that are minimally affected by human activities. The Andrews Creek HBN station data set of 168 samples collected from December 1971 through August 1991 is described and analyzed by Mast and Clow (2000). Mast and Clow concluded that apparent trends in calcium, magnesium, sulfate, and alkalinity were more than likely artifacts of analytical bias (due to changes in analytical methods or equipment) rather than indications of environmental change.

The Methow River near Pateros has been a long-term monitoring station for both the USGS and Ecology. Samples from the Methow River at Pateros historically have exceeded State water-quality criteria for pH and temperature (Washington State Department of Ecology, 2002). The Methow River also has been sampled from 1976 to date at two sites near Twisp (table 2). Site 48A130 was abandoned in 1989 in favor of site 48A140, which is sampled from the bridge in Twisp and which was sampled during this study and also by Ecology. The Methow River below Gate Creek was sampled periodically from 1976 to 1980. The Chewuch River at Winthrop and the Methow River at Weeman Bridge, near Mazama were sampled twice monthly during 1976.

Table 2. Long-term surface-water-quality sampling sites in the Methow River Basin, Okanogan County, Washington

[**Site No.**: Location of surface-water sampling sites are shown on figure 6. **Sampling agency:** USGS, U.S. Geological Survey; Ecology, Washington State Department of Ecology. **Years sampled**: Water years (October through September). **Number of samples**: Period of record through September 2000]

Site name	Sampling agency	Site No.	Years sampled	Number of samples
Andrews Creek near Mazama	USGS	12447390	1972-91	168
	Ecology	48C070	1972-81	99
Chewuch River at Winthrop	USGS	12448000	1976-96	23
	Ecology	48B070	1976	22
Methow River near Pateros	USGS	12449950	1960-70, 1972	98
	Ecology	48A070	1959-66, 1972; 1975-current	386
Methow River near Twisp	USGS	12449510	1976-80	67
	Ecology	48A130	1976-1988	139
Methow River at Twisp	Ecology	48A140	1982-current	131
Methow River at Weeman Bridge, near Mazama	USGS	12447385	1976	24
	Ecology	48A170	1976	24
Methow River below Gate Creek, near Mazama	USGS	12447374	1976-80	43
	Ecology	48A190	1976-80	43

From 1997 through 2001, Ecology investigated mining districts throughout the State to characterize water and sediment quality in streams that drain mining districts in Washington. Ecology collected and analyzed samples of surface water and sediment from the Twisp mining district in June and October 1997 (Raforth and others, 2000). Samples were collected from Alder Creek (fig. 1) at locations upstream and downstream of Alder Mine, the primary mine in the district. Comparisons show downstream increases in all measured field properties except pH, alkalinity, and hardness. The high-flow pH measurement of 4.91 at the middle site, about 0.5 mi below the upstream site, exceeds the State water-quality standard of 6.5 (Washington State Department of Ecology, 1997). Concentrations of lead in samples ranged from 0.022 to 0.17 µg/L; concentrations of arsenic were less than the limit of detection during high flow, but ranged from 1.0 to 1.3 µg/L during low flow at the downstream and upstream sites, respectively. Nearly all metals analyzed at the Alder Creek site were lower in concentration during low-flow conditions, except for arsenic. The higher arsenic concentrations during low flow indicate that ground water may be transporting arsenic. In most cases, concentrations of metals were lower at the upstream site; the highest concentrations were at the middle site, which is directly below the discharge from one of the adits (entrances) at Alder mine, and for which Raforth and others (2000) observed that the water-quality results correspond to the mineralogy of the ore produced from the mine. Concentrations of several metals in samples from Alder Creek exceeded State water-quality standards, but concentrations of lead and arsenic exceeded State water-quality standards only in samples from the adit discharge.

Samples of surface water and sediment from Goat Creek in the Mazama mining district were collected and analyzed by Ecology in October 2000 and April 2001 (Raforth and others, 2002). Comparison of concentrations between samples collected at low and high flow showed differences in pH and concentrations of dissolved solids and sulfate. Concentrations of lead in all samples were less than the detection limit (0.08 µg/L); concentrations of arsenic were less than the detection limit during low flow, and ranged from 0.62 to 0.94 µg/L during high flow at the upstream and downstream sites, respectively. None of the concentrations of metals in samples of surface water from the Mazama mining district exceeded State water-quality standards.

Samples of surface water and sediment also were collected and analyzed by Ecology in the Gold Creek mining district from Gold Creek and Foggy Dew Creek in October 2000 and April 2001 (Raforth and others, 2002). Raforth and others compared concentrations between samples from Foggy Dew Creek and samples collected downstream of the confluence of Foggy Dew Creek and Gold Creek, and observed few differences in measurements of specific conductance. Concentrations of lead in all samples were less than the detection limit. Concentrations of arsenic were higher at the downstream site, during low and high flows, ranging from less than the detection limit to 1.36 µg/L. Concentrations of arsenic also were greater during high flow, ranging from 0.3 to 1.6 µg/L at the upstream and downstream sites, respectively. None of the concentrations of metals in samples of surface water from the Gold Creek mining district exceeded State water-quality standards.

Sampling and Analytical Procedures

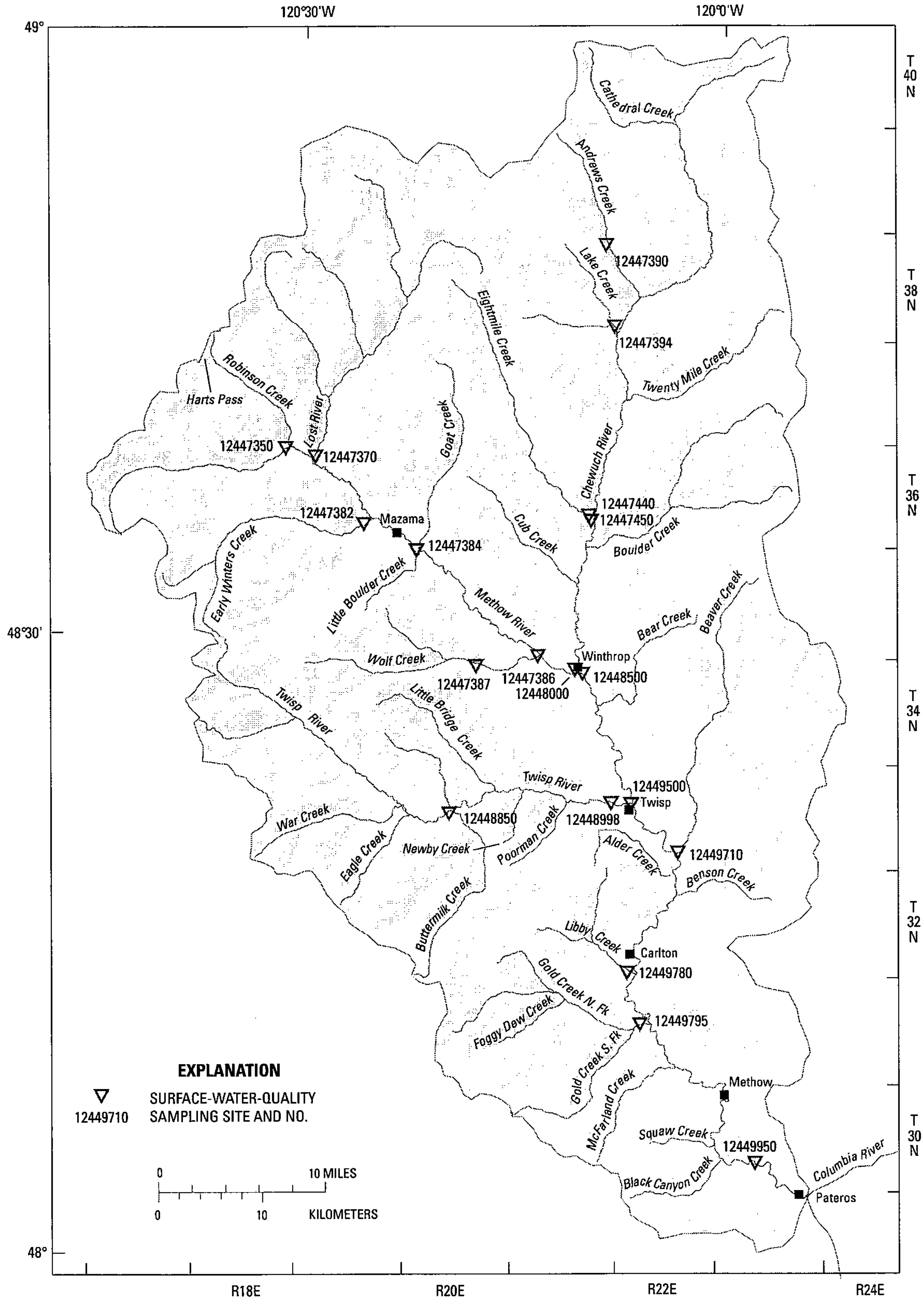
Nineteen surface-water sites (fig. 6) and 89 ground-water sites (fig. 7) were selected for sampling water quality in the Methow River Basin. Sites were selected to represent the variation of water quality in the surface and ground water throughout the basin. Ground-water samples were collected from domestic- or municipal-supply wells during June 2001. Surface-water samples were collected from rivers and streams during September 2001. Ground-water samples were analyzed for concentrations of nitrite plus nitrate, to assess possible leaching of fertilizer into the ground water, and for concentrations of chloride, to assess possible leaching of effluent from septic systems into the ground water or from other anthropogenic sources. In addition to nitrite plus nitrate and chloride, a subset of about 25 percent of the samples also was analyzed for major ions, lead, and arsenic.

Clean sampling protocols, as described by Wilde and others (1998), were used to collect samples. Teams of two persons coordinated to measure physical properties of ground or surface water and to collect samples of ground or surface water for shipment to the USGS National Water Quality Laboratory (NWQL) in Lakewood, Colo., for analysis. Samples for the analysis of major ions and trace metals were filtered and preserved as described by Pritt and Raese (1995) and USGS Office of Water Quality Technical Memorandum 98.06 (U.S. Geological Survey, 1998a). Samples for the analysis of total ammonia plus organic nitrogen and total phosphorus were collected and preserved as described by USGS Office of Water Quality Technical Memorandum 99.04 (U.S. Geological Survey, 1998b).

Surface-Water Sampling

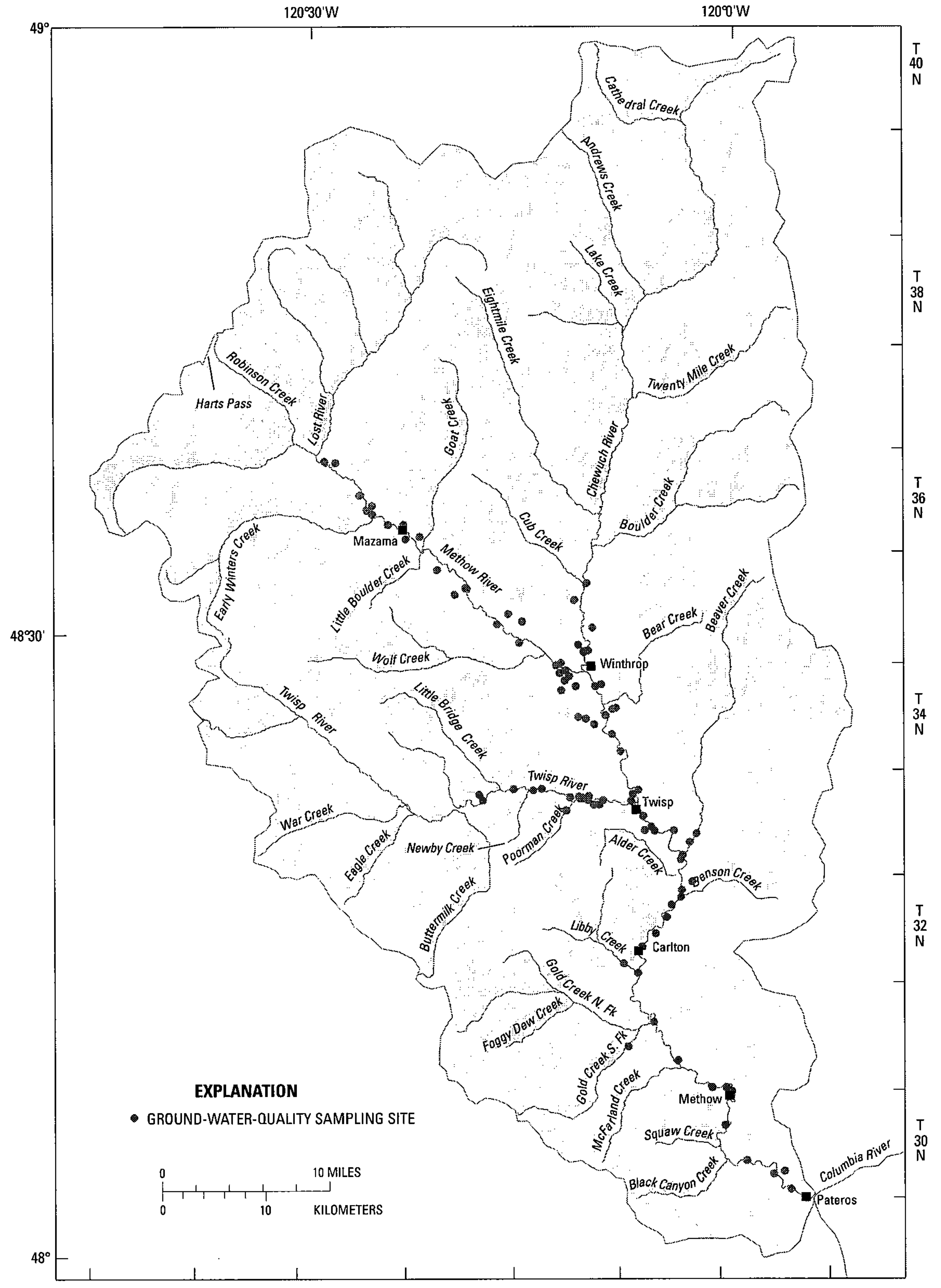
Surface-water sites in the Methow River Basin were sampled September 17-21, 2001, during low flow near the end of the irrigation season to assess basin-wide variations in nutrients, major ions, and, to a limited extent, concentrations of arsenic and lead in surface water (fig. 6 and table 14, at back of report). Sites were selected along the mainstems and tributaries of the Methow, Twisp, and Chewuch Rivers to provide a distribution of samples in and around the major valleys. The Methow River was sampled from the tributaries in the headwaters on Lost River, Early Winters Creek, and Goat Creek and from the mainstem of the upper Methow River at Goat Creek to near the mouth at Pateros, Washington. Surface-water sites along the Twisp River were sampled from above Buttermilk Creek to near Twisp. Sites in the Chewuch River Basin were sampled from Andrews Creek in the headwaters to the mouth at Winthrop, as well as the Eightmile Creek.

Water samples representative of the flow in the stream cross section were obtained by collecting depth- and width-integrated sub-samples at equally spaced intervals across the stream using a US DH-81 sampler, as described by Edwards and Glysson (1999). The sampler holds a 1-liter or 3-liter Teflon bottle, and all parts of the sampler coming in contact with the water sample are made of Teflon. Sub-samples were composited and split using a polyethylene churn splitter, as described by Wilde and others (1999a).



Base from U.S. Geological Survey Digital Data, 1:100,000, 1985
Universal Transverse Mercator projection,
Zone 10, Datum NAD 83

Figure 6. Location of surface-water-quality sampling sites in the Methow River Basin, Okanogan County, Washington.



Base from U.S. Geological Survey Digital Data, 1:100,000, 1985
Universal Transverse Mercator projection,
Zone 10, Datum NAD 83

Figure 7. Location of ground-water-quality sampling sites in the Methow River Basin, Okanogan County, Washington.

Samples for major ions, nutrients, lead, and arsenic were drawn from the churn splitter and filtered or preserved if necessary. Sub-samples for analysis of filtered nutrients were pumped through a disposable 0.45-µm filter cartridge into opaque polyethylene bottles and chilled to less than 4 °C. Samples for analysis of unfiltered nutrients were collected in translucent polyethylene bottles and preserved with 1 mL of 4.5 Normal sulfuric acid. Samples for analysis of major ions, lead, and arsenic were filtered through the same 0.45-µm filter cartridge, and the samples for analysis of cations, iron, manganese, lead, and arsenic were acidified with nitric acid to a pH less than 2. All samples were shipped on ice to the NWQL for analysis. All equipment used to collect and process samples was cleaned with a 0.2-percent non-phosphate detergent, rinsed with deionized water, soaked for 30 minutes in a 5-percent solution of hydrochloric acid, rinsed with deionized water, and stored in a dust-free environment prior to sampling.

Ground-Water Sampling

Ground-water sites were distributed in the major valleys of the Methow River Basin and included wells in the glaciofluvial sediments and bedrock (fig. 7 and table 15, at back of report).

All ground-water samples were collected following protocols described by Wilde and others (1999a) in order to ensure representative samples of ground water. Sampling equipment consisted of Teflon or polyethylene tubing with stainless steel fittings that was attached to a faucet at the wellhead or at a point before pressure tanks or treatment. The tubing was then connected directly to a mobile water-quality laboratory and water was pumped through the tubing to a flow chamber to monitor physical properties (temperature, pH, specific conductance, and concentrations of dissolved oxygen) and through a splitter to provide either raw or filtered water samples.

Water levels were measured before pumping, if possible, and the water level was used to calculate the volume of standing water in the well casing. Wells then were purged to remove at least three casing volumes of water, and samples were collected and processed after values of monitored field properties were within the allowable differences specified by Wilde and others (1999a). If a well was in use or an equivalent volume of purge water had already been pumped during the last 24 hours, the sampling equipment was flushed with ground water and samples were collected after ensuring the stability of physical properties. All pump lines and processing equipment that came in contact with the sample water after the point of collection were composed of Teflon, polyethylene, or stainless steel. Ground-water samples were pumped directly through a splitter or a filtration cartridge into sample bottles, and samples were preserved or stored on ice and shipped for analysis to the NWQL. All lines and processing equipment used to collect and process samples were cleaned with a 0.2-percent non-phosphate detergent, rinsed with deionized water, and stored in a dust-free environment prior to sampling.

Laboratory Methods

Water samples for the analysis of nitrate and other nutrients were received at the NWQL and stored at less than 4°C prior to analysis, as described by Pritt and Raese (1995). All samples were analyzed for nitrite plus nitrate and chloride and a subset of samples were analyzed for major ions, lead, and arsenic (table 3). Nutrient samples were analyzed for nitrite plus nitrate using a cadmium reduction-diazotization colorimetric method, for ammonia using a salicylate-hypochlorite colorimetric method, and for orthophosphate using a phosphomolybdate colorimetric method; all as described by Fishman (1993). Samples were analyzed for phosphorus as well as for ammonia plus organic nitrogen using microkjeldahl digestion and colorimetry, as described by Patton and Truitt (1992; 2000). Samples were analyzed for chloride and sulfate using ion chromatography, as described by Fishman and Friedman (1989); calcium, magnesium, sodium, and iron were analyzed using inductively coupled plasma, as described by Fishman (1993); and potassium was analyzed using flame atomic absorption, as described by Fishman and Friedman (1989). Arsenic, lead, and manganese were analyzed using inductively coupled plasma detected with a mass spectrometer (ICP/MS), as described by Garbarino (1999) for arsenic and by Faires (1993) for lead and manganese.

Table 3. Inorganic and organic analytes, analytical methods, reporting limits, and references for analysis of water quality in the Methow River Basin, Okanogan County, Washington

[**Analytical method:** AA, atomic absorption flame; ASF, automated-segment flow; IC, ion chromatography; ICP, inductively coupled plasma; ICP-AES, inductively coupled plasma with atomic emission spectrometry; ICP/MS, inductively coupled plasma/mass spectrometry; ISE, ion-selective electrode. **Laboratory reporting limit**: All concentrations are in milligrams per liter unless otherwise indicated. **Reference**: USEPA, U.S. Environmental Protection Agency. **Abbreviations**: µg/L, micrograms per liter]

Analytes	Analytical method	Laboratory reporting limit[1]	Reference
	Nutrients		
Nitrogen, ammonia, filtered as N	Colorimetry, salicylate-hypochlorite	0.041	Fishman, 1993
Ammonia plus organic nitrogen, filtered, as N	Colorimetry, microkjeldahl digestion	.10	Patton and Truitt, 2000
Ammonia plus organic nitrogen, unfiltered, as N	Colorimetry, microkjeldahl digestion	.08	Patton and Truitt, 2000
Nitrogen, nitrite, filtered, as N	Colorimetry, diazotization	.006	Fishman, 1993
Nitrite plus nitrate, filtered, as N	Colorimetry, cadmium reduction-diazotization	.047	Fishman, 1993
Phosphorus, orthophosphate, filtered, as P	Colorimetry, phosphomolybdate	.018	Fishman, 1993
Phosphorus, filtered, as P	Colorimetry, phosphomolybdate	.006	USEPA, 1993
Phosphorus, unfiltered, as P	Colorimetry, phosphomolybdate	.0037	USEPA, 1993
	Major ions and metals		
Arsenic, filtered (µg/L)	ICP/MS	0.18	Garbarino, 1999
Bromide, filtered	Colorimetry, fluorescein	[2].01	Fishman and Friedman, 1989
Calcium, filtered	ICP-AES	.011	Fishman, 1993
Chloride, filtered	IC	.08	Fishman and Friedman, 1989
Fluoride, filtered	Colorimetry, ASF/ISE	.16	Fishman and Friedman, 1989
Iron, filtered (µg/L)	ICP-AES	10	Fishman, 1993
Lead, filtered (µg/L)	ICP/MS	.08	Faires, 1993
Magnesium, filtered	ICP-AES	.008	Fishman, 1993
Manganese, filtered (µg/L)	ICP/MS	3.2	Faires, 1993
Potassium, filtered	AA, flame	.09	Fishman and Friedman, 1989
Residue, filtered (180 degrees Celsius)	Gravimetric, residue on evaporation	[3]10	Fishman and Friedman, 1989
Silica, filtered	Colorimetry, ASF, molybdate blue	.48	Fishman and Friedman, 1989
Sodium, filtered	ICP-AES	.06	Fishman, 1993
Sulfate, filtered	IC	.11	Fishman and Friedman, 1989

[1] The Laboratory Reporting Level (LRL) generally is equal to twice the yearly determined long-term method detection level (LT-M DL). The LRL controls false negative error. The probability of falsely reporting a non-detection for a sample that contained an analyte at a concentration equal to or greater than the LRL is predicted to be less than or equal to 1 percent. The value of the LRL will be reported with a "less than" remark code for samples in which the analyte was not detected. The U.S. Geological Survey National Water Quality Laboratory collects quality-control data from selected analytical methods on a continuing basis to determine LT-MDLs and establish LRLs. These values are re-evaluated annually based on the most current quality-control data and may change.

[2] Reporting limit is the U.S. Environmental Protection Agency method detection limit (MDL), described as the minimum concentration of a substance that can be measured and reported with a 99-percent confidence that the analyte is greater than zero.

[3] Reporting limit is the minimum reporting level (MRL), described by Timme (1995) as the smallest measured concentration of a constituent that may be reliably reported by using a given analytical method.

Quality Assurance

About 15 percent of all samples submitted to the laboratory for analysis were quality-control samples, which included field blanks and equipment blanks to measure possible contamination and bias and replicate samples to measure variability. The quality-control techniques for sample processing are described by Wilde and others (1999b). Additionally, quality-control samples were routinely analyzed as part of the NWQL quality-assurance plan described by Pritt and Raese (1995).

Field- and equipment-blank samples for surface water were free of compounds of interest, except for low-level detections of phosphorus, chloride, and sulfate in the equipment blank and a low-level detection of ammonia plus organic nitrogen in one field blank. Field- and equipment-blank samples for ground water were free of compounds of interest, except for low-level detections of calcium and dissolved solids in one of the equipment blanks and a detection of chloride in one of the field blanks. Concentrations of the analytes detected in blanks were all at or near detection levels and generally were much lower than ambient concentrations in ground and surface water; thus, there is little chance that the environmental concentrations for these constituents are biased.

The combined precision of sample collection and laboratory analysis is shown by the relative percentage of difference between replicate analyses that were collected in the field and submitted to the laboratory for analysis (table 16, at back of report). Relative percentage of differences ranged from 0.0 to 69.7 percent, with a median of 2.3 percent. There were 15 of a total of 122 replicate pairs submitted with a percentage of difference greater than 10 percent, ranging in concentration from differences of 0.01 mg/L between replicates submitted for analysis of bromide and nitrite plus nitrate to a difference of 2 µg/L between replicates submitted for analysis of iron. These quality-control results for analyses of replicates generally are an indication of good precision for field collection and laboratory analytical techniques and present no problems for interpretation of data.

The quality of data collection and analysis also may be measured by the calculation of ion balances of a chemical water analysis. Ion balances for 43 ground- and surface-water quality samples that have complete major-ion balances ranged from -3.00 to 3.69 percent, indicating that analytical measurements were of good quality and that data-collection and analysis techniques for major ions generally were free from bias.

Results of Water-Quality Analyses

Surface and ground water generally was of high quality in the Methow River Basin. Concentrations of constituents in surface water (table 17, at back of report) did not exceed any Federal drinking-water standards or health advisories (U.S. Environmental Protection Agency, 2002). Water temperature measured at all surface-water sites at the time of sampling was within the criteria for class AA (extraordinary) streams (Washington State Department of Ecology, 1997). Values of pH measured for all sites except for Beaver Creek also meet the criteria for class AA streams; the pH at Beaver Creek (8.8) meets the criteria for a class C (fair) stream. Concentrations of constituents in ground water (table 17) exceeded Federal drinking-water standards only for arsenic in one well, which is discussed below. Statistical summaries of data collected for samples of surface water are shown in table 4 and for samples of ground water in table 5.

Specific conductance of ground water ranged from 95 to 1,550 µS/cm with a median of 293 µS/cm, whereas specific conductance of streams was much lower, ranging from 60 to 373 µS/cm with a median of 163 µS/cm. Concentrations of dissolved oxygen in samples of ground water ranged from 0 to 11.0 mg/L with a median of 6.8 mg/L, and dissolved oxygen in samples of surface water generally were higher, ranging from 9.20 to 11.1 mg/L, with a median of 10.2 mg/L. pH in ground-water samples ranged from 7.0 to 9.4 with a median of 7.62, and pH in surface-water samples ranged from 7.6 to 8.8, with a median of 8.2. Ground-water temperature ranged from 6.1 to 13.8 °C with a median of 10.7 °C, and surface-water temperature ranged from 6.5 to 14.7 °C with a median of 11.3 °C.

Table 4. Statistical summary of selected surface-water quality data collected in the Methow River Basin, Okanogan County, Washington, September 2001

[**Descriptive statistics**: **Minimum**: E, estimated. Identification is confirmed, but the concentration is estimated because the calculated concentration is less than the laboratory reporting level (LRL, less than the lowest calibration standard, or because the compound was detected in instrument blanks).
Mean, Median: Asterisk (*) indicates that concentration is estimated by using a log-probability regression to predict the values of data less than the detection limit. **Abbreviations**: NWIS, U.S. Geological Survey National Water Information System; ft^3/s, cubic feet per second; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; µg/L, micrograms per liter. <, less than; –, insufficient data for statistical calculation]

NWIS parameter code	Physical property or water-quality constituent	Sample size	Descriptive statistics			Median
			Minimum	Maximum	Mean	
00061	Discharge, instantaneous (ft^3/s)	17	0.44	220	6.97	13.0
00300	Dissolved oxygen, filtered (mg/L)	19	9.20	11.1	10.1	10.2
00400	pH, field (standard units)	19	7.6	8.8	8.2	8.2
00095	Specific conductance (µS/cm)	19	60	373	168	163
00020	Air temperature (degrees Celsius)	19	8.2	27.7	17.6	17.0
00010	Water temperature (degrees Celsius)	19	6.5	14.7	11.0	11.3
00915	Calcium, filtered (mg/L)	19	7.5	53.7	23.7	21.6
00925	Magnesium, filtered (mg/L)	19	1.06	11.4	4.28	3.76
00935	Potassium, filtered (mg/L)	19	.25	.45	.75	.60
00930	Sodium, filtered (mg/L)	19	1.7	11.9	3.78	3.40
39086	Alkalinity, filtered (mg/L as $CaCO_3$)	19	28	165	74.2	64.0
00453	Bicarbonate, filtered (mg/L as HCO_3)	19	34	202	89.6	78.0
00452	Carbonate, filtered (mg/L as CO_3)	19	0	4	.325	.0
00940	Chloride, filtered (mg/L)	19	.1	3.3	.821	.60
00950	Fluoride, filtered (mg/L)	19	.1E	.3	.147*	.127*
00955	Silica, filtered (mg/L)	19	7.1	21.1	11.1	10.5
00945	Sulfate, filtered (mg/L)	19	.5	30.5	7.72	5.50
00608	Nitrogen ammonia, filtered (mg/L as N)	19	.023E	.07	–	<.04
00623	Ammonia plus organic nitrogen, filtered (mg/L as N)	19	.05E	.230	.082*	.073*
00625	Ammonia plus organic nitrogen, unfiltered (mg/L as N)	19	.04E	.320	.085*	.066*
00631	Nitrite plus nitrate, filtered (mg/L as N)	19	.023E	.259	.079*	.047*
00613	Nitrogen, nitrite, filtered (mg/L as N)	19	.003E	.048	–	<.006
00666	Phosphorus, filtered (mg/L as P)	19	.003E	.016	–	<.006
00671	Phosphorus, orthophosphate, filtered (mg/L as P)	19	<.02	.077	–	<.02
00665	Phosphorus, unfiltered (mg/L as P)	19	.002E	.025	.004*	.003*
01000	Arsenic, filtered (µg/L)	5	<.2	.5	([1])	.2
01046	Iron, filtered (µg/L)	19	6E	21	([1])	<10
01049	Lead, filtered (µg/L)	5	.07E	.14	([1])	<.08
01056	Manganese, filtered (µg/L)	19	1.06E	6.1	2.47*	2.23*

[1] Constituent was not detected in majority of samples.

Table 5. Statistical summary of selected ground-water quality data collected in the Methow River Basin, Okanogan County, Washington, June 2001

[**Descriptive statistics**: **Minimum**: E, estimated. Identification is confirmed, but the concentration is estimated because the calculated concentration is less than the laboratory reporting level (LRL, less than the lowest calibration standard, or because the compound was detected in instrument blanks).
Mean, Median, Asterisk (*) indicates that concentration is estimated by using a log-probability regression to predict the values of data less than the detection limit. **Abbreviations**: NWIS, U.S. Geological Survey National Water Information System; ft, feet; NGVD of 1929, National Geodetic Vertical Datum of 1929; mm, millimeters; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; µg/L, micrograms per liter; –, insufficient data for statistical calculation]

NWIS parameter code	Physical property or water-quality constituent	Sample size	Descriptive statistics			Median
			Minimum	Maximum	Mean	
72008	Depth of well (feet below land surface)	89	24.0	450.0	105	74.5
72000	Altitude of land surface (ft above NGVD of 1929)	89	790	2,350	1,740	1,800
00025	Air pressure (mm of mercury)	86	696	745	715	713
00300	Dissolved oxygen, filtered (mg/L)	89	0	11.0	5.79	6.8
00400	pH, field (standard units)	89	7.0	9.4	7.62	7.6
00095	Specific conductance (µS/cm)	89	95	1,550	323	293
00020	Air temperature (degrees Celsius)	85	7.6	31.5	20.1	20.4
00010	Water temperature (degrees Celsius)	84	6.1	13.8	10.4	10.7
00915	Calcium, filtered (mg/L)	24	.13	111.0	33.3	27.8
00925	Magnesium, filtered (mg/L)	24	.019	36.7	6.88	5.25
00935	Potassium, filtered (mg/L)	24	.14	2.73	.783*	.62*
00930	Sodium, filtered (mg/L)	24	2.0	85.0	15.4	4.40
39086	Alkalinity, filtered (mg/L as $CaCO_3$)	24	41	203	111	98.0
00453	Bicarbonate, filtered (mg/L as HCO_3)	24	49	247	133	120
00452	Carbonate, filtered (mg/L as CO_3)	22	0	10	.455	0
71870	Bromide, filtered (mg/L)	24	<.01	.02	.007*	.005*
00940	Chloride, filtered (mg/L)	89	.2	14.9	1.22	.90
00950	Fluoride, filtered (mg/L)	24	.1E	1.9	.267*	.20*
00955	Silica, filtered (mg/L)	24	7.6	20.7	13.2	12.2
00945	Sulfate, filtered (mg/L)	24	3.6	473	31.5	10.8
70300	Residue, filtered (180 degrees Celsius, mg/L)	24	64	884	178	127
00631	Nitrite plus nitrate, filtered (mg/L as N)	89	.025E	6.28	.722*	.19*
01000	Arsenic, filtered (µg/L)	24	.10E	25.4	1.48	.30
01046	Iron, filtered (µg/L)	24	<10	120	–	<10
01049	Lead, filtered (µg/L)	24	.06E	2.01	.423*	.175*
01056	Manganese, filtered (µg/L)	24	1.8E	21.0	4.29*	2.32*

Nitrate and Chloride as Contaminant Indicators

Nitrite, nitrate, and chloride concentrations serve as indicators of potential contamination of ground and surface waters from leaking septic tanks, agricultural fertilizer runoff, or other anthropogenic causes. Most nitrite concentrations in both surface water and ground water were less than the detection limit; thus nitrite plus nitrate is referred to hereafter simply as nitrate. Concentrations of nitrate in surface-water samples ranged from less than the detection limit to a maximum of 0.259 mg/L with a median of 0.047 mg/L and concentrations of chloride ranged from 0.1 to 3.3 mg/L with a median of 0.60 mg/L. Concentrations of nitrate in ground-water samples ranged from less than the detection limit to a maximum of 6.28 mg/L, with a median of 0.19 mg/L (fig. 8). Concentrations of chloride in ground-water samples ranged from 0.2 to 14.9 mg/L, with a median of 0.90 mg/L (fig. 8). Nitrate concentrations were greater than 3 mg/L in five ground-water samples and may be an indicator of anthropogenic sources of contaminations (Madison and Brunett, 1985), although natural sources also can contribute to this level of nitrate concentration. The concentration of nitrate in all samples was less than the Federal Primary Drinking Water Standard maximum contaminant level of 10 mg/L (U.S. Environmental Protection Agency, 2002). Overall, the concentrations of chloride were very low in ground-water and surface-water samples, however, one ground-water sample was more than 10 times the median. Overall, the concentrations of nitrate and chloride in samples of ground and surface water were relatively low and indicate little likelihood of contamination from leaking septic tanks or excess nitrate fertilizer.

Lead and Arsenic as Contaminant Indicators

Lead and arsenic also may serve as indicators of potential contamination of ground and surface waters. Both lead and arsenic were used historically as pesticides in orchards. Runoff from historical mining sites in the Methow River Basin also may contribute to elevated concentrations of lead and arsenic in the ground or surface water (Peplow and Edmonds, 2002). Lead and arsenic also occur naturally in rocks and can dissolve into the surrounding ground and surface waters.

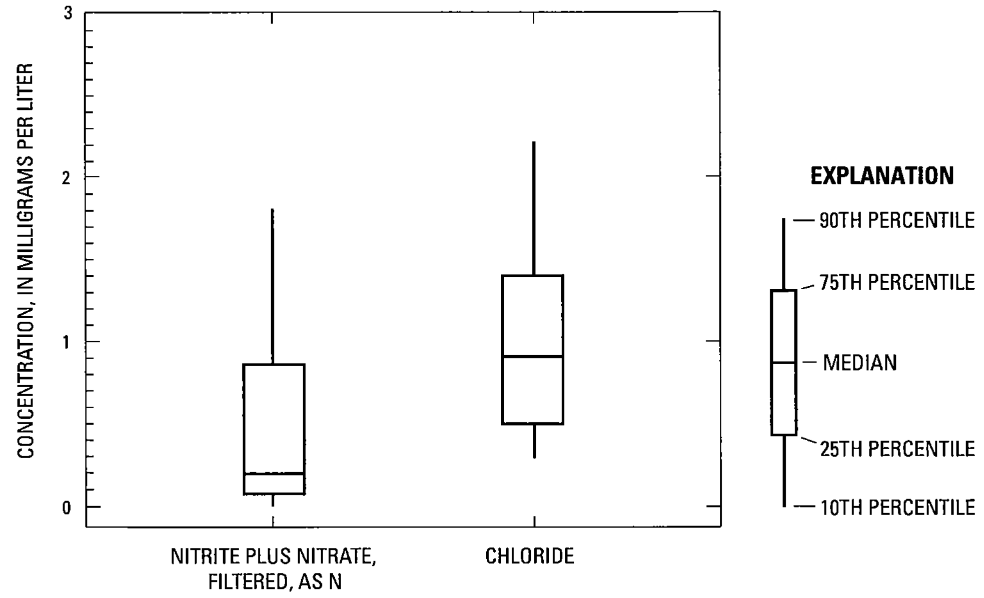


Figure 8. Distributions of nitrate and chloride concentrations in ground- and surface-water-quality samples from the Methow River Basin, Okanogan County, Washington.

Concentrations of lead in surface water ranged from a minimum estimated value of 0.07 µg/L in a sample from Andrews Creek to a maximum of 0.14 µg/L in a sample from the Chewuch River at Winthrop. Concentrations from the remaining sites (Early Winters Creek, Eightmile Creek and Twisp River near Twisp) were 0.08 µg/L. Concentrations of arsenic ranged from less than 0.2 to 0.5 µg/L. Concentrations were less than 0.2 µg/L in samples from Andrews Creek, Chewuch River at Winthrop, and Eightmile Creek. Concentrations of arsenic were 0.5 µg/L in samples from Early Winters Creek and Twisp River near Twisp.

Concentrations of lead in samples of ground water ranged from a minimum estimated value of 0.06 to 2.01 µg/L, with a median of 0.175 µg/L (fig. 9). All 24 detections of lead in samples of ground water, which range in concentration from 0.06 to 2.01 µg/L, are less than the "action level" of 15 µg/L, which triggers treatment or other requirements for water-supply systems but not for domestic wells (U.S. Environmental Protection Agency, 2002).

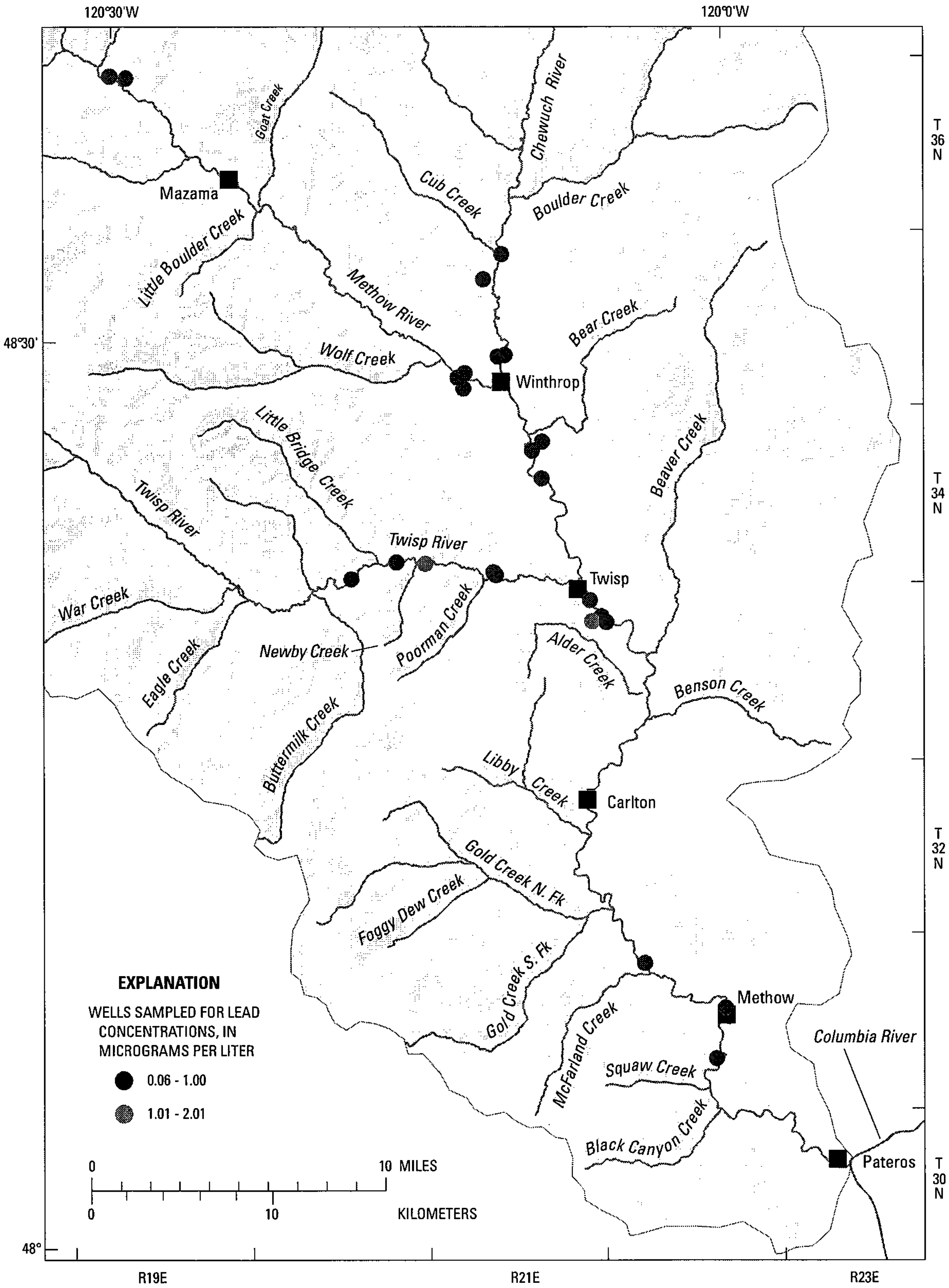
Concentrations of arsenic in samples from ground water ranged from 0.1 to 25.4 µg/L (fig. 10). Only the sample with an arsenic concentration of 25.4 µg/L exceeded the Federal drinking water standard maximum contaminant level (MCL) for drinking water of 10 µg/L for arsenic (U.S. Environmental Protection Agency, 2002). The well (33N/22E-20G01) with the highest concentration of arsenic also had the second highest concentration of lead.

Concentrations in three nearby wells that also were sampled (33N/22E-21E01, 33N/22E-17L01, and 33N/22E-20A04) ranged from 0.1 to 0.9 µg/L of arsenic and 0.10 to 0.19 µg/L of lead, which were very close to the basin-wide medians of 0.30 µg/L arsenic and 0.175 µg/L lead. The large difference in arsenic concentrations between relatively nearby wells may be natural or anthropogenic. The three wells are located on the opposite side of the river from well 33N/22E-20G01, and a river typically divides ground-water flow. The wells are constructed in different hydrogeologic units. Whereas 33N/22E-20G01 was drilled 450 ft in sedimentary bedrock and is only cased in the upper 40 ft, the three nearby wells are constructed in glaciofluvial deposits (Qga; table 12). Thus, the arsenic may be leaching from the bedrock. Alternatively, the high concentration of arsenic in well 33N/22E-20G01 may be due to arsenic leaching from the abandoned mines on the hillside above the well.

Ionic Composition of Surface and Ground Water

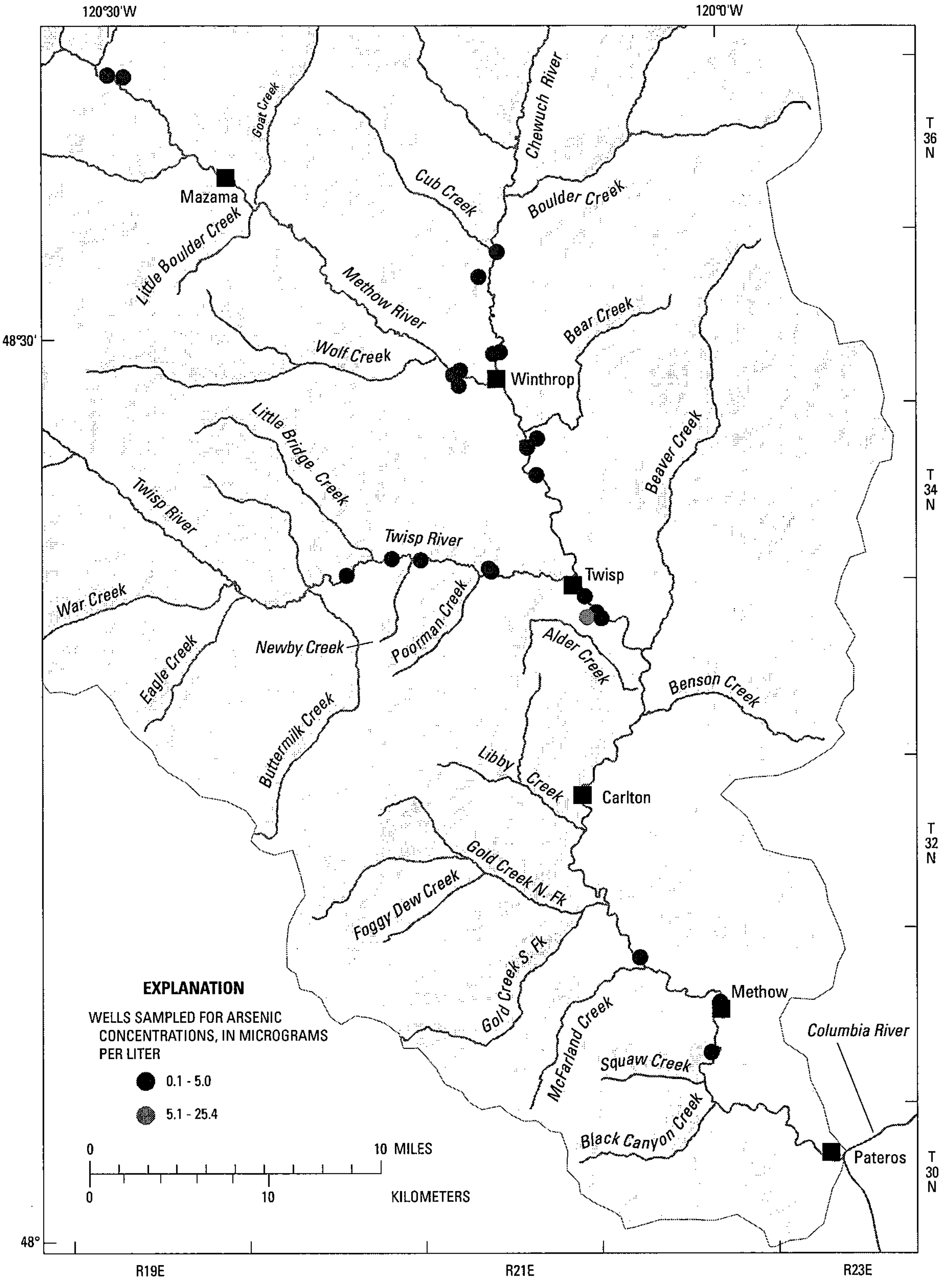
Water chemistry can be characterized generally by the relative percentage of major ions, which are depicted using a trilinear diagram as described by Hem (1985). Water types are described by the combination of dominant cations (calcium, magnesium, sodium, and potassium) and anions (sulfate, chloride, carbonate, bicarbonate, fluoride, and nitrite plus nitrate). Surface water in samples from the Methow River Basin generally was of the same ionic composition: predominantly calcium bicarbonate (fig. 11) and varied only in strength of ionic composition. Samples from the headwaters (Andrews Creek, Lake Creek, Early Winters Creek, Lost River, and Chewuch River at Eightmile Ranch) consisted of water of relatively low ionic strength, as measured by specific conductance that was less than 100 µS/cm. Specific conductance ranged from 60 µS/cm at Andrews Creek to 98 µS/cm at the Lost River.

The ionic strength of surface-water samples from the Methow River increased downstream, ranging from 113 µS/cm in a sample from above Robinson Creek to 205 µS/cm in a sample from the Methow River at Pateros. Input from tributaries may account for some of the increase. For example, a sample from Goat Creek measured 227 µS/cm, a sample from Beaver Creek measured 322 µS/cm, and a maximum of 373 µS/cm was measured in a sample from Libby Creek. The downstream increase in ionic strength also is likely due to ground-water inflow to the river. The ionic strength of samples from the tributaries also increased downstream, which may reflect ground-water inflow: specific conductance in the Twisp River increased from 113 µS/cm above Buttermilk Creek to 213 µS/cm near Twisp, and specific conductance in the Chewuch River increased from 97 µS/cm above Eightmile Creek to 163 µS/cm at Winthrop. The concentrations of major ions in samples of surface water also varied in proportion to the changes observed in specific conductance, but concentrations of the limited number of trace-element samples (lead and arsenic) did not show any relation to streamflow or location.



Base from U.S. Geological Survey Digital Data, 1:100,000, 1985
Universal Transverse Mercator projection,
Zone 10, Datum NAD 83

Figure 9. Concentrations of lead in selected wells in the Methow River Basin, Okanogan County, Washington, June 2001.



Base from U.S. Geological Survey Digital Data, 1:100,000, 1985
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Figure 10. Concentrations of arsenic in selected wells in the Methow River Basin, Okanogan County, Washington, June 2001.

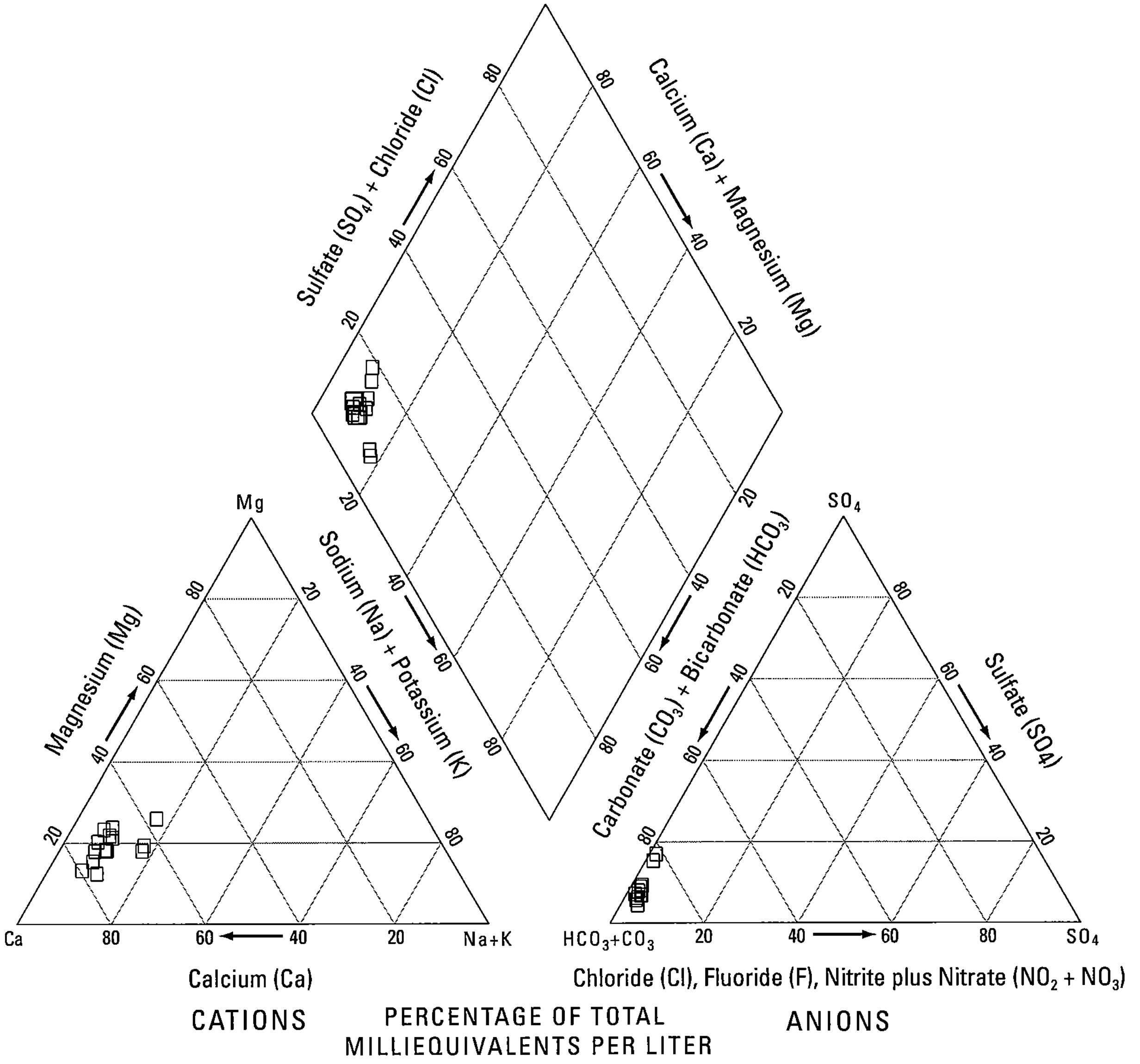


Figure 11. Major ions in surface-water samples from the Methow River Basin, Okanogan County, Washington, September 2001.

Three types of water chemistry were evident from the ionic composition of ground-water samples (fig. 12). Twenty of the samples were calcium-bicarbonate water types, representative of waters from wells that are open to aquifers in Pleistocene glacial drift, or glaciofluvial lithology (Qga). Samples from three wells were sodium-bicarbonate water. Two of these samples are from wells (34N/21E-13K01 and 35N/21E-15K01) that draw water from sedimentary bedrock. The third sample of sodium-bicarbonate water is somewhat anomalous because the well (35N/21E-11M01) draws water from older Pleistocene glaciofluvial deposits (Qga), which are usually associated with calcium-bicarbonate types of water. Water from this site also is the lowest in ionic strength, which may indicate mixing of the water from a different source. Water from well 33N/22E-20G01 represents a third type of water sampled: primarily calcium and sulfate. This well also is open to water from sedimentary bedrock.

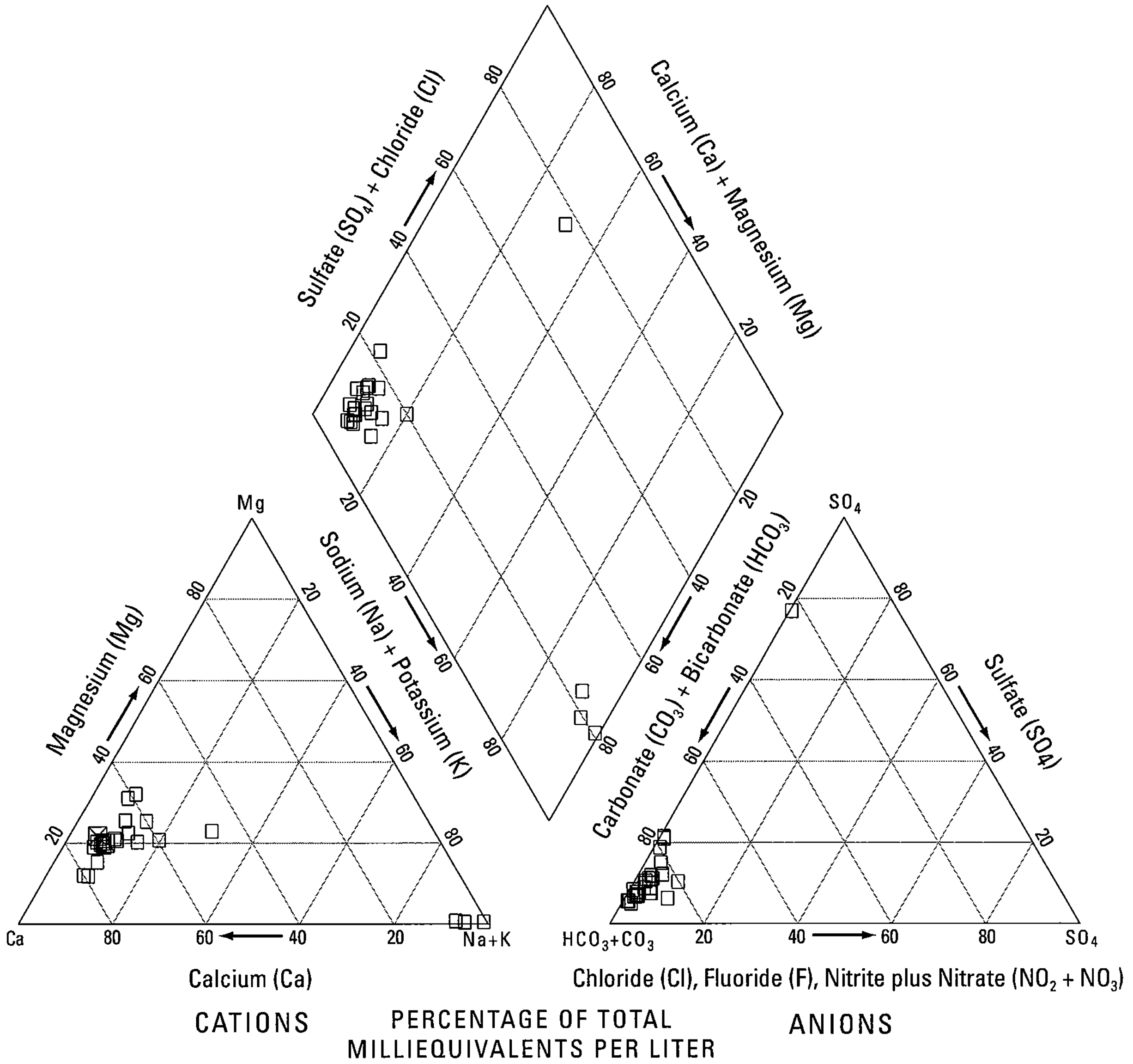


Figure 12. Major ions in ground-water samples from the Methow River Basin, Okanogan County, Washington, June 2001.

Comparison of Water-Quality Results with Historical Records

The quality of surface water in the Methow River Basin as indicated in this study generally is consistent with longer term monitoring results. Physical properties and analytical measurements made at Andrews Creek compared well with the median values for the period from December 1971 to August 1995 described by Mast and Clow (2000). Percentage of differences between the concentrations of cations measured during this study and the median concentration of cations historically measured ranged from 7 to 11 percent (except for a difference of 27 percent for potassium, because of the small range of concentrations of potassium). Percentage of differences between anions and specific conductance measured during this study and historical measurements also compared well, ranging from -17 to 7 percent.

Water temperature and specific conductance exceeded values measured in 1976 for the Chewuch River at Winthrop, but streamflow was lower during sampling in 2001 for this study than in 1976. Although pH and water temperature in the Methow River near Pateros historically have exceeded State water-quality criteria, values in samples collected for this study in September 2001 did not exceed those criteria and compare favorably with samples also collected by Ecology during September (Hallock, 2002). Walters and Nassar (1974) describe the water from the Methow River at Pateros as a calcium magnesium bicarbonate type, suitable for most common uses. Results from analysis of water-quality samples collected from the Methow River at Twisp during this study are within the range of historical values for samples collected by Ecology from the Methow River near Twisp and at Twisp except for streamflow, which was less than the minimum measured during previous sample collections.

EXCHANGES BETWEEN GROUND AND SURFACE WATER IN THE METHOW RIVER VALLEY AND LOWER TWISP RIVER VALLEY

Ground-water discharge from unconsolidated sedimentary deposits in the Methow River Basin is a primary source of baseflow in the Methow and Twisp Rivers. Unconsolidated aquifers, in turn, are recharged by infiltration of snowmelt and rainfall, ground-water flow from adjacent unconsolidated or bedrock aquifers, and seepage from rivers and irrigation canals. The location, rate, and seasonal patterns of exchanges between ground water and surface water were investigated in the Methow and lower Twisp River valleys using streamflow records and ground-water monitoring wells.

Previous Studies

Surface water has been the historical focus of most water-resources investigations in the Methow River Basin, largely because of its uses as water supply in agriculture and for power generation. The USGS first collected continuous records of streamflow in the Methow River beginning in 1904 at Pateros (12450500). Measurements of irrigation diversions in the Methow River Basin were made as early as 1912 (Walters and Nassar, 1974). In an assessment of streamflow depletion from irrigation in the Columbia River Basin, Simons (1953) calculated total consumptive water use in the Methow River Basin of 22,450 acre-ft in 1946, based on an annual consumptive use rate of 1.75 ft per acre applied over 12,830 acres of crops.

The availability and use of ground-water and surface-water resources in the Methow River Basin were first described by Walters and Nassar (1974). Walters and Nassar developed an annual water budget with estimated precipitation of 3 million acre-ft, which is equivalent to 32 in., discharge to the Columbia River of 1.2 million acre-ft, ground-water discharge out of the basin of 0.7 million acre-ft, and evapotranspiration of 1.2 million acre-ft. They noted, however, that ground-water discharge from the basin likely was lower, given ground-water hydraulic conditions at the basin outlet. If ground-water discharge was indeed lower, then either precipitation was lower or evapotranspiration was higher than their estimates.

Walters and Nassar (1974) estimated that annual water use in the basin was 114,500 acre-ft, which is equivalent to a mean annual rate of 158 ft^3/s, with irrigation accounting for 95 percent of the total. Because irrigation generally is practiced only 5 months of the year, total diversions in the basin during the peak irrigation season from May through August may have been more than 300 ft^3/s. Walter and Nassar estimated that more than 95 percent of the water used for irrigation came from rivers and streams. They noted that the high rate of water use per irrigated acre, which was more than 8 ft/yr, was due in part to seepage from irrigation canals. Walter and Nassar cited a study by the Pacific Northwest River Basins Commission (1971) that estimated seepage from canals was 36,000 acre-ft and accounted for 45 percent of the water used for irrigation in the Methow River Basin.

Milhous and others (1976) also comprehensively assessed water resources in the Methow River Basin. They revised estimates of water use in the basin, updated the water budget accordingly, and compiled streamflow records to calculate gains and losses along the Methow River from Robinson Creek to the Weeman Bridge (Washington State Highway 20), between Mazama and Winthrop. They estimated that annual water use in the basin was 88,000 acre-ft (mean annual rate of 120 ft^3/s), again with irrigation accounting for 95 percent and surface-water diversions providing more than 95 percent of the water for irrigation. They estimated that 1.6 million acre-ft (mean annual rate of 2,240 ft^3/s) was lost to the atmosphere by evapotranspiration, with crops accounting for an annual loss of 27,000 acre-ft (mean annual rate of 37 ft^3/s). Ground-water discharge from the basin was estimated as 62,000 acre-ft (85 ft^3/s). Their review of estimates of irrigated acreage in the basin showed a wide range, from 3,200 to 13,400 acres.

Milhous and others (1976) calculated gains and losses for the Methow River above Weeman Bridge from their compilation of streamflow measurements. The river gained 7.4 ft^3/s from Early Winters Creek to Weeman Bridge (31 percent of outflow from the reach) in January 1944. The river lost 45 ft^3/s (24 percent of inflow to the reach) from Robinson Creek to the Mazama Bridge, downstream of Early Winters Creek, in August 1971. In late summer and early autumn of 1972, the river lost flow from Mazama to Fawn Creek, with a mean loss of 36 ft^3/s for 4 days from mid-September to October when streamflow at Mazama ranged from 135 to 63.5 ft^3/s. Losses from Mazama to Fawn Creek were not significantly greater than measurement uncertainty earlier in the summer when streamflow was greater than 159 ft^3/s. Gains in streamflow from Fawn Creek to the Weeman Bridge were documented from August to October 1972, with a mean loss rate of 44 ft^3/s for 7 days. Streamflow at the Weeman Bridge ranged from 576 to 88 ft^3/s during this period.

Kauffman and Bucknell (1977) established policies on water-resources management in the Methow River Basin for Ecology with regard to protection of existing water rights, baseflows intended to preserve instream uses, closures of certain surface waters to further consumptive appropriation, and quantities of water available for additional appropriation in the basin. They noted the importance of the unconsolidated aquifer for domestic and irrigation use and public concern for aquifer recharge from irrigation-canal seepage among their other findings. The policies described by Kauffman and Bucknell (1977) were codified in Chapter 173-548 of the Washington State Administrative Code (1991), which describes the water-resources program for the Methow River Basin.

More recently, Larson (1991) described continuity between ground water and surface water in the Methow River Basin, based on a compilation of information from other, unpublished reports. Larson used 10 ft/d as the lateral velocity for ground water in the upper basin (near Mazama) to estimate a travel time of 200 to 300 days for ground-water recharged from the river flow to wells within 0.5 mi of the river. Downvalley ground-water flow was estimated to be 56 ft^3/s near Mazama and aquifer recharge from the river and its tributaries was 30 ft^3/s during autumn storms and 170 ft^3/s during peak runoff. Downvalley ground-water flow was estimated to be 13 ft^3/s near Winthrop.

Irrigation-canal seepage was documented by Klohn Leonoff, Inc. (1990) for the Methow Valley Irrigation District (MVID). Losses of flow were calculated for both the MVID East Canal (total length of 13.8 mi) and West Canal (total length of 9.8 mi) in August 1989 and September 1989. The mean seepage rates were 2.1 $(ft^3/s)/mi$ for the East Canal and 2.3 $(ft^3/s)/mi$ for the West Canal in August. The mean seepage rates decreased in September to 0.8 $(ft^3/s)/mi$ for the East Canal and 1.5 $(ft^3/s)/mi$ for the West Canal.

Methods for Analyzing Ground-Water and Surface-Water Exchanges

Two types of ground-water and surface-water exchanges were analyzed in the Methow River Basin: flow between rivers and aquifers and aquifer recharge from irrigation-canal seepage. River-aquifer exchanges were analyzed using gains and losses in streamflow calculated from a surface-water discharge balance. Irrigation-canal seepage was estimated from measured losses in discharge for canals, but also was assessed by observing seasonal changes in ground-water levels in the Twisp River valley.

Surface-Water Discharge Balance

Exchanges between the Methow and Twisp Rivers and the adjacent unconsolidated aquifers were calculated using a surface-water discharge balance wherein the exchange rate is equal to the difference between inflows to and outflows from a reach. Gains in streamflow (outflows greater than inflows) were attributed to ground-water discharge, and losses (inflows greater than outflows) were attributed to ground-water recharge. Exchanges between rivers and aquifers were calculated for nine reaches of the Methow River and three reaches of the Twisp River during three low-flow periods. Exchanges were calculated on a daily basis for water years 2001 and 2002 in four reaches of the Methow River and one reach of the Twisp River where continuous records of major inflows and outflows were available. Streamflow was measured using vertical-axis current meters in accordance with Rantz and others (1982) or were calculated from stage-discharge curves at gaging stations. Surface-water measurement sites are listed in table 18 (at back of report).

Exchanges During Low-Flow Conditions

Gains and losses of streamflow in the Methow and Twisp River were calculated for three low-flow periods (September 11-14, 2001, February 11-14, 2002, and September 17-19, 2002). Records of continuous discharge demonstrate that streamflow throughout the basin was steady during these periods (fig. 13). Discharge in the mainstem of the Methow River, its major tributaries, and one surface-water diversion were measured to calculate gains and losses for nine reaches of the Methow River from Lost River to near Pateros (table 19, at back of report). The diversion to the Foghorn Canal was estimated from measurements made earlier in the year.

Tributaries contributing unmeasured inflow to the Methow River included Little Boulder Creek, tributary to the Methow River above Goat Creek, and Benson Creek, tributary to the Methow River above Carlton (fig. 1). The inflow from these tributaries was likely to be less than 1 percent of discharge in the respective reaches of the Methow River, based on measurements of larger tributaries, and was neglected in the surface-water discharge balance for low-flow conditions. Inflow from McFarland Creek, Squaw Creek, and Black Canyon Creek, tributaries to the Methow River above Pateros, was measured on October 24, 2000. The combined inflow contributed by these tributaries was 4.0 ft^3/s, compared to 363 ft^3/s for the Methow River near Pateros. Inflow from the unmeasured tributaries was estimated to be 3 ft^3/s for low-flow conditions.

Flow in the mainstem of the Twisp River and two surface-water diversions were measured to calculate gains and losses for three reaches of the Twisp River from Newby Creek to near Twisp. Daily inflow to the Twisp River returned by the Twisp Valley Power and Irrigation (TVPI) Canal was estimated from stage measurements at a rectangular metal weir at the end of the canal (M. Williams, TVPI Co., written commun., 2002). Tributaries contributing unmeasured inflow included Newby and Poorman Creeks. Based on measurements during higher flow periods (table 18) and observations during low-flow conditions, inflow from these tributaries was estimated to be less than 0.1 ft^3/s each and was neglected in the surface-water discharge balance for low-flow conditions.

Daily Gains and Losses in Streamflow

Daily exchanges between ground water and four reaches of the Methow River from Lost River to near Pateros were estimated with a surface-water discharge balance using continuous records for water years 2001 and 2002 from streamflow-gaging stations in the basin (table 6). The four reaches are from the Lost River to Goat Creek, from Goat Creek to the Chewuch River, from the Chewuch River to Twisp River, and from the Twisp River to Pateros (fig. 1). Discharge records for water year 2001 were rated as good except for Early Winters Creek (12447382), Wolf Creek (12447387), Twisp River near Twisp (12448998), and Beaver Creek (12449710), which were rated as fair. The main ungaged inflow or tributaries to the Methow includes the Methow River above Lost River and Little Boulder Creek (inflows from the Lost River to Goat Creek); Goat and Little Boulder Creeks (from Goat Creek to the Chewuch River); and Benson Creek, Gold Creek, Libby Creek, and McFarland Creek (from the Twisp River to Pateros). Unmeasured inflows to each reach were estimated using a hydrologic simulation model for the Methow River Basin (Ely, 2003). The calculated difference between outflow and inflow on some days may have an upward bias, indicating a larger gain or smaller loss than the actual exchange, because of unmeasured tributary inflow.

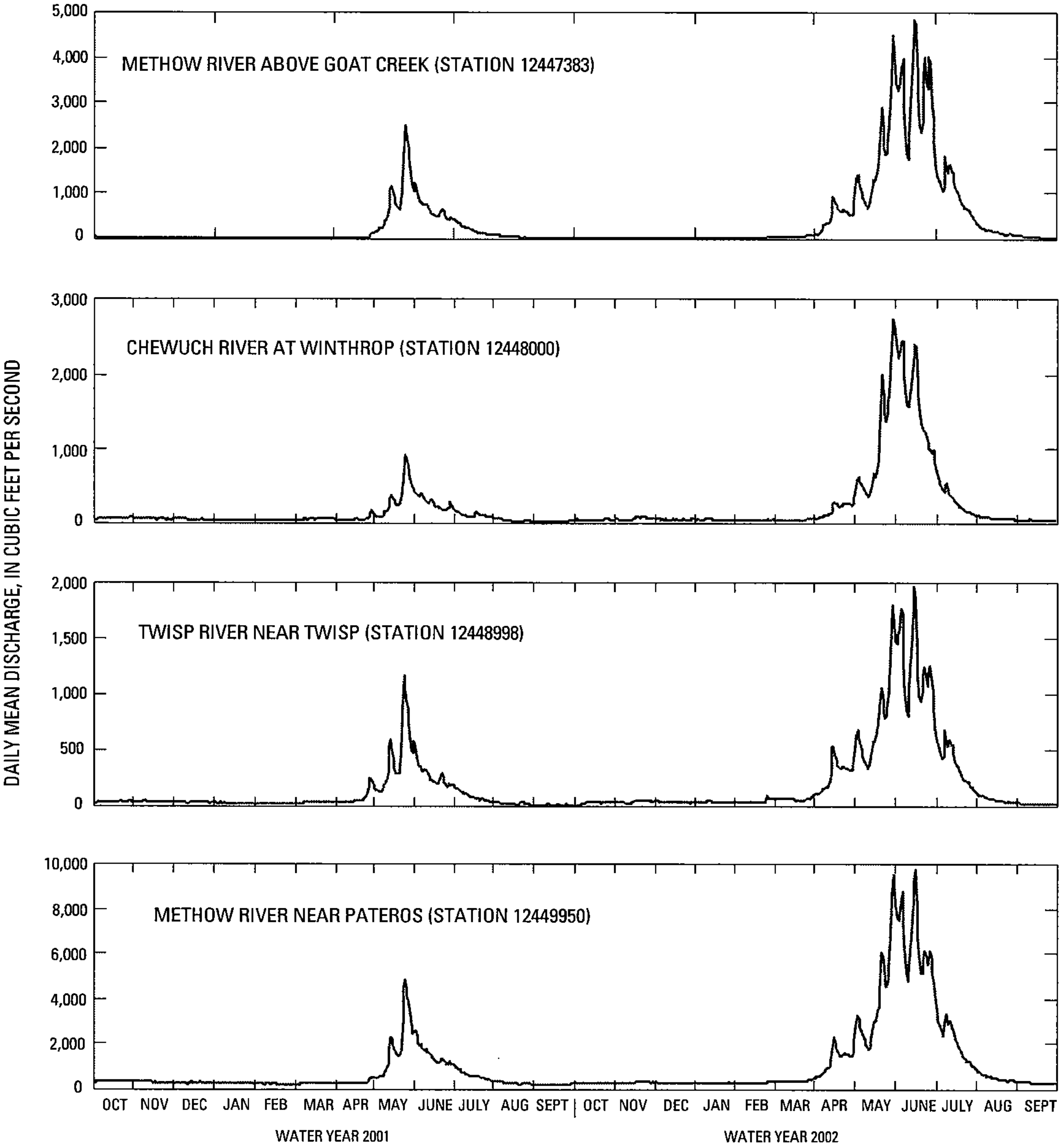


Figure 13. Daily mean discharge in the Chewuch, Methow, and Twisp Rivers in the Methow River Basin, Okanogan County, Washington, during water years 2001 and 2002.

Table 6. Streamflow-gaging stations with continuous streamflow records used to calculate daily exchanges in the Methow and Twisp Rivers and mean discharge in the Methow River Basin, Okanogan County, Washington, water years 2001 and 2002

[**Station No:** Location of gaging stations are shown on figure 1. –, no data available]

Station No.	Station name	Drainage area (square mile)	Mean discharge (cubic feet per second) Water year 2001	Mean discharge (cubic feet per second) Water year 2002
	Methow River			
12447370	Lost River near Mazama	146	88	268
12447382	Early Winters Creek near Mazama	80	68	179
12447383	Methow River above Goat Creek	373	153	581
12447387	Wolf Creek below diversion	33	13	40
12448000	Chewuch River at Winthrop	525	101	315
12448500	Methow River at Winthrop	1,007	430	1,143
12448998	Twisp River near Twisp	245	100	264
12448620	Methow Valley Irrigation District - East Diversion	–	[1]8	[1]8
12449500	Methow River at Twisp	1,301	508	1,352
12449710	Beaver Creek near mouth	110	6	–
12449950	Methow River near Pateros	1,772	576	1,420
	Twisp River			
12448990	Twisp River above Newby Creek	207	108	276
12448998	Twisp River near Twisp	245	100	262
12448996	Methow Valley Irrigation District - West Diversion	–	[1]8	[1]8
12448992	Twisp Valley Power and Irrigation Company Diversion	–	[1]4	[1]4

[1] Annual mean diversion.

A daily discharge balance from November 1, 2000 through September 30, 2002 for the lower Twisp River from Newby Creek to near Twisp was calculated from continuous-streamflow records collected at streamflow-gaging stations (table 6). Inflow was measured continuously in the Twisp River above Newby Creek (12448990). Outflows were measured continuously in the Twisp River near Twisp (12448998), the TVPI Canal (12448992) and the MVID West Canal (12448996). The irrigation canals divert water from late April to early October. Discharge records were rated good for the Twisp River above Newby and MVID West Canal and fair for the TVPI Canal and Twisp River near Twisp. At its downstream end, the TVPI Canal returned water back to the river about 1 mi upstream of station 12448998. The return-flow rate from the canal to the Twisp River was estimated on the basis of daily observations of stage at a rectangular metal weir at the end of the canal (M. Williams, TVPI Co., written commun., 2002). Although inflows to the reach from Newby and Poorman Creeks were not measured continuously, the combined tributary discharge of Newby and Poorman Creeks was 1.6 ft^3/s on May 9-10, 2001 (0.7 percent of daily inflow to the reach) and 0.6 ft^3/s on June 5-6, 2001 (0.2 percent of daily inflow). Streamflow in both of these creeks continued to decrease through the summer of 2001. Because of their small contribution to total inflow to the lower Twisp River, these creeks were neglected in the daily discharge balance.

Uncertainty of Calculated Daily Gains and Losses in Streamflow

The gains and loses calculated from daily streamflow records have errors associated with unsteady flow and the accuracy of the record. Rapidly rising or falling streamflow, which does not occur simultaneously along a river, may produce a difference in streamflow between two gaging stations. Daily discharges at stations throughout the Methow River Basin, however, rise and fall synchronously, even during high flows, so errors associated with unsteady flow are assumed to be negligible.

The uncertainty of the exchanges calculated from the streamflow records was estimated using a first-order analysis of measurement accuracy (Benjamin and Cornell, 1970) based on the accuracy rating of the records. The accuracy rating of the streamflow records was determined, in part, by the interval around a stage-discharge curve that spans 95 percent of the manual streamflow measurements made during the record period. Streamflow records used to calculate exchanges had accuracy ratings of good or fair. A good rating indicates that about 95 percent of the daily streamflow values are expected to be plus or minus (±) 5 percent of the actual streamflow. In practice, streamflow records were rated as good if 95 percent of the discharge measurements were within 5 percent of the discharge indicated by the rating curve for the gaging station. If discharge measurements are assumed to be normally distributed and unbiased (their mean value is the actual discharge), then the standard error (σ_Q) of good measurements is 2.5 percent of the measured value. A fair rating indicates that about 95 percent of discharge measurements are expected to be within ±7.5 percent of the actual discharge, in which case $\sigma_Q = 3.8$ percent of the measured value.

For normally distributed and unbiased measurements, 95 percent of the calculated exchanges are expected to be within two standard errors of the actual exchange, where the standard error of the calculated exchange ($\sigma_{\Delta Q}$) is given by

$$\sigma_{\Delta Q} = \sqrt{\sum_i (\sigma_{Q_i})^2} \tag{1}$$

where

Q_i is the i^{th} discharge measurement used to calculate a gain or loss along a given reach.

The uncertainty of a calculated exchange, then, depends on the number of discharge measurements used for the calculation and the relative value of each measurement. The 95-percent confidence interval for an exchange calculated from two good measurements with similar values is about ±7 percent of measured discharge. The confidence interval (uncertainty) of an exchange expands with the number of measurements used to calculate the exchange and with lower quality ratings. For example, the 95-percent confidence interval for an exchange calculated from four fair measurements with equal values (a reach starting at the confluence of two tributaries with a large diversion where all inflow and outflow rates are approximately equal) is ±15 percent of any one of the measurements.

The standard error of daily (continuous) exchanges ($\sigma_{\Delta Q}$) was estimated using equation 1, where σ_{Qi} was specified as 0.025 or 0.038 of each daily discharge value used to calculate the exchange, depending on whether the record was rated as good or fair, respectively, and as 0.1 for estimated discharges. The 95-percent confidence interval around each calculated exchange corresponds to $\pm 2\ \sigma_{\Delta Q}$.

Exchanges during low-flow periods generally were calculated from two good measurements, so calculated gains greater than 7 percent of outflow from a reach, and calculated losses greater than 7 percent of inflow to a reach, are likely to indicate actual gains or losses of flow rather than only measurement error.

Continuous Ground-Water Levels in the Lower Twisp River Valley

Ground water occurs in alluvial, glaciofluvial, and glaciolacustrine deposits as well as bedrock in the Twisp River valley. Alluvial and glaciofluvial deposits (Qa and Qga) form the primary aquifer in the lower Twisp River. The width (cross-valley) of the deposit ranges from 300 to 1,600 ft. The thickness of the deposit is not known precisely except at wells that have penetrated through the alluvium into bedrock, but it ranges from 30 ft to more than 170 ft. The potentiometric surface of ground water in the alluvium slopes down-valley, with a gradient of 1.4 percent from Newby Creek to Twisp (pl. 1). Other deposits of unconsolidated sediments include terraces along the valley walls and fill in tributary valleys, particularly in the lower part of the valley.

Ground-water levels and river stage were monitored at three sites on the north side of the Twisp River (fig. 14), beginning in May 2001, to evaluate the ground-water response to irrigation-canal seepage and to assess the relation between river-aquifer exchanges and ground-water levels. Each site has two ground-water monitoring wells (table 7) and one river stage station (see fig. 14).

The upstream site is located in Elbow Coulee at Twisp, river mile (RM) 6.5, where an unconsolidated deposit forms a terrace more than 20 ft above the Twisp River and extends north, filling the dry valley (fig. 14). Waitt (1972) identified Elbow Coulee as an ice-marginal channel formed through a combination of fluvial and glacial erosion. The wells at the upstream site are located north of the river and straddle the TVPI Canal. Both wells penetrate a confined aquifer formed by an unconsolidated glacial deposit (sand, gravel, cobbles, and clay). The north well (33N/21E-09D02, or TW1N) is located 1,300 ft north of the river and extends 61 ft below the land surface into a fractured shale unit with a top altitude of 27 ft above the riverbed altitude. The lower 8 ft of the well is open (no casing). The south well (33N/21E-09D03, or TW1S) is located 660 ft north of the river and extends 38 ft below the land surface, all of which is cased. The lower 5 ft of the well casing is perforated. The bottom of the hole is 6.2 ft above the riverbed altitude but does not extend to bedrock.

The middle site is located at the southwestern margin of a large glacial terrace north of the Twisp River at RM 4.9. The wells are located north of the river on a hillslope forming the southern edge of the large terrace. The TVPI Canal is about 1,300 ft north of the river at the northern margin of the terrace. The wells penetrate a confined aquifer formed by an unconsolidated glacial deposit (sand, gravel, cobble, and clay). The north well (33N/21E-10L02, or TW2N) is located 390 ft north of the river and extends 80 ft below the land surface to a shale unit that is 40 ft below the altitude of the river. The lower 2 ft of the well is open. The south well (33N/21E-10L03, or TW2S) is located 260 ft north of the river and extends 38 ft below the land surface. The casing extends to the entire length of the hole and is open at its bottom, which is 21 ft below the altitude of the river.

Table 7. Continuous monitoring wells in the lower Twisp River Valley in the Methow River Basin, Okanogan County, Washington

[**Monitoring site No.**: Location of wells are shown on figure 14]

Monitoring site No.	Site No.	Well No.
TW1N	482252120134501	33N/21E-09D02
TW1S	482246120134101	33N/21E-09D03
TW2N	482224120115401	33N21E-10L02
TW2S	482221120115601	33N/21E-10L03
TW3N	482213120103601	33N/21E-11P03
TW3S	482212120104001	33N/21E-11P04

The downstream site is located at the southern margin of the large terrace at RM 3.5. The TVPI Canal is about 0.5 mi north of the river at the northern edge of the terrace. The north well (33N/21E-11P03, or TW3N) is located near the top of the terrace and is 525 ft north and 80 ft above the river. TW3N penetrates through the unconsolidated material forming the terrace into a confined aquifer formed by an igneous unit. The well is cased for 100 ft to the top of the igneous unit, which is 15 ft below the altitude of the river in this area; the bottom of the well is 75 ft below the riverbed. The south well (33N/21E-11P04, or TW3S) is located 260 ft north of the river on a floodplain and extends 30 ft below the land surface. The entire well is cased and the lower 5 ft of the casing is perforated. The well is open to a confined aquifer in unconsolidated material. The bottom of the hole is 22 ft below the riverbed altitude.

Ground-water levels in all wells were measured and recorded hourly from May 2001 through October 2002 using a non-submersible pressure transducer with an integrated data logger. Water levels were measured manually with an electric-contact tape measure about every 2 months. Water levels from the pressure transducer were within 0.1 ft of all manual measurements with no bias (drift) over the period of record. The land-surface altitude at one well at each site was measured to within 1 ft using differential GPS (see section “Well Inventory and Water-Level Measurements”). Land-surface altitudes for the other wells were surveyed with a level (theodolite) using the land-surface altitude from the differential GPS as a reference.

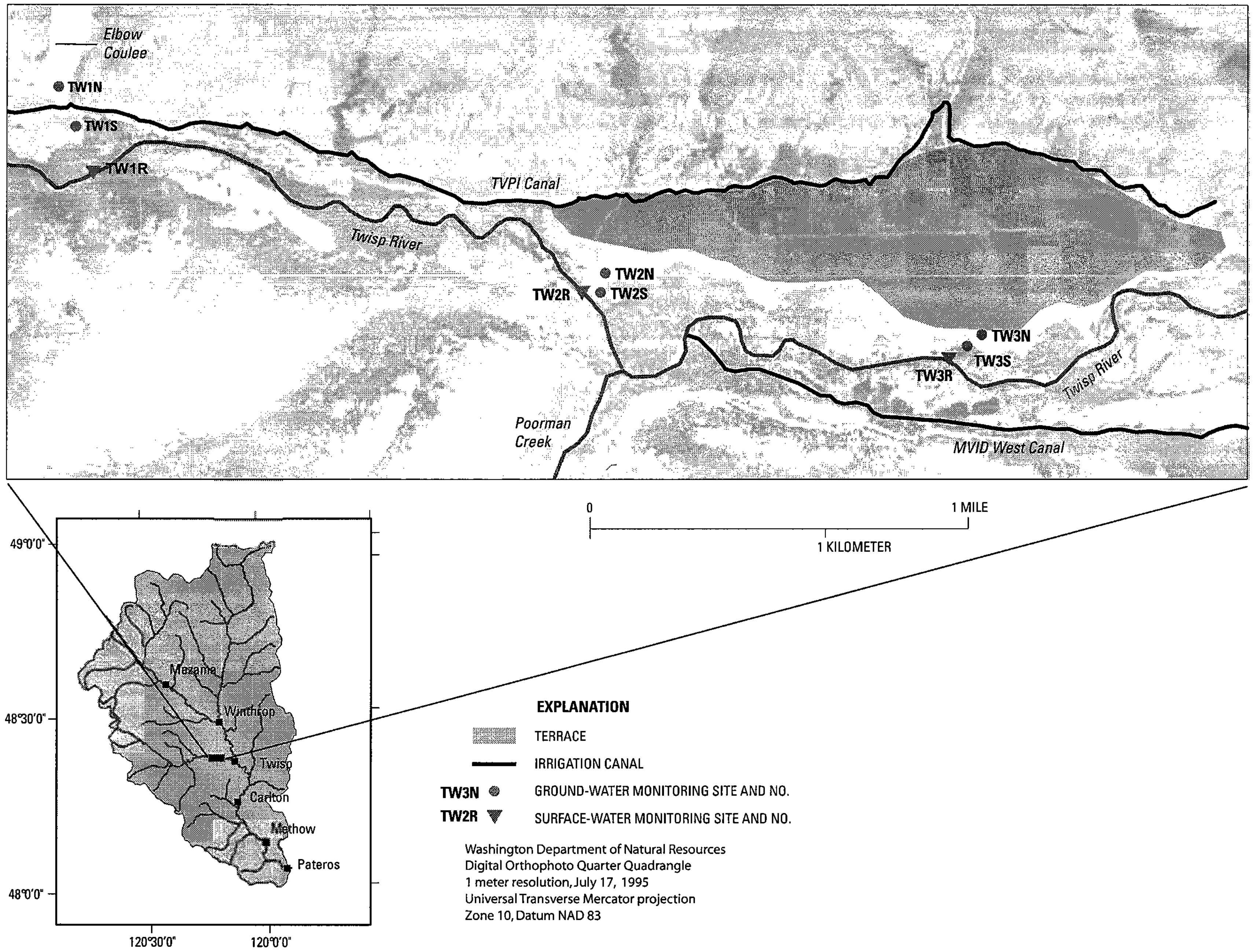


Figure 14. Location of ground-water and surface-water monitoring sites in the Lower Twisp River valley in the Methow River Basin, Okanogan County, Washington.

River stage at the middle and downstream sites also was recorded continuously using non-submersible pressure transducers with integrated data loggers. There were gaps in the stage record when the instruments were inundated by high flows. The stage record for the middle site was terminated in April 2002 when the instrument was washed away by high flows. The stage record for the lower site was discontinued in August 2002 after high flows. Stage at the upstream site was measured manually relative to a reference mark on a boulder along the channel bank on five occasions. A synthetic time-series of stage at each site was developed for gaps in the records based on a logarithmic regression of stage measured at each site and stage measured at the Twisp River near Twisp (12448998). The relation between stage measured at a site and stage measured near Twisp had a correlation coefficient r^2 greater than 0.99 for each site. The altitude of the stage datum at each site was determined by surveying with a level at each site using the altitude of the wells as references.

Estimates of Aquifer Recharge from Irrigation Canals Using a Surface-Water Discharge Balance

Aquifer recharge from irrigation-canal seepage in the Methow River Basin was calculated using a surface-water discharge balance and discharge measurements made in 13 irrigation systems. Discharge was measured at the upstream and downstream ends of 45 canal reaches totaling 29.8 mi, which was about one-half of the total length of unlined irrigation canals (not including lateral canals) operating in the Methow River Basin during water year 2001. Measurement locations were chosen to exclude large water users and spills from the canals; however, there may have been some small users in some of the reaches and, as a result, a small upward bias in the estimates of recharge. The mean seepage rate for each canal was calculated as the sum of the measured losses for each reach divided by the sum of canal-reach lengths. Reach lengths were calculated from digital raster graphics of 7.5-minute quadrangle maps (1:24,000 scale) using a geographic information system. The mean seepage rate for all canals was calculated as the sum of measured losses for all canals divided by the total length of canals over which measurements were made, rather than the average of seepage rates of each canal.

Methods for Developing a Water Budget

A simple water budget for the Methow River Basin was developed using the Modular Modeling System (MMS) (Ely, 2003). MMS integrates individual programs that simulate spatially distributed hydrologic processes including interception, evaporation, transpiration, infiltration, ground-water flow, and runoff. Runoff from the Methow River Basin was calculated in MMS using the USGS Precipitation-Runoff Modeling Systems (PRMS). Model inputs include time series of precipitation, temperature, and surface-water diversions, land-surface altitudes, and land cover (vegetation). The model was calibrated for the period from 1992 to 2001 based on streamflow records from six USGS streamflow-gaging stations.

The water budget has four terms: precipitation, evapotranspiration, ground-water recharge, and runoff (or streamflow). Ground-water flow into and out of the basin was assumed to be zero. Changes in ground-water storage over the 11-year period are not known and were not constrained in the simulations. Ground-water recharge due to infiltration of precipitation, irrigation-canal seepage, and over-application of water to crops was simulated by the model. Fluvial recharge is not simulated by the model and consequently, is included as streamflow in the water budget. Consumptive domestic uses were not accounted for in the model, but are likely to be small relative to basin-wide evapotranspiration. Consumpitve domestic use was estimated based on the per capita water use in Twisp and estimates of percentage of water consumed by domestic use and irrigation in Solley and others (1993).

Gains and Losses in Streamflow Along the Methow River

The annual mean discharge of the Methow River near Pateros was 576 ft^3/s for water year 2001 and was the second lowest annual value for the period from water years 1960 to 2002. Streamflow returned to near normal conditions in water year 2002, when annual mean discharge at Pateros was 1,420 ft^3/s, compared to a mean discharge of 1,550 ft^3/s for water years 1960 to 2002. The difference in annual mean discharge between 2001 and 2002 can be attributed largely to higher flows from May through July in 2002 (fig. 13): maximum daily mean discharge near Pateros was 4,870 ft^3/s on May 25, 2001, for water year 2001 and 9,780 ft^3/s on June 16, 2002, for water year 2002. Baseflow in the Methow River near Pateros during September, which is representative of baseflow conditions with diversions of surface water for irrigation, also was lower in water year 2001 than water year 2002, with a monthly mean discharge of 238 ft^3/s for September 2001 compared to 322 ft^3/s for September 2002.

Spatial Patterns During Low-Flow Conditions

Gains and losses of streamflow along the Methow River were calculated during three low-flow periods: September 2001, February 2002, and September 2002 (table 19, fig. 15). The lowest flows of the three periods were measured on September 12 and 13, 2001, when daily mean discharge near Pateros was 239 and 240 ft^3/s, respectively. Streamflow was higher at most locations on February 12 and 13, 2002, when daily mean discharge at Pateros was 288 and 282 ft^3/s, respectively. The highest flows of the three periods were on September 17 and 19, 2002, when daily mean discharge at Pateros was 302 and 297 ft^3/s, respectively.

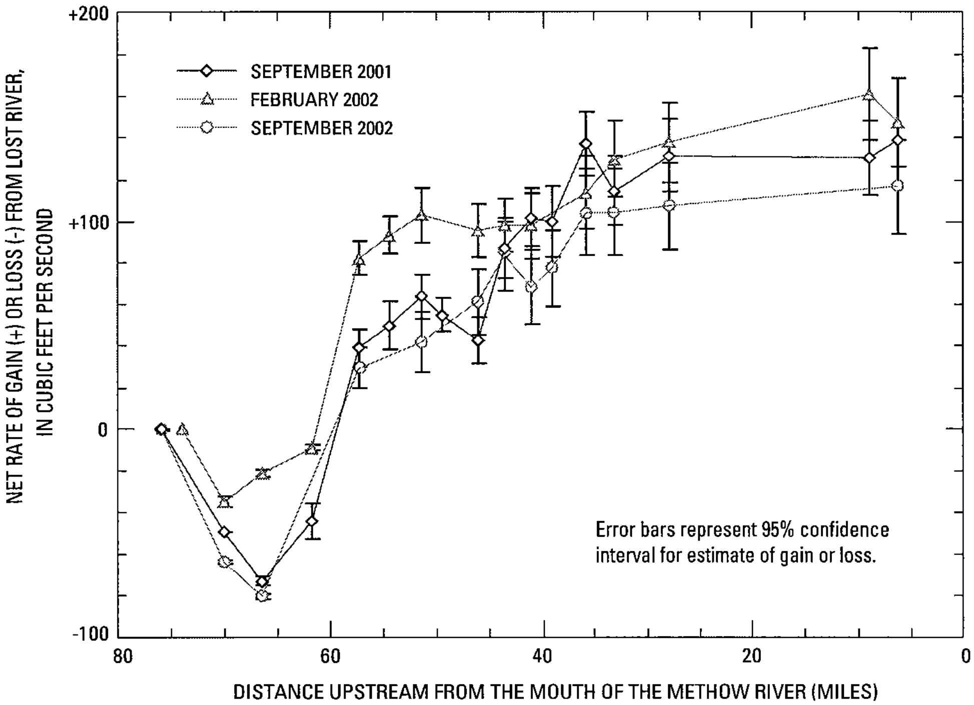


Figure 15. Cumulative gains and losses along the Methow River from Lost River to Pateros under low-flow conditions, Methow River Basin, Okanogan County, Washington.

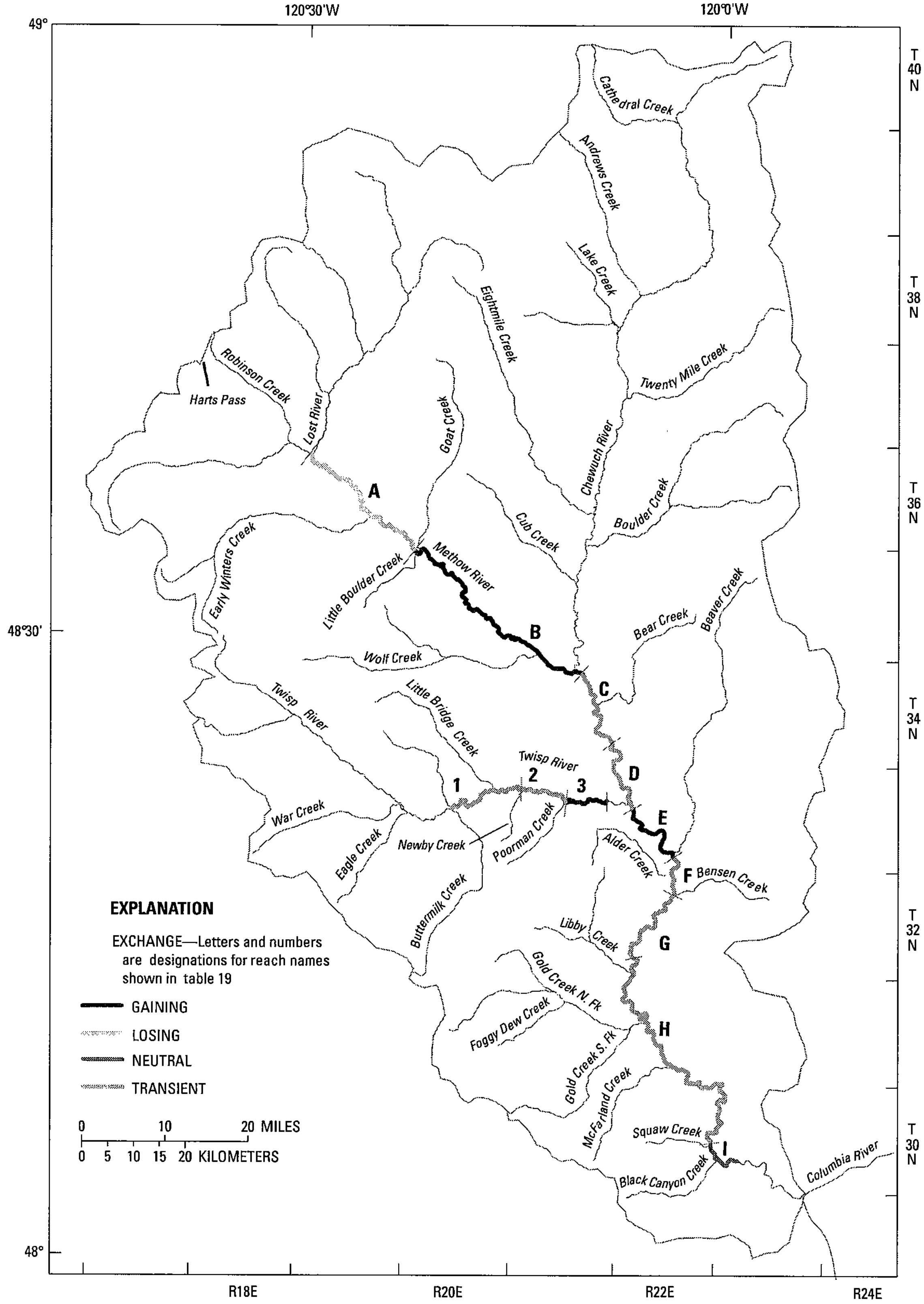
The Methow River had a net gain of 135.6 ft^3/s in September 2001, which was 57 percent of daily mean discharge near Pateros on September 12, 2001. The net gain decreased slightly in February 2002 to 109.7 ft^3/s, which was 39 percent of daily mean discharge near Pateros on February 13, 2002. In September 2002, the Methow River had a net gain of 113.2 ft^3/s, which was 37 percent of daily mean discharge near Pateros on September 17, 2001. The net gain was inversely related to streamflow, with the largest gains during the lowest flows.

Generalized patterns of gains and losses for eight reaches of the Methow River during low-flow conditions are shown in figure 16. Two reaches consistently gained flow: Goat Creek to Winthrop (reach B) and Twisp River to Beaver Creek (reach E). One reach consistently lost flow: Lost River to Goat Creek (reach A). Reach I from Burma Road to Pateros was neutral (no significant gains or losses). The directions of exchanges were not consistent during low flow in the other reaches, which are labeled "transient" in figure 16. Exchanges in individual reaches of the Methow River are described below.

Reach A of the Methow River (from Lost River to Goat Creek) lost 72.6, 55.3, and 80.0 ft^3/s in September 2001, February 2002, and September 2002, respectively. The large losses are characteristic of the Methow River above Goat Creek, which has had periods of no flow in 8 of 12 years from water years 1991 to 2002, despite perennial flow in the Methow River above Lost River, in the Lost River, and in Early Winters Creek. The Methow River above Lost River and its tributaries flow out of surrounding mountains, where they have steep channels confined by narrow valleys with only thin alluvial deposits over bedrock. Downstream of Lost River, the thickness of alluvial deposits in the Methow River valley increases to as much as 1,000 ft and its width increases from less than 1,000 ft to as much as 1.2 mi. As a result of the increased width and thickness of the deposit, ground-water levels are likely to be lower than the river surface, promoting recharge of the unconsolidated aquifer by the river.

Ground water consistently discharged to the Methow River along reach B (from Goat Creek to Winthrop) during low-flow conditions, producing a gain in streamflow of 136.4 ft^3/s in September 2001, 123.8 ft^3/s in February 2002, and 122.2 ft^3/s in September 2002. Most of the gain for each period was concentrated between Goat Creek and RM 56. The consistent gain in this location may depend on a number of factors, but the downstream decrease in the thickness of the unconsolidated basin-fill sediments from Mazama to Winthrop is likely to be the primary reason (pl. 1).

Downstream of Winthrop, the relative and absolute magnitudes of exchanges were smaller and were less consistent over time. In reach C (from Winthrop to RM 45), there was a loss of 21.0 ft^3/s in September 2001, a loss of 7.0 ft^3/s in February 2002, and a gain of 19.0 ft^3/s in September 2002. Reach D (from RM 45 to RM 43), gained 59.0 ft^3/s in September 2001 but 2.0 ft^3/s in February 2002 and 7.0 ft^3/s in September 2002. Reach E (from Twisp to Beaver Creek) gained 35.6 ft^3/s in September 2001, 15.9 ft^3/s in February 2002, and 36.0 ft^3/s in September 2002. Reach F (from Beaver Creek to Benson Creek) lost 23.0 ft^3/s in September 2001, gained 16.0 ft^3/s in February 2002, but had no measurable gain or loss in September 2002. Reach G (from Benson Creek to Carlton) gained 17.0 ft^3/s in September 2001 but gained only 8.0 ft^3/s in February 2002 and 2.7 ft^3/s in September 2002. There were no significant exchanges downstream of Carlton other than a gain of 23.3 ft^3/s in reach H (from Carlton to Burma Road) and a loss of 17.0 ft^3/s in reach I in February 2002. These exchanges, however, may have been artifacts of measurement error.



Base from U.S. Geological Survey Digital Data, 1:100,000, 1985
Universal Transverse Mercator projection,
Zone 10, Datum NAD 83

Figure 16. Location of gaining and losing reaches of the Methow and Twisp Rivers in the Methow River Basin, Okanogan County, Washington.

Annual and Seasonal Patterns

The Methow River from the Lost River to Pateros had an annual mean gain of 97 ft^3/s in water year 2001 and 27 ft^3/s in water year 2002. Total daily gains for the four reaches where daily exchanges between the river and aquifer were calculated equaled 153,000 acre-ft in water year 2001 and 157,000 acre-ft in water year 2002 (table 8). The total daily losses, however, increased from 82,000 acre-ft in water year 2001 to 137,000 acre-ft in water year 2002. The higher losses during water year 2002 represent increased recharge of the unconsolidated aquifer by the river that may have been a consequence of both low ground-water levels brought about by the drought during water year 2001 and near-average streamflow, particularly during the middle to late summer when aquifer recharge by the river is at its highest levels.

In both years, there were three distinct seasonal patterns in river-aquifer exchanges at the reach scale: consistent losses from Lost River to Goat Creek (fig. 17*A*), consistent gains from Goat Creek to Winthrop (fig. 17*B*), and seasonally dependent gains and losses from Winthrop to Twisp (fig. 17*C*) and Twisp to Pateros (fig. 17*D*). Gains in streamflow were relatively steady between water years 2001 and 2002 in all reaches except from Lost River to Goat Creek, which had smaller gains during water year 2001, the drier year, than water year 2002 (table 8). Similarly, all of the reaches had greater losses during water year 2002 than water year 2001.

The Methow River consistently loses flow to aquifer recharge above Goat Creek, with the exception of high-flow periods during May and June (fig. 17*A*). The annual mean loss of streamflow from Lost River to Goat Creek was 81 ft^3/s in water year 2001 and 53 ft^3/s in water year 2002. Cumulative daily losses were 60,000 acre-ft in water year 2001 and 58,000 acre-ft in water year 2002 (table 8). The seasonal pattern of losses in streamflow from Lost River to Goat Creek was similar in both water years 2001 and 2002, with losses generally varying directly with inflow to the reach. After the onset of high flows in the spring, however, the reach gained flow for periods in both years (fig. 17*A*). After high flows receded, the reach returned to a losing condition. This reach accounted for 73 and 42 percent of the total losses of streamflow in the Methow River between Lost River and Pateros in water years 2001 and 2002, respectively.

Table 8. Summary of cumulative gains and losses for four reaches of the Methow River Basin from Lost River to Pateros and for the Twisp River, Methow River Basin, Okanogan County, Washington, water years 2001–2002

[**Annual net exchange**: Values in parentheses ( ) represent the 95-percent confidence interval around the annual net exchange. Because of rounding, totals may not equal the sum of the reaches gains and losses]

Water year	Cumulative daily gains (+) and losses (-) in reach, in thousands of acre-feet					
	Methow River reaches					Lower Twisp River
	Lost River to Goat Creek[1]	Goat Creek to Winthrop	Winthrop to Twisp	Twisp to Pateros[1]	Total	
2001						
Cumulative daily gains	+2	+115	+5	+31	+153	+4.7
Cumulative daily losses	-60	+0	-15	-7	-82	-2.0
Annual net exchange	-58 (±50.9)	+115 (±1.8)	-10 (±2.2)	24 (±2.4)	+71 (±3.8)	+2.7 (± 0.65)
2002						
Cumulative daily gains	+20	+104	5	+28	+157	+9.2
Cumulative daily losses	-58	-11	-38	-30	-137	-6.4
Annual net exchange	-38 (±2.7)	+94 (±5.5)	-34 (±6.3)	-2 (±6.7)	-20 (±11)	+2.8 (± 1.7)

[1] Some inflow estimated.

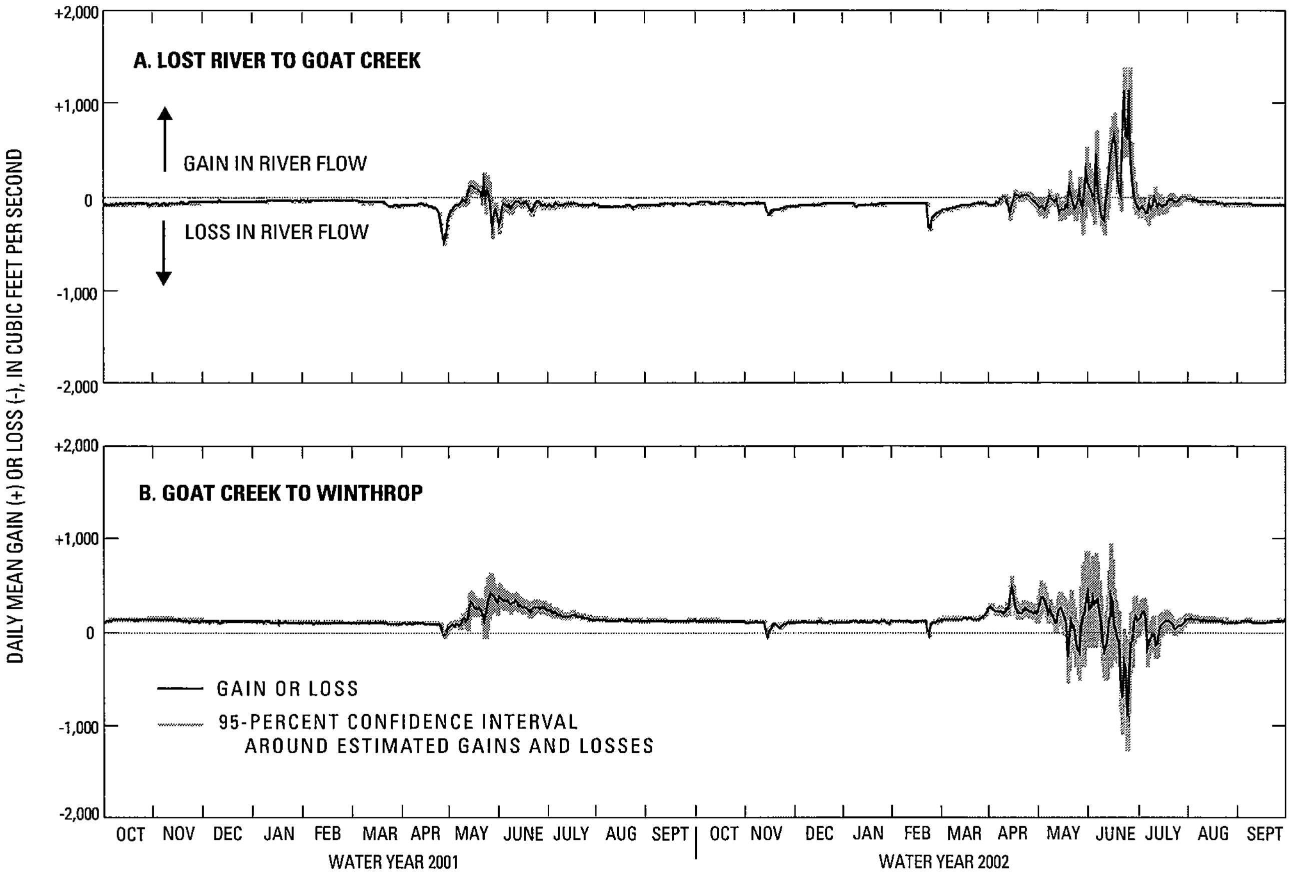


Figure 17. Daily gains and losses for four reaches of the Methow River in the Methow River Basin, Okanogan County, Washington, water years 2001 and 2002.

The Methow River from Goat Creek to Winthrop consistently gained flow from ground-water discharge throughout the year, except for a brief period during high flows in June 2002 (fig. 17*B*). The annual mean gain in streamflow from Goat Creek to Winthrop was 159 ft^3/s in water year 2001 and 115 ft^3/s in water year 2002. Total daily gains were 115,000 acre-ft in water year 2001 and 104,000 acre-ft in water year 2002 (table 8). Daily ground-water discharge along this reach was relatively consistent much of the time (fig. 17*B*), with more variation during high flows. The reach appears to have lost streamflow during high flow in water year 2002. Most of the ground water that discharges to the Methow River occurs along this reach, which accounted for 75 and 67 percent of the annual ground-water inflow between the Lost River and Pateros in water years 2001 and 2002, respectively.

River-aquifer exchanges in the Methow River from Winthrop to Twisp is relatively neutral during much of the year (fig. 17*C*). The reach had annual mean losses of 14 ft^3/s in water year 2001 and 47 ft^3/s in water year 2002. Losses during high flows account for most of the annual exchange volume of water in this reach, although the river gained about 30 ft^3/s during August and September in both 2001 and 2002. Cumulative daily gains, which mostly occurred during late summer in the reach, were consistent in 2001 and 2002 and were estimated to be 5,000 acre-ft annually.

The Methow River from Twisp to Pateros generally gained flow except in high-flow periods (fig. 17*D*). The reach had an annual mean gain of 34 ft^3/s in water year 2001 but an annual mean loss of 2 ft^3/s in water year 2002, although the loss was not significantly greater than the uncertainty of the record. Gains from Twisp to Pateros were consistent in 2001 and 2002 (31,000 and 28,000 acre-ft, respectively, but losses were higher in 2002 (30,000 acre-ft) than in 2001 (7,000 acre-ft).

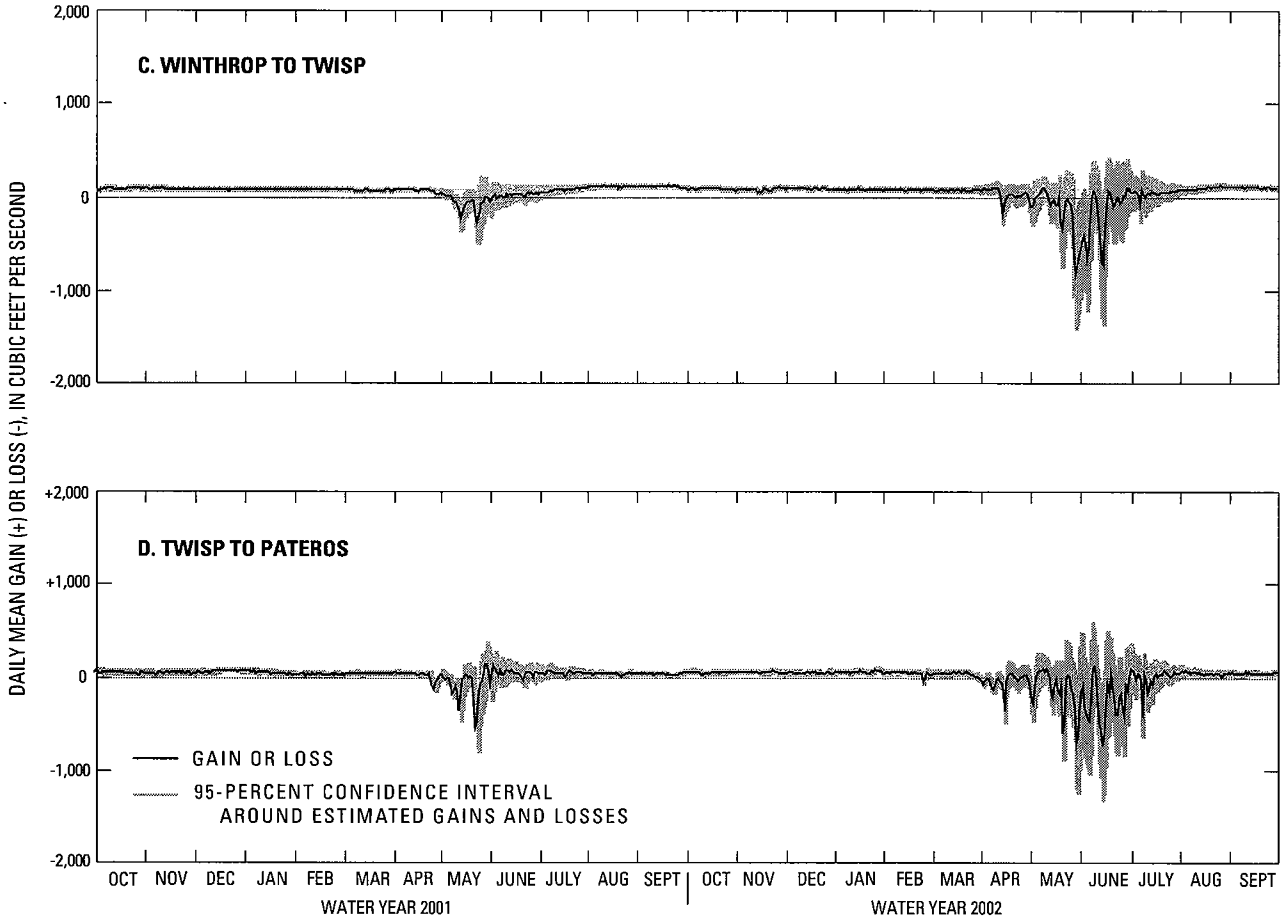


Figure 17. — *Continued.*

Gains and Losses in Streamflow Along the Lower Twisp River

The mean annual discharge of the Twisp River near Twisp was 262 ft^3/s for the 17-year period from water years 1976-79 and 1990-2002. Streamflow in the Twisp River was well below average in water year 2001 but returned to near average during water year 2002, as in the Methow River. Annual mean discharge of the Twisp River in water year 2001 was 108 ft^3/s above Newby Creek and 100 ft^3/s near Twisp. In contrast, annual mean discharge of the Twisp River in water year 2002 was 272 ft^3/s above Newby Creek and 264 ft^3/s near Twisp.

Maximum daily mean discharge for the Twisp River in water year 2001 was 1,110 ft^3/s above Newby Creek and 1,180 ft^3/s near Twisp on May 24, 2001. Maximum daily mean discharge for the Twisp River in 2002 was 2,061 ft^3/s above Newby Creek and 1,970 ft^3/s near Twisp on June 16, 2002. Baseflow in the Twisp River was lower in water year 2001, with a monthly mean discharge of 19 ft^3/s for September 2001 compared to 33 ft^3/s for September 2002. The minimum daily mean discharge for the Twisp River near Twisp was 15 ft^3/s on several days in September 2001 and equaled the lowest recorded daily mean discharge for the 17-year streamflow record.

The TVPI and MVID West Canals diverted water from the Twisp River at a mean combined rate of 29 ft^3/s from April 29 to October 15, 2001. Diversions were highest during the early summer, with a monthly mean rate of 33 ft^3/s in July, which was equal to 21 percent of monthly mean discharge of the Twisp River above Newby Creek. Combined diversions decreased to a monthly mean rate of 21 ft^3/s in September, which was equal to 79 percent of the monthly mean discharge of the Twisp River above Newby Creek. Diversions to the MVID West Canal were stopped on four occasions (for 1 to 3 days each) from August 21 to September 25, 2001. The combined diversions of the TVPI and MVID West Canals were 26 ft^3/s from April 29, 2002 to September 30, 2002 and decreased to a monthly mean rate of 23 ft^3/s in September 2002, which was 53 percent of monthly mean discharge of the Twisp River above Newby Creek. Mean (estimated) return flow from the TVPI Canal was 1.3 ft^3/s for the 2001 irrigation season and 1.4 ft^3/s for the 2002 irrigation season.

Spatial Patterns During Low-Flow Conditions

Gains and losses along the lower Twisp River, from Buttermilk Creek to near Twisp, were calculated for a series of three reaches during three low-flow periods in September 2001, February 2002, and September 2002 (table 19, fig. 18). The lowest flows of the three periods were measured on September 11, 2001, when daily mean discharge above Newby Creek was 27 ft^3/s. Streamflow was higher on February 11, 12, and 14, 2002, when daily mean discharge above Newby Creek was 39, 36, and 45 ft^3/s. Although streamflow varied during the February seepage run, the daily net gain from above Newby Creek to near Twisp ranged only between 2 and 3 ft^3/s for the 3 days. Daily mean discharge above Newby Creek was 39 ft^3/s on September 18, 2002.

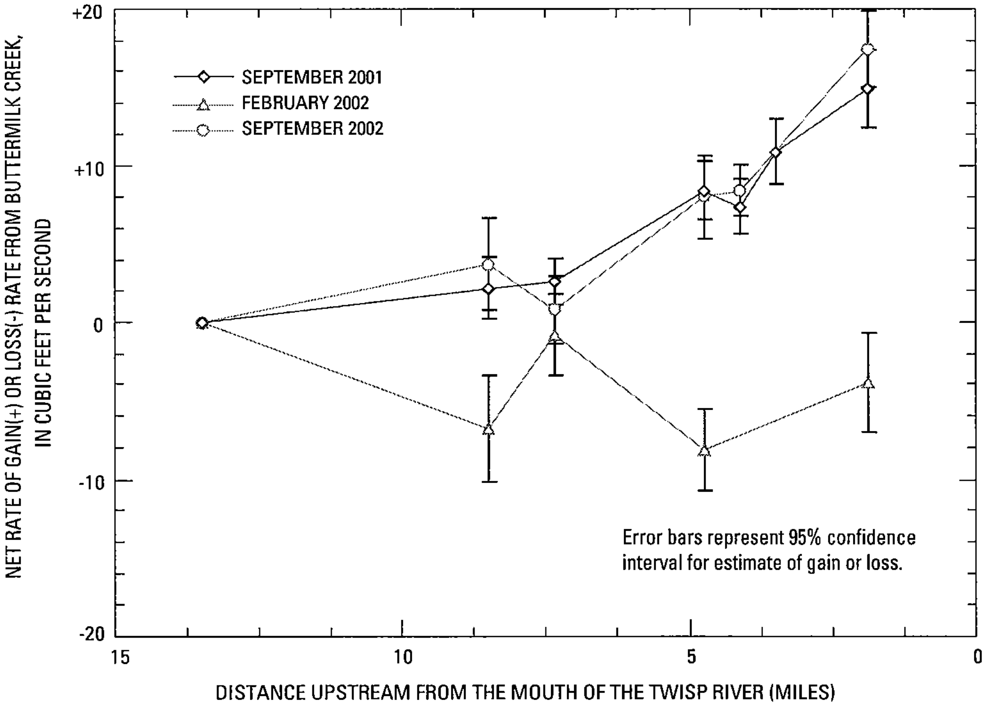


Figure 18. Cumulative gains and losses along the lower Twisp River from Buttermilk Creek to near Twisp under low-flow conditions, Methow River Basin, Okanogan County, Washington.

The lower Twisp River from Buttermilk Creek to near Twisp had a net gain of 14.9 ft^3/s on September 11, 2001, which was 45 percent of daily mean discharge near Twisp, a net loss of 3.8 ft^3/s in February 2002, which was 7 percent of the Twisp River discharge measured below Buttermilk Creek on February 14, 2002, and a net gain of 16.8 ft^3/s on September 18, 2002, which was 52 percent of daily mean discharge near Twisp. Reach 1 (from Buttermilk Creek to Newby Creek) had net gains during September 2001 and 2002 (2.2 and 3.7 ft^3/s, respectively), but a net loss of 6.8 ft^3/s on February 14, 2002. Similarly, reach 2 (from Newby Creek to Poorman Creek) had net gains in September 2001 and 2002 (6.2 and 7.2 ft^3/s, respectively), but lost 1.3 ft^3/s in February 2002. The Twisp River from Poorman Creek to the gaging station near Twisp (reach 3) gained 6.5 ft^3/s on September 11, 2001, and 8.4 ft^3/s on September 18, 2002, but gained only 4.3 ft^3/s on February 12, 2002.

During low-flow conditions, river-aquifer exchanges in the lower Twisp River exhibit a seasonal pattern of large gains (about 16 ft^3/s) during late summer and losses (about 4 ft^3/s) or small gains during winter. High flows in the river and ground-water flow from glacial terraces and unconsolidated sediments filling side valleys such as Elbow Coulee are likely to recharge the unconsolidated aquifer in the lower valley, which then discharges to the river during summer. As the unconsolidated aquifer drains and recharge of unconsolidated sediments from irrigation-canal seepage ceases in early autumn, ground-water inflow to the river decreases.

The gains in reach 1 during September 2001 and 2002 likely represent the discharge of ground water that had been recharged by the river and its tributaries during high flows earlier in the summer. As the unconsolidated aquifer drained, declining ground-water levels are likely to have caused the transition to a losing condition in reach 1 during February 2002. The seasonal gains along reach 2 likely represent the same mechanism, but also ground-water flow from Elbow Coulee, which includes seepage from the TVPI Canal. The seasonal gains in reach 3 are likely due to ground-water flow from the glacial terrace north of the river, which would include seepage from the TVPI Canal, ground-water flow from Elbow Canyon south of the river, and seepage from the MVID Canal. As with reach 1, however, aquifer recharge by the river and its tributaries during high flows may also contribute to increased ground-water discharge back to the river later in the summer in reaches 2 and 3. Thus, irrigation-canal seepage may account for only a portion of the seasonal difference of about 18 ft^3/s between the streamflow gains in September and loss in February in reaches 2 and 3.

Annual and Seasonal Patterns

The lower Twisp River from Newby Creek to near Twisp had an annual mean gain of 4.1 ft^3/s in water year 2001 and 3.9 ft^3/s in water year 2002. Exchanges calculated for water year 2001 do not include October 2000. Magnitudes of daily exchanges were larger in 2002 than in 2001, despite the similar annual mean gains. Total daily gains for the reach were equal to 4,700 acre-ft in water year 2001 and 9,200 acre-ft in water year 2002 (table 8). Total daily losses for the reach were equal to 2,000 acre-ft in 2001 and 6,400 acre-ft in 2002.

Exchanges had a seasonal pattern characterized by three distinct regimes: ground-water discharge to the river decreasing from late summer to early spring; fluctuating ground-water discharge and recharge as river rose during the late spring; and ground-water recharge in early summer (fig. 19). The seasonal patterns in river-aquifer exchanges were similar between water years 2001 and 2002, with the exception of the earlier onset of initial streamflow losses in 2002. The rate of streamflow gains during the winter and late summer also were similar. During low flows from November 1, 2000, through April 23, 2001 (regime 1), the river had a consistent daily gain with a mean of 4.5 ft^3/s and a standard deviation of 1.3 ft^3/s. During this period, ground-water discharge accounted for as much as 21 percent of the daily mean discharge in the Twisp River near Twisp.

The first regime of steady ground-water discharge to the river was disrupted by the onset of higher flows in spring. From April 24 to July 24, 2001, the river alternated between gaining and losing conditions (regime 2), with the largest magnitude of exchanges for the year. A high daily loss of 35 ft^3/s on May 12, 2001, was followed by a brief (2-day) gaining period that coincided with a peak in streamflow on May 14, 2001. After another week of losing flow, the lower river gained flow at rates as high as 110 ft^3/s during the period of maximum runoff from the basin (May 23 to June 14).

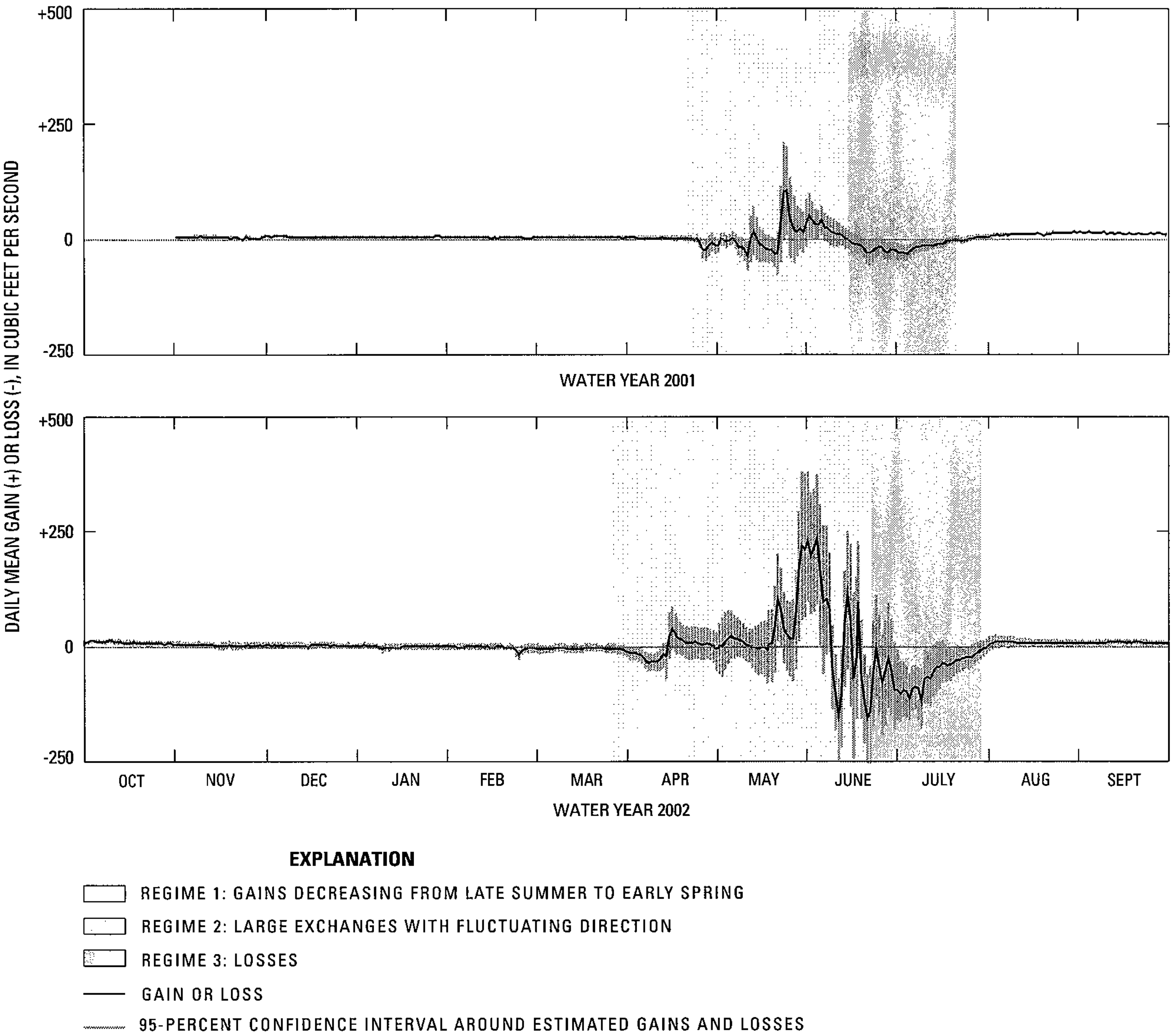


Figure 19. Daily gains and losses for the lower Twisp River in the Methow River Basin, Okanogan County, Washington, water years 2001 and 2002.

This gaining period was followed by the longest losing period for the river, from June 15 to July 25 (regime 3). Losses during high flows were likely a result of bank storage, whereas gains were likely produced by a combination of increased ground-water inflow to the study area from the main valley (upstream) and tributary valleys and release of bank storage during recessional periods. Unaccounted surface-water inflow from tributaries was likely to be only a small component of the calculated gains.

The river returned to a consistently gaining condition (regime 1) on July 26, 2001, but the rate of ground-water inflow to the river was higher than during the previous autumn and winter. Mean daily net ground-water inflow to the Twisp River was 12 ft^3/s, with a standard deviation of 3.1 ft^3/s for July 26 through October 20, 2001. The largest gain in streamflow for any month occurred during September 2001, when the mean ground-water inflow was 13 ft^3/s and accounted for 71 percent of the discharge of the Twisp River near Twisp. Ground-water inflow to the lower reach accounted for as much as 90 percent of the daily mean discharge (on September 9, 2001) for the Twisp River near Twisp during this period.

The gain along the lower Twisp River steadily decreased from autumn to winter with a mean gain of 1 ft^3/s for February 2002. When streamflow rose briefly in February and again in April, the Twisp River lost flow between Newby Creek and Twisp, which represented a transition to the second regime of river-aquifer exchanges. The river changed back to a gaining condition in the spring with the highest gains of the year. By mid-June, the river was losing flow (regime 3). The losing condition persisted until July 30, 2002, when there was an abrupt transition back to a gaining condition (regime 1). The mean rate of gain increased to 11.2 ft^3/s for September 2002.

Ground-Water Levels and Timing of Aquifer Recharge in the Lower Twisp River Valley

The monitoring wells were installed and instrumented at the three sites in the lower Twisp River valley (fig. 14) as ground-water levels increased during the spring of 2001. Ground-water levels in the lower Twisp River valley generally declined from late spring and summer 2001 to late autumn 2001 and winter 2002, when they were at minimum annual levels. Ground-water levels rose in spring 2002 and attained maximum levels in summer 2002. This pattern is consistent with the smaller gains in streamflow (lower rate of aquifer discharge) observed during winter and larger gains in streamflow (higher rate aquifer of discharge) observed during summer. The specific timing of changes and minimums and maximums, however, varied from well to well and likely reflected differences in geology and sources of recharge.

Ground-water levels in wells at the upstream site at Elbow Coulee (TW1N and TW1S in fig. 14) were relatively steady day-to-day, although seasonal patterns in ground-water levels were evident. In water year 2001, ground-water levels at the site rose during May, reaching maximum altitudes of 1,962.8 ft in TW1N on May 27, 2001, and 1,942.8 ft in TW1S on May 25, 2001 (fig. 20). Water levels declined steadily through the summer and autumn, with a mean rate of 0.007 ft/d in TW1N and 0.02 ft/d in TW1S from June 15 to October 15, 2001. Water levels declined more rapidly in TW1S from October 15 to 31, 2001, at a mean rate of 0.08 ft/d, while the rate of decline increased only slightly in the north well to 0.01 ft/d.

Water levels continued to decline through the rest of autumn 2001 and winter 2002, reaching minimum altitudes on February 16, 2002, of 1,961.2 ft in TW1N and 1,937.8 ft in TW1S. Water levels rose slowly from mid-February 2002 to the end of April 2002, and then rose more rapidly during May 2002 to annual maximum altitudes of 1,962.7 ft in TW1N on May 25, 2002, and 1,942.4 ft in TW1S on May 28, 2002.

The maximum water levels in TW1N and TW1S were within 0.6 ft during late spring 2001 (partial record only) and 2002, despite drought conditions in water year 2001. The similar levels indicate that seasonal recharge may not be sensitive to annual fluctuations in precipitation. Moreover, most of the water-level rise in both wells occurred during May, indicating that the source of recharge is relatively close to the wells (or recharge would likely be more gradual over time) and varies seasonally. Recharge also has a larger effect on water levels in the south well than in the north well. All these characteristics are consistent with aquifer recharge from the TVPI Canal, which is located between the two wells. Because ground-water flow generally is from the north well toward the south well, canal seepage disproportionately affects ground-water levels in the south well. The timing of the fluctuations in May and October coincides with the seasonal operation of the canal.

Ground water at the upstream site at Elbow Coulee had a high cross-valley hydraulic gradient sloping toward the river: the gradient between the TW1N and TW1S was 3 percent in May 2002 (annual maximum water level) and 4 percent in February 2002 (annual minimum water level); the gradient between the TW1S and the river was 2 percent during both periods. Because of the steep hydraulic gradient between the wells and the river, there was little response in ground-water levels to fluctuations in river stage (fig. 20).

Ground-water levels in wells at the middle site (wells TW2N and TW2S in fig. 14) varied much more through the year than those at the upstream site (fig. 20). Water levels in the two wells fluctuated synchronously, with no more than 0.2 ft difference between their altitudes at any time, and generally they coincided with changes in river stage. Water levels for this site are discussed in terms of the mean water altitudes for the two wells.

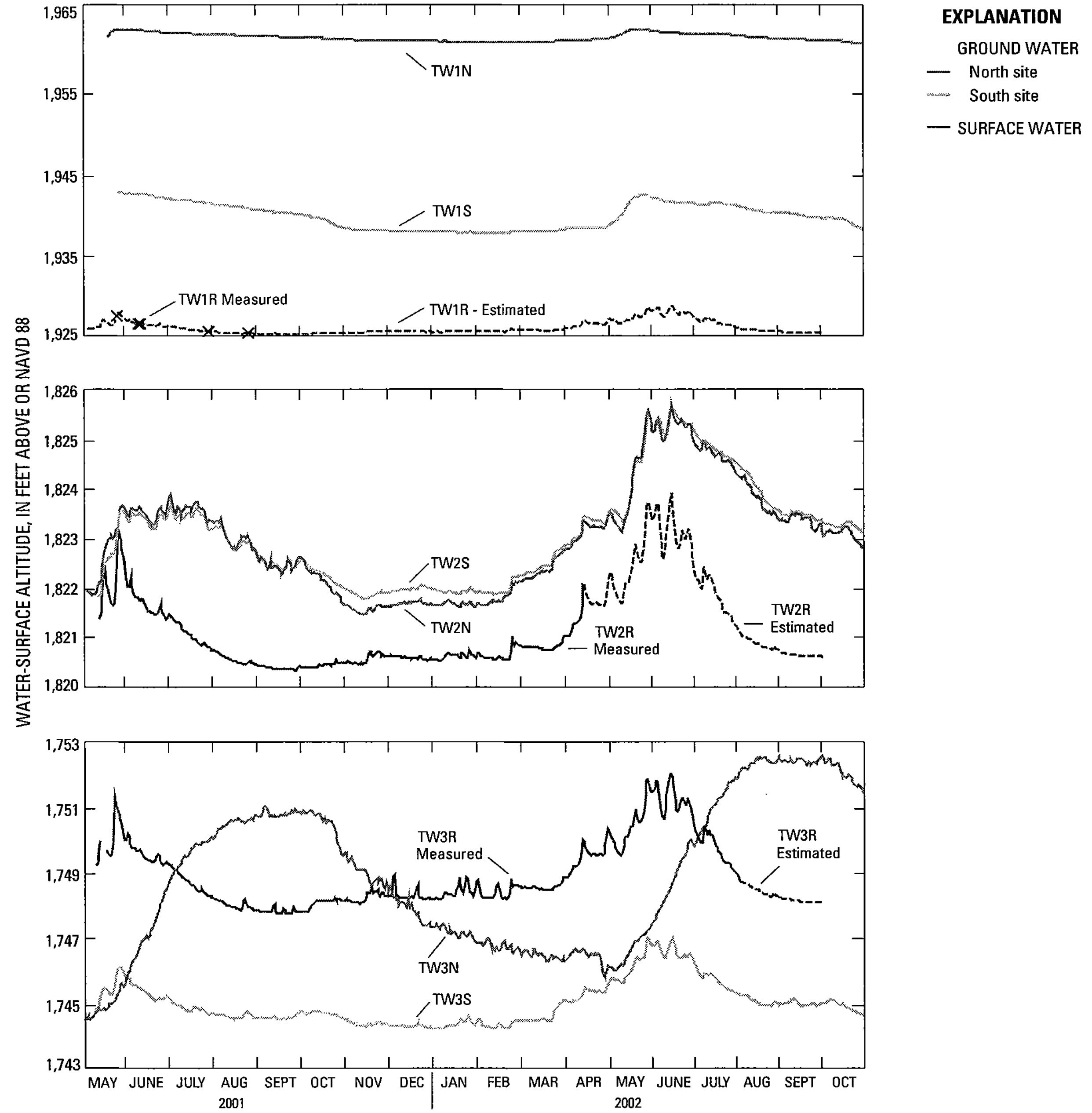


Figure 20. Ground-water and surface-water levels in the lower Twisp River valley, Methow River Basin, Okanogan County, Washington, water years 2001 and 2002.

Water levels rose abruptly in May 2001, reached maximum altitude of 1,823.8 ft, and remained high until the middle of July 2001. Water levels declined during summer and autumn, falling to a minimum altitude of 1,821.6 ft on November 13, 2001. They remained relatively steady until March 2002, when they rose in conjunction with spring snowmelt at lower altitudes. The initial rise in ground-water levels in early spring preceded a faster increase during April, May, and June that coincided with high river stages, driven by snowmelt from higher altitudes, and the beginning of the irrigation season. Ground water reached a maximum altitude of 1,825.7 ft on June 16, 2002, and was higher than in water year 2001.

The relative contribution to recharge from snowmelt, the river, irrigation-canal seepage, and water applied to crops is difficult to distinguish at the middle site. The increase in water levels during March 2002 likely was due to recharge from melting snow that infiltrated into the ground. The increase in water levels during April 2002 also may reflect recharge from the Twisp River. Irrigation-canal seepage and infiltration of water applied to crops likely contributed to increasing water levels during May 2001 and 2002, and then sustained high water levels during both summers while streamflow was receding. The seasonal effect of recharge from irrigation-canal seepage and applied water may persist until mid-November, when ground-water levels generally stop declining and only appear to change in response to river stage.

Ground water at the middle site had a lower and more variable cross-valley hydraulic gradient than at the upstream site. The gradient between TW2S and the river ranged from 0.4 percent in June 2002 to 1 percent in November 2001. The gradient between TW2N and TW2S was essentially flat, indicating that ground water had at most only a small component of flow across valley. Ground water at the downstream site sloped down toward the river during late summer and autumn, with a maximum gradient of 0.9 percent in September 2002, indicating ground-water flow toward the river. Ground-water levels sloped away from the river in other seasons, with a minimum gradient of -0.5 percent in June 2002, indicating flow from the river into the aquifer. These patterns are consistent with the seasonal increase in ground-water inflow to the river during late summer and autumn compared with winter and spring.

Ground-water levels in wells at the downstream site (TW3N and TW3S in fig. 14) had the most complex spatial and temporal patterns of all the sites (fig. 20). Water levels in TW3S, located on the floodplain north of the river, fluctuated synchronously with river stage. The water-surface altitude in TW3S was consistently lower, on average 3.6 ft, than the water-surface level of the river. Maximum ground-water altitudes in the south well were 1,746.1 ft on May 27, 2001, and 1,747.0 on June 16, 2002, and lagged peak river stage by 4 and 3 days, respectively. Although the lowest stage of the Twisp River for the monitoring period was in late September 2001, the minimum altitude in well TW3S was 1,744.2 ft on January 4, 2002. The seasonal patterns of water-level changes in TW3N were the most consistent of any of the wells with the three regimes of river-aquifer exchanges for the lower Twisp River. Water levels in well TW3N initially were lower than the water-surface level of the river in May 2001, but rose above river stage by early July and reached a maximum altitude of 1,751.0 ft on September 5, 2001. Water levels declined during the autumn, winter, and early spring to a minimum altitude of 1,745.9 ft on April 30, 2002. Water levels rose quickly and steadily in the spring and summer to a maximum of 1,752.6 ft on September 29, 2002. Water levels in TW3S were consistently lower than the Twisp River at all times. In contrast, the hydraulic gradient between TW3N and the river was positive during the summer and early autumn (indicating flow toward the river), but negative the rest of the year.

The differences between water levels in wells at the downstream site are likely a result of differences in the hydrogeology of the aquifers and their seasonal recharge. The volume of water released from a unit volume of an aquifer under a unit decline in hydraulic head, which is specific storage, generally is smaller for bedrock than for unconsolidated alluvium. As a result, the larger changes in potentiometric surface in TW3N, which is open to a bedrock aquifer, in comparison to the changes in TW3S, which is open to the alluvial aquifer, do not necessarily represent differences in the volume of water stored in and released from these aquifers. The seasonal patterns in recharge, however, are distinctly different for the two aquifers: the alluvial aquifer responds primarily to increases in river stage; in contrast, the water level in the bedrock aquifer shows little relation to river stage. Irrigation-canal seepage and infiltration of water applied to crops are likely the primary source of seasonal variation in recharge of the bedrock aquifer because (1) the timing of water-level changes coincides with the irrigation season; and (2) aquifer recharge from other sources (snowmelt, streamflow, or ground-water flow from tributary basins) is unlikely to sustain ground-water levels at a steady high level during summer only to decrease in autumn.

Estimates of Aquifer Recharge by Rivers and Irrigation Canals in the Methow River Basin

Annual fluvial recharge of the unconsolidated aquifer in the Methow River valley from Lost River to Pateros by the Methow and Twisp Rivers is equal to the total daily losses in streamflow described in the section on gains and losses of streamflow. For the four reaches of the Methow River from Lost River to Pateros, total daily streamflow losses in the Methow River, which represents annual recharge of the unconsolidated aquifer by the river, were estimated to be 82,000 acre-ft in water year 2001 and 137,000 acre-ft in water year 2002 (table 8). Much of the annual recharge (between 60 and 73 percent) by the river occurs between Lost River and Goat Creek. Annual fluvial recharge of the unconsolidated aquifer in the lower Twisp River valley was estimated to be 2,000 acre-ft in water year 2001 and 6,400 acre-ft in water year 2002. Combined, fluvial recharge by the Methow and Twisp Rivers ranged from 84,000 acre-ft in 2001 to 143,000 acre-ft in 2002. During high flows, the river likely recharges the aquifer in many places; however, some of this recharge may be shallow bank storage that returns quickly to the river.

The 2001 drought influenced the results of this investigation. Ground-water levels and streamflow generally were lower than they would have been in most years. Ground-water discharge from the unconsolidated aquifer was a larger component of streamflow during the drought. For example, the net discharge from the unconsolidated aquifer to the Methow River from the Lost River to Pateros was 135.6 ft^3/s (57 percent of the discharge near Pateros) in September 2001, 109.7 ft^3/s (39 percent) in February 2002, and 113.2 ft^3/s (39 percent) in September 2002. This difference was a result of higher streamflow but also smaller gains in September 2002. The unconsolidated aquifer appears to have acted as a buffer against annual variation in low flow by discharging at higher rates to the river during lower flows in September 2001 than in February 2002 or September 2002.

Upstream of Winthrop, however, cumulative daily ground-water discharge was higher in water year 2002. In contrast, cumulative daily ground-water recharge from Winthrop to Pateros was higher in 2002 than in 2001. Thus, the effect of the drought varied depending on the period: streamflow gains during low-flow periods were higher in the drought, but cumulative exchanges over the year (both gains and losses) were lower.

Regardless of its annual variation, ground-water discharge from the unconsolidated aquifer provides a large component of streamflow during low-flow periods in the Methow and Twisp Rivers. The rates of river-aquifer exchanges in the Methow and Twisp River were relatively steady during most of the year, with the exception of high-flow periods when the magnitude of exchanges are high and their direction may fluctuate from recharge (streamflow loss) to discharge (streamflow gain) and vice versa. The lower Twisp River and the Methow River from Winthrop to Twisp, however, demonstrated a seasonal pattern distinct from the other reaches of the Methow River: both reaches has relatively high, steady gains of streamflow during late summer and early autumn but lower rate exchanges (gains and losses) during winter. For example, the Methow River from Winthrop to Twisp on average gained 35 ft^3/s for September 2001 and 29 ft^3/s for September 2002, but lost 1 ft^3/s in February 2001 and lost 4 ft^3/s in January 2002. Likewise, the lower Twisp River from Newby Creek to near Twisp on average gained 13 ft^3/s for September 2001 and 11 ft^3/s for September 2002, but gained only 3 ft^3/s for February 2001 and 1 ft^3/s for February 2002.

The contribution of irrigation-canal seepage to aquifer recharge was calculated from discharge measurements spanning 29.8 mi of 13 canals in the Methow River Basin (table 20, at back of report). The mean seepage rate from unlined irrigation canals, calculated from the total losses divided by the total length of canals that were measured, was 1.8 $(ft^3/s)/mi$. Seepage estimates for individual irrigation canals ranged from 1.0 to 10.7 $(ft^3/s)/mi$ from May through August (table 21, at back of report). Seepage rates also vary along individual canals. The large range in seepage rates reflects, in part, canal maintenance, which can disturb the surface of the canal bottom and increase the seepage rate. Differences in seepage rates also reflect the material forming the canal, which in the Methow River Basin includes unconsolidated glaciofluvial deposits, colluvium (landslide deposits), clay placed artificially to line canals in places, and fractured bedrock.

Seepage rates decrease during the late summer because of the combined effects of subsurface saturation, reduction in the infiltration capacity of the canal beds from the accumulation of fine materials, and lower diversion rates. The average decrease for two canals (TVPI and MVID West) between early (May through August) and late (September) seasons was 35 percent, compared to a 50-percent decrease observed by Klohn Leonhoff, Inc. (1990) for the MVID East and West Canals.

Annual aquifer recharge from irrigation canals for seven subbasins (table 9) assuming a seepage rate of 1.8 (ft^3/s)/mi for May through August and a lower rate of 1.2 (ft^3/s)/mi for September. If the calculated seepage rate from a canal exceeded its maximum measured diversion rate, then the seepage rate was assumed to equal 50 percent of the diversion rate. The length of unlined irrigation canals and their period of operation are not known precisely, but were estimated to be at most 72.9 mi in water years 2001 and 2002. For the specific seepage rate and estimate length of unlined irrigation canals, the maximum total annual recharge from irrigation canal seepage is estimated to be 37,800 acre-ft in the Methow River Basin (table 9). This corresponds to an instantaneous rate of 124 ft^3/s from May to September, however, ground-water discharge to rivers as a result of irrigation-canal seepage would be lower because the ground water would return to the rivers over a longer period of time. In the lower Twisp River valley, irrigation-canal seepage may have contributed up to 4,900 acre-ft annually to aquifer recharge.

Table 9. Estimates of annual aquifer recharge from irrigation-canal seepage in the Methow River Basin, Okanogan County, Washington

Subbasin	Length of unlined irrigation canal (miles)	Annual seepage from canals (thousands of acre-feet)
Beaver	3.9	1.8
Chewuch	10.5	5.5
Lower Methow (below Twisp)	14.5	7.4
Middle Methow (Winthrop to Twisp)	25.2	13.2
Upper Methow (Goat Creek to Winthrop)	6.1	3.2
Headwaters Methow	3.4	1.8
Twisp	9.3	4.9
Total	72.9	37.8

The calculation of recharge from irrigation canals has two primary sources of uncertainty. First, the estimated length of unlined irrigation canals neglects lateral canals, which convey water from main canals to the field where the water is applied for irrigation. Second, some irrigation canals may not be used currently or are operated for less than the May to October period, and seepage rates are likely to be less than 1.8 (ft^3/s)/mi in small canals. The negative bias introduced by neglecting lateral canals may offset the positive bias introduced by assuming continuous operation and uniform seepage from all canals; however, some error is likely to remain in the estimate.

If all seepage from irrigation canals returned to the river as steady ground-water flow with no seasonal variation, irrigation-canal seepage would at most account for a steady (year round) gain of about 20 ft^3/s in the Methow River from Winthrop to Twisp and 7 ft^3/s in the lower Twisp River. Alternatively, if irrigation-canal seepage returned to the rivers at the rate it seeped out of the canlas, it would account for a 43 ft^3/s gain in the Methow River from Winthrop to Twisp and a 16 ft^3/s gain in the lower Twisp River. In this case, however, the gains in streamflow due to irrigation-canal seepage would cease at the end of the irrigation season. The seasonal differences in river-aquifer exchanges in both reaches likely represent a transient increase in ground-water discharge to rivers during late summer and early autumn as a result of irrigation canal seepage: the Methow River from Winthrop to Twisp gained about 30 ft^3/s more streamflow in late summer (September) compared to mid-winter (February); the Twisp River gained about 10 ft^3/s more streamflow in late summer compared to mid-winter. Based on fluctuations of ground-water levels with the operations of the irrigation canals in the lower Twisp River valley, the seasonal increase in ground-water discharge to these rivers likely was due primarily to irrigation-canal seepage rather than fluvial recharge. Consequently, most of the water recharged by irrigation canals was likely to have drained back to the rivers by February and any component of ground-water discharge in February that could be attributed to irrigation canal seepage is likely to be negligible in the Methow River and at most 2 ft^3/s in the Twisp River.

$$\frac{37800 \text{ AF}}{365 \text{ days}} = 52 \text{ cfs}$$

The Twisp River from Buttermilk Creek to Newby Creek, however, also had seasonally high gains in streamflow in September 2001 and 2002 compared to February 2002, even though there is likely to be little irrigation-canal seepage along this reach. In this case, natural recharge also may contribute to increased ground-water discharge during late summer to some rivers in the Methow River Basin.

The seasonal increase in streamflow gains along the Methow River from Winthrop to Twisp and the lower Twisp River during late summer and autumn may be due in part to the hydraulic effect of irrigation-canal seepage: ground water mounds underneath canals in response to recharge rather than rising uniformly across the aquifer. Ground-water flow would increase in response to the higher hydraulic gradient between the mound and the regional ground-water system and the increased saturated thickness of the aquifer at the mound. As a result, ground-water flow from irrigation-canal seepage would not return to the river steadily throughout the year, but instead would be greatest in late summer and decrease as diversions decrease in the autumn. The transient rise in ground-water levels is supported further by the continuous water-level data from the lower Twisp River valley (fig. 20). The seasonal effect of canal recharge on ground-water discharge to both the lower Twisp River and the Methow River from Winthrop to Twisp appears to dissipate by January at which point the lower Twisp has a steady gain of about 4 ft^3/s and the Methow River from Winthrop to Twisp has no significant gain or loss of streamflow during the winter.

Water Budget for the Methow River Basin

Mean annual precipitation in the Methow River Basin for 1991 to 2001 was estimated to be 32.6 in. (3.15 million acre-ft). Simulated runoff from the basin was 1,570 ft^3/s (or 36 percent of precipitation) compared to 1,529 ft^3/s for mean discharge of the Methow River near Pateros. Evapotranspiration accounted for 19 in. (or 58 percent of precipitation). The residual between precipitation less evapotranspiration and runoff was the change in ground-water storage for the simulation period, but is not a physically based measure of the change in ground-water storage. Mean annual ground-water recharge due to the infiltration of precipitation and irrigation canal seepage (but not fluvial recharge) was estimated to be 4.2 in. or 410,000 acre-ft over the whole basin, not just the unconsolidated aquifer. Annual recharge due to irrigation-canal seepage and over application of water to crops was simulated to be 35,000 acre-ft based on an efficiency of 50 percent in the delivery of water for 16 surface-water diversions in the basin. The simulated recharge from irrigation-canal seepage of water is about 3,000 acre-ft less than the estimate based on a seepage rate of 1.8 $(ft^3/s)/mi$ and a maximum of 73 mi of unlined irrigation canal. The difference between the estimates is not significant compared to the uncertainty of either estimate.

Domestic use of water was not explicitly simulated in the hydrologic model for the Methow River Basin. Annual domestic use of water, including irrigation of lawns, other landscaping, and non-commercial gardens, is estimated to be 2,100 acre-ft based on an estimated municipal use of 400 gallons per person per day for the City of Twisp (R. Lane, U.S. Geological Survey, written commun., September 16, 2003) and a population of 4,669 in 2000 for the Methow River Basin (Washington State Office of Financial Management, 2002). A portion of domestically used water is discharged to the Methow River as treated wastewater or to the soil column as effluent from onsite septic systems. The remaining portion of water that is consumed by domestic uses is uncertain. A USGS study of water use in the United States in 1990 estimated that 17 percent of domestic use was consumptive while 56 percent of irrigation use was consumptive (Solley and others, 1993). Depending on the extent to which domestic users irrigate landscaping and gardens, annual consumptive domestic use of water is estimated to range between 360 to 1,170 acre-ft. The estimate of consumptive domestic water use does not account for water used by non-residents. Water use by non-residents particularly irrigation of landscaping or gardens on rental or intermittently occupied properties represents an additional but unknown component of consumptive domestic water use in the Methow River Basin.

SUMMARY

An understanding of the availability and quality of water is an important aspect of managing the water resources in the Methow River Basin. The U.S. Geological Survey, in cooperation with Okanogan County and with support from the U.S. Congress, studied the hydrogeology of the unconsolidated sediments, the quality of surface and ground waters, and the exchanges between surface water and ground waters during water years 2001 and 2002.

Unconsolidated sediments were deposited by fluvial and glacial processes along the bottoms and lower slopes of valleys in the Methow River Basin. The sediments are largely coarse-grained materials (sands and gravels). Alluvium and glaciofluvial sediments deposited during the Quaternary period constitutes the primary aquifer in the Methow River Basin for maintaining streamflow during seasonal dry periods and for domestic and public-water supplies. It forms a nearly continuous deposit along the valley bottom from above Lost River to the confluence of the Methow and Columbia Rivers, covering over 45 square miles of the basin's surface. The deposit is 0.5 mile wide and more than 1,000 ft thick at its upper end near Mazama, decreases to less than 100 ft thick near Winthrop, and increases again south of Twisp to 200 ft thick or more in places. Ground-water levels in the unconsolidated aquifer are highest during the summer and lowest in the late winter and early spring.

Both surface and ground water generally are of high quality. Water-quality results from wells indicated the possibility of ground-water contamination from nitrate and arsenic concentrations at only two locations in the basin. In both cases, potential contamination was isolated to a single well. No major differences in water quality were apparent when comparing the results of this investigation with previous studies.

The flow of water between rivers and aquifers is important for regulating the availability of water resources for in-stream and out-of-stream uses in the Methow River Basin. Ground-water discharge from the unconsolidated aquifer to the Methow River from Lost River to Pateros was determined from daily gains in streamflow and was relatively steady both years of study, ranging from an estimated 153,000 acre-ft in water year 2001 to 157,000 acre-ft in water year 2002. Ground-water discharge to the Methow River contributed 37 to 57 percent of the streamflow near Pateros during low-flow conditions in September 2001, February 2002, and September 2002. The Methow River gained most of the flow between Goat Creek and Winthrop. Ground-water discharge to the lower Twisp River from Newby Creek to near Twisp ranged from 4,700 acre-ft in water year 2001 to 9,200 acre-ft in water year 2002. Ground-water discharge to the lower Twisp River contributed 45 to 52 percent of streamflow near Twisp during September 2001 and 2002, respectively, but was negligible during February 2001.

The Methow and Twisp Rivers, among others in the basin, are major sources of recharge for the unconsolidated aquifer, particularly during high-flow periods in May and June. Aquifer recharge by both rivers increased with streamflow in water year 2002 compared to water year 2001 as indicated by daily losses of streamflow. Aquifer recharge by the Methow River from Lost River to Pateros was estimated to be 82,000 acre-ft in water year 2001 and 137,000 acre-ft in water year 2002. Aquifer recharge by the Twisp River from Newby Creek to near Twisp was estimated to be 2,000 acre-ft in water year 2001 and 6,400 acre-ft in water year 2002. Combined, mean annual recharge of the unconsolidated aquifer by the Methow and Twisp Rivers for water years 2001 and 2002 was equal to 28 percent of annual recharge by all nonfluvial sources of all aquifers in the basin as calculated by a hydrologic simulation model for water years 1992 to 2001.

Seepage from unlined irrigation canals also recharges the unconsolidated aquifer during the late spring and summer and may contribute as much 38,000 acre-ft annually to aquifer recharge in the basin. In this case, irrigation-canal seepage would represent about 9 percent of annual non-fluvial ground-water recharge in the basin as simulated by the model for water years 1992 to 2001. Seepage from the canals is likely to have the greatest effect on streamflow in September and October, when streamflow and diversions are relatively low but ground-water flow from the seepage is still relatively high. A transient increase in ground-water discharge of about 30 ft^3/s to the Methow River from Winthrop to Twisp and of about 10 ft^3/s to the lower Twisp River was observed in late summer and early autumn correspond to winter. The increased rate of ground-water discharge to these reaches likely is due primarily to irrigation canal seepage, however, fluvial recharge during the summer may also contributed to the increase. The increased rate of ground-water discharge decays by February in both reaches.

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Ground-water storage in the Methow River Basin through artificial aquifer recharge

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Ground water is an important resource in the Methow River Basin (MRB) sustaining streamflow and providing water supplies for domestic, agricultural, and commercial uses. Artificial recharge of shallow aquifers in the MRB using streamflow during high-flow periods may be able to increase ground-water storage in the basin, but its effectiveness depends on the availability of streamflow, aquifer properties at the recharge site, and ground-water levels.

Shallow ground water in the unconsolidated sediment filling the bottoms of valleys in the MRB flows into rivers, sustaining streamflow from late summer through the spring. Ground water is also used widely for domestic supplies and may be used increasingly for new residential and commercial development in the valley and for irrigation as an alternative to surface-water diversion. Unconsolidated aquifers in the Methow, Twisp, and Chewuch River valleys are recharged by a variety of sources including rivers, streams, unlined irrigation canals, and subsurface flow from surrounding hillslopes, valleys, and, possibly, deeper bedrock aquifers. Each of these sources of recharge ultimately depends on snowmelt and rainfall.

In some locations in the MRB, streamflow during high-flow periods may be used to recharge aquifers to augment streamflow and ground-water supplies later in the year. The premise for artificial aquifer recharge is that streamflow exceeds the level needed for instream uses at times and, during these times, would be available to recharge aquifers. As an initial step for assessing the availability of water for artificial aquifer recharge, daily streamflow at six stream gages was compared to Washington State regulatory base flows established to protect instream uses. The comparison is described in Section 1. The difference between streamflow and regulatory base flow represents one limitation on the water available for artificial aquifer recharge. There are likely to be other limitations, which are not assessed here, particularly in locations where a reduction in streamflow during periods of aquifer recharge has negative ecological or social impacts even if regulatory base flow is satisfied.

Shallow aquifers can be recharged artificially by distributing water over the land surface (e.g., in ponds) or in the soil column (e.g., through perforated pipes). Artificial aquifer recharge will increase the volume of ground water available for water supplies or instream uses only when three conditions are satisfied: 1) the streamflow used to recharge the aquifer would not otherwise have recharged the aquifer, 2) the aquifer is not fully saturated when streamflow is available for artificial recharge; and 3) ground water remains in the aquifer until it is needed for water supply or instream uses. To benefit instream uses, artificially-recharged ground water must continue to flow back into a river after artificial recharge has ceased for the season.

Streamflow naturally recharges the alluvial aquifer in the Methow River Basin. Artificial aquifer recharge at a given location will not increase ground-water storage if a river goes dry downstream of the location. Thus, the effective period for artificial ground-water recharge (condition 1) is limited to periods when there is streamflow downstream of a site. Condition 1 is achieved when streamflow downstream of a location exceeds regulatory base flows because regulatory base flows are greater than zero for all stations in the MRB and, consequently, is not assessed separately.

Although the shallow aquifer in the unconsolidated sediments may be confined in places, the confining units are not continuous (Konrad and others, in review), so artificial recharge is unlikely to be able to store water under more than atmospheric pressure. The availability of storage capacity in an aquifer (condition 2) is assessed by considering the depth to ground water at a site during summer when ground-water levels are typically at their annual maximum and when streamflow in excess of regulatory base flow is likely available for artificial recharge. The depth to ground water represents the approximately thickness of unsaturated material that could be used to store water.

The availability of recharged water for water supply or instream uses (condition 3) depends on the time that the water resides in the aquifer and the hydraulic effect of artificially recharged water on ground water flow. Any increase in ground-water discharge from the aquifer (or flow to parts of the aquifer where the water cannot be used) as a consequence of artificial recharge effectively reduces the net volume of water stored. Likewise, the time required for artificially recharge water to flow to a river will depend on the hydraulic conductivity of the aquifer, the hydraulic gradient between a recharge site and the river, and the distance separating the site and the river. Section 2 provides the hydraulic gradient of the regional ground-water system at each site and the horizontal length of ground-water flow paths to a point of seepage such as a river channel. Section 2 also identifies layers of fine-grained sediments in wells close to each site that are likely to have low permeabilities. These layers could impede vertical flow and, thus recharge rates. Artificially recharged ground water could also perch on these layers allowing recharged water to saturate the material above the layer and reducing the effective storage capacity of the unsaturated zone. Fine-grained layers close to the land surface also could promote shallow horizontal ground-water flow.

The response of ground-water levels to artificial recharge will need to be analyzed at a specific location before the net volume of artificially-recharged water and the storage time of that water can be estimated. In the lower Twisp River valley, ground-water mounding of 1 to 5 ft in 2 wells located between 100 and 1000 ft from an irrigation canal dissipated approximately 2 months after the flow in the canal was shut off for the season (Konrad and others, in review). Elevated gains in streamflow from the lower Twisp valley also persisted for approximately 2 months after the end of the irrigation season. Ultimately, condition 3 also depends on the time when water is needed for instream or out-of-stream uses, which is not evaluated here.

The Methow Basin Planning Unit identified six sites to investigate for artificial aquifer recharge. Two types of sites for artificial aquifer recharge were investigated: 1) floodplains and 2) terraces and valley fill deposits above floodplains. Each type of site has distinct attributes affecting its suitability for artificial aquifer recharge. Floodplains are located along rivers, so streamflow may be easily supplied to a floodplain for artificial recharge. Recharge and storage in floodplain areas are likely to be limited by a high ground-water table, lenses of fine-grained sediment with low permeability, and short ground-water flow paths back to the river. Aquifer recharge and storage in terraces and valley-fill deposits may also be limited by the same conditions, however, ground-water tables are likely to be deeper and flow paths back to rivers longer.

1. Comparison of streamflow to regulatory base flow at six gaging stations

Daily discharge records for Water Years (WY) 1992 to 2001 from six U.S. Geological Survey (USGS) stream gaging stations were analyzed to determine the volume and period when streamflow exceeded Washington State regulatory base flows. Figure 1 shows the location of the stations in relation to the aquifer-recharge sites. The six gaging stations correspond to locations downstream of eight sites that the Methow River Basin Planning Unit is considering for artificial aquifer recharge projects. The stations are:

1. Methow River above Goat Creek (USGS Station 12447383)
2. Chewuch River at Winthrop (USGS Station 12448000)
3. Methow River at Winthrop (USGS Station 12448500)
4. Twisp River near Twisp (USGS Station 1248994)
5. Methow River at Twisp (USGS Station 12449500)
6. Methow River near Pateros (USGS Station 12449950)

Washington State has established regulatory base flows at each of these stream stations for the purposes of determining the availability of water for out-of-stream uses and protecting in-stream uses of water (Washington Administrative Code 173-548-020(2)). Unlike hydrologic base flow, which represents the relatively stable discharge in a stream during periods without surface runoff, regulatory base flow is a minimum discharge used for administering the appropriation of water subsequent to the establishment of the base flow. The regulatory base flows for the 1st and 15th day of each month at each station are listed in table 1. Regulatory base flows for all other days were estimated by linear interpolation between each value in table 1.

Daily streamflow at each station from October 1, 1992 to September 30, 2002 was compared to the regulatory base flow for the respective day to determine the volume of streamflow in excess of the regulatory base flow. The period from WY 1993 to 2002 is generally representative of the long-term average of streamflow conditions in the basin as well as its inter-annual variability. Mean discharge for WY 1992 to 2002 was 1562 cfs compared to 1550 cfs for WY 1960 to 2002. The median annual discharge the Methow River near Pateros was 1647 cfs for WY 1993 to 2002 compared to 1567 cfs for WY 1960 to 2002 (table 2). Annual variation for the two periods was similar with a coefficient of variation for annual discharge of 0.36 for WY 1993 to 2002 compared to 0.33 for WY 1960 to 2002.

For WY 1993 to 2002, there was a net excess of streamflow above regulatory base flow at all six gages in the Methow River Basin (table 3). Excess streamflow ranged from 162 cfs for the Twisp River near Twisp (USGS station 12448998) to 944 cfs for the Methow River at Winthrop (USGS station 12448500). There was an annual net excess of streamflow volume in all years except WY 2001, when the total regulatory base flow for the year exceeded the total volume of streamflow at all of the stations except the Methow River at Winthrop (table 4). Daily streamflow exceeded regulatory base flow on most days in most years (table 5). The median number of days each year when streamflow exceeded regulatory base flows was 189 days for the Methow River above Goat Creek and 220 days for the Methow River near Pateros, which were the sites with the fewest number of days when streamflow exceeded state regulatory base flows. In drier years (e.g., 1993, 1994 and 2001), however, daily streamflow frequently did not meet regulatory base flow at many stations in the MRB.

Figure 2 shows the frequency (number of years) that daily streamflow at each station exceeded regulatory base flow. At most stations, daily streamflow exceeded regulatory base flow from March through July. Notable exceptions when streamflow was less than regulatory base flow in most years include: all stations during September except the Methow River at Winthrop (12448500); and the Methow River above Goat Creek (12447383), the Methow River at Twisp (12449500), and the Methow River near Pateros (12449950) from September through March.

There were days in every year when streamflow exceeded regulatory base flow. The annual volume of streamflow for days when streamflow exceeded regulatory base flow ranged from 9,000 acre ft for the Chewuch River at Winthrop in WY 2001 to 1,090,000 acre ft for the Methow River near Pateros in WY 1999 (table 6). Although streamflow exceeded regulatory base flow on some days during the 2001 drought, the total volume of streamflow in excess of state regulatory base flow was limited.

2. Hydrologic conditions related to artificial aquifer recharge at six sites of the Methow River Basin

Hydrologic conditions were investigated at six sites in the MRB as an initial assessment of the potential for artificial aquifer recharge. The general locations of the six sites in the basin are shown in figure 1. Sites 1-3 are located on floodplains along the Methow or Twisp Rivers (table 7, figs. 3-5). Sites 4-6 are located on terraces or valley-fill deposits above floodplains (table 7, figs. 6-8).

Depth to ground water, hydraulic gradient, and distance along the subsurface flow path to the nearest river channel were determined for each site. Depth to ground-water was determined from water level measurements using a geographic information system (GIS). A raster (grid) coverage (10 m cells) of ground-water elevations for the unconsolidated deposits was interpolated from ground-water levels for 254 wells measured in June and July 2001, which represents seasonally high ground-water levels, (Konrad and others, in review) and land surface elevations for 29 points along rivers taken from the National Elevation Dataset (NED) (USGS, 2003). The resulting raster coverage of ground-water elevations was used to estimate the hydraulic gradient between each site and either the Methow or Twisp River.

Horizontal flow paths were determined by manually digitizing lines from the boundary of the each site perpendicular to equipotential (contour) lines of the ground water to the point of intersection with a river. The actual flow paths have a vertical component and are likely to deviate from the paths depicted because of variation in the hydraulic conductivity within the unconsolidated sediment. As a result, actual flow paths are likely to be longer than the estimates presented here.

The raster coverage of ground-water elevations was subtracted from the NED land-surface elevations for the valley floor to produce a raster coverage of depth to ground water. Contours corresponding to 3 ft, 10 ft, and 20 ft depths were manually digitized from the raster coverage of depth to ground water.

Well reports for wells in and near each site [Washington Department of Ecology, 2003] were reviewed to characterize the local lithology and any fine-grained sediments that could represent low-permeability layers. Wells are referred to by their Township, Range, Section, and a letter identifying the quarter-quarter section with "A" representing the northeast quarter of the northeast quarter section, "D" representing the northwest quarter of the northwest quarter, "N" representing the southwest quarter of the southwest quarter section, and "R" representing the southeast quarter of the southeast quarter section. "I" is omitted from quarter-quarter section identifiers. If the well has been inventoried by USGS, then a sequence number follows the quarter-quarter section identifier.

Soil information for sites 2, 4, 5, and 6 was compiled from the Soil Conservation Service (1980). Soils at the other sites were not mapped by Soil Conservation Service.

Sites 1-3 were surveyed in April 2003 to locate the primary side channels, water surfaces, and elevations of the side channels relative to the adjacent river channels. A TOPCON total station and HP48GX/TDS surveying system was used. Surveys at sites 1 and 2 included nearby benchmarks to georeference the surveyed points. A handheld global positioning system (GPS) receiver was used to obtain the approximate geographic coordinates of the surveyed points in site 3.

2.1. Methow River above Early Winters Creek

The floodplain southwest of the Methow River has a braided side-channel network approximately 1.5 miles upstream of Early Winters Creek (fig. 3). The network extends over approximately 45 acres (table 8) with as many as four distinct, parallel channels in places. There are multiple entrances where water flows into the network during high flows. The main side channel is 3,900 ft long (table 9). The median combined width of the side channels at their banks is 83 ft for three cross-sections.

The unconsolidated sediments in valley are 3,400 ft wide at the land surface and more than 850 ft thick at the valley center (for example, well 36N/19E-22C [E-12]). The sediments are mostly coarse (gravel, sand, cobbles, some clay) (table 10). Depth to ground water ranged from more than 10 ft to less than 3 ft (fig. 9). Small, discontinuous areas of standing water were observed at six locations in the side-channel network in April 2003. The source of this water was not certain, but it may have been seepage of shallow ground-water, which was perched on fine-grained facies deposited in the side-channel network. Fine-grained layers, described as "silt" or "hardpan" with top elevations ranging from 2,158 to 2,168 ft (table 10), were identified in four wells near to the site. These layers are 19 to 46 ft below the land surface, which is deeper than the ground-water table in most locations, and similar fine-grained layers were not reported in two other wells west of the site. Although there is not a continuous layer of fine-grained material at the site, there may be shallow, discontinuous lenses of fine-grained material which could limit aquifer recharge in places. Ground water generally flows away from the river in the northern part of the site and toward the river at the southern end. The length of horizontal flow paths between the site and the river ranges from 1,800 ft to 1 mile (fig. 3). The hydraulic gradient between ground-water at the site and the Methow River along the flow paths is 0.01.

2.2. Methow River at Fawn Creek

The floodplain southwest (right) of the Methow River has a series of side channels that begins 0.5 miles upstream of the confluence with Fawn Creek (fig. 4) and covers about 62 acres (table 8). A levee along the right (facing downstream) river bank limits inflows to the side-channels to two culverts and ground-water seepage (through the levee or from the alluvial aquifer). The main side channel is 5,600 ft long. It has been used to convey water from the Methow River to two irrigation canals. The median combined width of the side channels at their banks is 65 ft for six cross-sections, however, the cross-section did not include all side channels.

The unconsolidated sediments are 4,000 ft wide at the land surface and 860 ft thick on the southern side of site (for example, well 36N/20E-04N [E-10]). The sediments are coarse (cobbles, sand, and gravel). Depth to ground water is less than 3 ft (fig. 9): ground-water seepage into the side channels and surface-flow were observed throughout the site in April 2003. Three logs were available for wells near to the site. The log of one well in the site (35N/20E-04N01) reported the top of a "silt and gravel" layer at an elevation of 1,978 ft. A well log close to the site (35N/20E-10E01) reported the top of a "clay" layer at an elevation of 1,969 ft. Ground water generally flows toward the river with a path length from the site to the river from less than 100 ft to 1.5 miles (fig. 4). The hydraulic gradient between ground water at the site and the Methow River ranges along the flow paths from 0 (ground-water and surface-water levels are equal) to 0.006. Soils at the site include xerofluvent, Boesel fine sandy loam, and river wash [table 7, SCS, 1980].

2.3. Twisp River at War Creek

The floodplain northwest of the Twisp River has a large side channel that begins approximately 500 ft upstream of the confluence with War Creek. It served as the main channel for the Twisp River, as depicted in the Oval Peak 7.5 minute quadrangle topographic map of 1969 (fig. 5). The side channel branches downstream, forming a distributary network that is more than 1000 ft wide and covers about 50 acres (table 8). The main side-channel is 3,300 ft long. The median combined width of the side channels at their banks is 144 ft for three cross-sections.

The unconsolidated sediments are 2,000ft wide and more than 100 ft thick toward the valley wall. They are likely thicker in the center of the valley under the river. The sediments are mostly coarse sand, gravel. No ground-water levels were available for this site, but based on the water surface in the river, depth to ground-water is likely to range from 3 to 10 ft below the land surface, though it may be shallower at the upstream and downstream ends of the site (fig. 11). No standing water was observed at the site in April 2003. The report for the well at the edge of the study area (33N/20E-07N01) identified the top of "river sand and blue clay" at an elevation of 2,306 ft (depth of 102 ft) and the top of "clay and sandstone" at an elevation of 2,291 ft (depth of 117 ft) (table 10). These layers are unlikely to affect artificial recharge due to their depth, however, there may be other fine-grained lenses closer to the land surface at the site. The primary direction of ground-water flow is likely down valley (fig. 5), in which case, horizontal flow paths would be approximately 3,200 ft. The hydraulic gradient between the site and the river is estimated be 0.01.

2.4. Big Twin Lake

Big Twin Lake is a 77-acre lake formed in a closed depression on a glacio-lacustrine terrace 2 miles south of Winthrop (fig.7). The unconsolidated sediments are more than 100 ft thick in the center of the terrace and poorly sorted (clay, silt, sand, gravel, cobble, and boulders) and may fill a paleo-channel that is approximately 3,000 ft wide in the bedrock beneath the terrace (Konrad and others, in review). The water-surface elevation in the lake is approximately the same as ground-water levels in surrounding shallow wells. Depth to ground-water increase to more than 20 ft at a distance of 100 to 1,000 ft from the lake shore as the land surface rises away from the lake. The saturated thickness of the unconsolidated aquifer is more than 100 ft southeast of the lake (well 34N/21E-15R01). Potential low-permeability layers were reported in 5 of 6 well logs with tops of the layers reported at an elevation of 1,818 to 1,832 ft in four wells. These layers may not have been continuous, however, as they were reported variously as "clay like" at an elevation of 1,818 ft, "silt" at an elevation of 1,822 ft , "clay" at an elevation of 1,825 ft, and "clay and gravel" at an elevation of 1,832 ft (table 10). Ground water generally flows to the southwest with horizontal flow paths to the Methow River that are likely 1.5 to 2 miles long. The hydraulic gradient between ground water at the site and the Methow River along the flow paths ranges from 0.011 to 0.015 . The soil is Owhi extremely stony fine sandy loam with a permeability of 2 to 6 inches per day [SCS, 1980].

2.5. Elbow Coulee

Elbow Coulee is a north-south trending valley, north of the Twisp River between Newby and Poorman Creeks (fig. 6). The valley was likely formed through erosion by glacial ice and melt water. The valley is filled with poorly sorted, unconsolidated sediments (clay, silt, sand, gravel, cobble, and boulders) that are at most 800 ft wide at the land surface with a total thickness of approximately 50 ft and a saturated thickness of approximately 10 ft at its southern end. The depth to ground-water is generally more than 20 ft (fig. 13). Ground-water levels may be closer to the land surface in the upper (north) part, but there are no wells in this part of Elbow Coulee that could confirm this. Ground water flows to the south, down Elbow Coulee toward the Twisp River. Unconsolidated sediments form a terrace along the north side of the Twisp River that is continuous with the sediments filling Elbow Coulee. Ground water seeps from the east side of the base of the terrace to a wetland area adjacent to the river. Ground-water flow paths to the river range from about 1,200 ft at the lower end of Elbow Coulee to about 2.3 miles at the upper end (fig. 6). The hydraulic gradient between ground water in the lower portion of Elbow Coulee and the Twisp River is 0.03. The soil in Elbow Coulee is Newborn gravelly loam, with a permeability of 0.6 to 20 inches per day [SCS, 1980].

2.6. Terrace southeast of Twisp

A terrace formed of coarse unconsolidated sediments (sand and gravel) with a thickness of 80 to more than 100 ft is located 1.5 miles southeast of Twisp on the northeast side of the Methow River (fig. 8). The terrace was deposited over bedrock forming the divide between the Methow River and Beaver Creek. The depth to ground water is more than 20 ft under the terrace (fig. 14) with two wells (33N/21E-16R [6"] and [8"] in the terrace having depths to water of 71 and 84 ft. The ground-water surface under the terrace is higher, by approximately 40 ft, than the ground-water in the alluvial deposits along the Methow River to the west. The saturated thickness of the unconsolidated aquifer in these wells ranges from 10 to more than 19 ft. The bedrock surface below the terrace is likely to dip to the southwest toward the Methow River. Ground-water flow paths from the terrace to the river are likely 1,100 to 3,100 ft. (fig. 7). The hydraulic gradient between ground water at the site and the Methow River along the flow paths ranges from 0.007 to 0.02. The soils on the terrace are Newbon gravelly loam, Winthrop gravelly loamy sand, and Newbon loam, which have permeabilities ranging from 0.6 to more than 20 inches per day [SCS, 1980].

3. Hazards of artificial recharge

Artificial aquifer recharge can be expected to increase ground-water levels, ground-water flow rates, and associated hazards. Specific hazards of artificial aquifer recharge were not assessed at any of the sites, but some likely hazards are listed. In general, increased ground-water levels will increase any associated flooding from ground-water seepage and hillslope instability. Increased ground-water levels can also mobilize and transport contaminants from previously unsaturated soils into ground water. This is particularly a hazard if artificial aquifer recharge raises ground-water to a level where waste has been buried and around drain fields for septic systems. The terrace south of Twisp (site 6) includes a closed Okanogan County landfill. Buried wastes at site 6 represent a potential source of contaminants that artificial recharge could mobilize. Septic effluent from residences around the Twin Lakes area (site 4) could also contaminate ground water if artificial recharge increased ground-water levels to the point that drain fields were saturated by the artificially recharged water. Contaminants on the land surface may also be transported by water infiltrating into soils, for example, where hazardous material are stored or airborne contaminants deposit on the land surface.

4. Summary and conclusions

Artificial aquifer recharge represents one approach for re-distributing water resources in the Methow River Basin from periods of high runoff during the late spring and early summer to periods of low runoff later in the summer and into the winter. Annual streamflow volume exceeds regulatory base flow volume in all but drought years (e.g., WY 2001) at the six gages where regulatory base flows have been established in the MRB. Overall, the reliability of excess streamflow is highest during late spring and summer for all gages: streamflow exceeded regulatory base flow from May through August at all gages for 7 out 10 years in the period from WY 1993 to 2002 and may be a reliable period for using streamflow for artificial aquifer recharge. Streamflow was commonly (fewer than 5 out of 10 years) less than regulatory base flow from September through March for the Methow River above Goat Creek, the Methow River at Twisp, and the Methow River near Pateros. Streamflow in the Chewuch River at Winthrop and the Twisp River near Twisp was frequently less than regulatory base flow during September. It is unlikely, then, that surface-water diversions could be used from September through March for artificial aquifer recharge.

The hydrogeology of unconsolidated sediments in the Methow River basin varies spatially with regard to a number of important conditions that could affect aquifer recharge including depth to ground water, hydraulic gradient, and length of flow paths to a river. Ground water levels near the Methow River above Early Winters and the Twisp River at War Creek are likely deep enough to allow artificial aquifer recharge throughout the year except for periods of sustained high streamflows in some years. Ground water at the Methow River at Fawn Creek is relatively shallow. As a result, there is little storage capacity available in the aquifer and any water artificially recharged is likely to flow along shallow, horizontal paths quickly back to the river.

Ground-water levels at Big Twin Lake, Elbow Coulee, and the terrace south of Twisp are likely to be deep enough to allow artificial recharge throughout the year and, in particular, during periods of high flows when streamflow generally exceeds state regulatory base flow. The closed landfill south of Twisp, however, represents a potential source of contaminants that artificial aquifer recharge could mobilize and transport. In comparison to the terrace south of Twisp, Big Twin Lakes and Elbow Coulee have long ground-water flow paths that would delay the return of artificially-recharged water to the Methow and Twisp Rivers, respectively. Streamflow in excess of regulatory base flow may be available for artificial aquifer recharge in most years from April through August except, however, during late June and early July for the Methow River near Pateros and the Twisp River near Twisp.

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Artificial aquifer recharge can be expected to increase ground-water levels and ground-water flow at and around a recharge site. As a result, the total volume of water artificially recharged will be reduced by the increase in ground-water flow rate over time. Likewise, the increase in ground-water discharge to a river as a consequence of artificial recharge will persist only as long as ground-water levels are elevated by the artificial recharge. The response of the ground-water system to artificial recharge will need to be analyzed at a specific location before the net volume of artificially-recharged water can be estimated.

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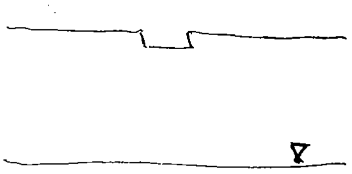
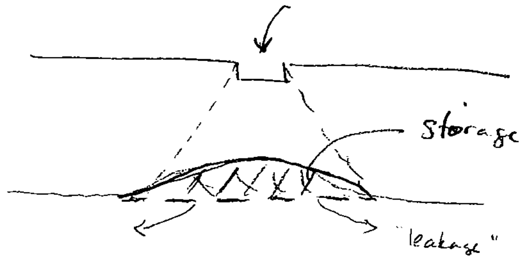
In general, an aquifer would likely support additional ground-water flow under artificial recharge without substantial ground-water mounding where the aquifer is wide and has a large saturated thickness, a high hydraulic gradient, and high hydraulic conductivity. Based on these conditions, the floodplain sites and Big Twin Lake are likely to have least mounding in response to aquifer recharge. Any mounding at the floodplain sites, however, could result in shallow, horizontal ground-water flow back to the river particularly for the Methow River at Fawn Creek where ground water is naturally shallow. Overall, artificial recharge at the Methow River above Early Winters Creek, the Twisp River at War Creek, and Big Twin Lake is less likely cause changes in ground-water flow than at other sites and artificially-recharged ground-water can be expected to flow at the same velocities and along the same paths as the existing ground-water system.

The same factors that prevent mounding, however, also limit the temporary increase in streamflow that may result after a period of artificial aquifer recharge. As a consequence, artificial recharge at these sites may not cause a seasonal increase streamflow, even as they may contribute a small but steady component of ground-water inflow to downstream river reaches. In contrast, artificial recharge at Elbow Coulee and the terrace south of Twisp might produce the largest seasonal (temporary) increase in streamflow of any of the sites after periods of artificial recharge because of mounding that would increase the already high hydraulic gradients between these sites and the respective rivers. Elbow Coulee has potentially longer flow paths back to the Twisp River than the terrace south of Twisp does to the Methow River. The longer flow paths could provide a longer delay between periods of artificial recharge and inflow back to the river assuming similar hydraulic conductivity and gradients at the two sites.





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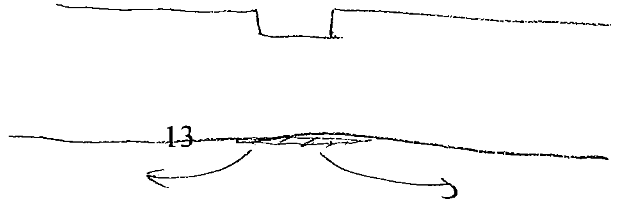

low mounding
low S,
low time lag

5. References

Konrad, C.P., Drost, B.W., and Wagner, R.J., in review, The hydrogeology of the unconsolidated deposits, water quality, and ground-water surface-water exchanges in the Methow River Basin, Okanogan County, Washington, U.S. Geological Survey, Water-Resources Investigations Report 03-XXXX, x p.

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U.S. Forest Service, 1998c, Digital orthophoto of the Oval Peak quadrangle, image taken on July 8, 1998, http://rocky.ess.washington.edu/data/raster/usfs/concrete/images/48120d2_1998.zip accessed on October 17, 2002.

U.S. Forest Service, 1998d, Digital orthophoto of the Winthrop quadrangle, image taken on July 8, 1998, http://rocky.ess.washington.edu/data/raster/usfs/concrete/images/48120c1_1998.zip accessed on October 17, 2002.

U.S. Forest Service, 1998e, Digital orthophoto of the Twisp East quadrangle, image taken on July 8, 1998, http://rocky.ess.washington.edu/data/raster/usfs/concrete/images/48120c4_1998.zip accessed on October 17, 2002.

Table 1. Comparison of streamflow conditions for the Methow River near Pateros (USGS station 12449950) for WY 1959.

	WY 1960-2002	WY 1993-2002
Mean	1550 cfs[1]	1562 cfs
Median	1567 cfs	1647 cfs
Minimum	565 cfs	576 cfs
Maximum	3413 cfs	2251 cfs
Coefficient of variation of daily mean discharge	1.5	1.5

[1] cubic feet per second

Table 2. Washington regulatory base flows at six locations in the Methow River Basin.

Day of the year	Methow River above Goat Creek (USGS Station 12447383)	Chewuch River at Winthrop (USGS Station 12448000)	Methow River at Winthrop (USGS Station 12448500)	Twisp River near Twisp (USGS Station 12448998)	Methow River at Twisp (USGS Station 12449500)	Methow River near Pateros (USGS Station 12449950)
			cubic feet per second			
1-Oct	45	56	122	35	260	360
15-Oct	60	68	150	45	320	425
1-Nov	60	68	150	45	320	425
15-Nov	60	68	150	45	320	425
1-Dec	51	62	135	39	290	390
15-Dec	42	56	120	34	260	350
1-Jan	42	56	120	34	260	350
15-Jan	42	56	120	34	260	350
1-Feb	42	56	120	34	260	350
15-Feb	42	56	120	34	260	350
1-Mar	42	56	120	34	260	350
15-Mar	42	56	120	34	260	350
1-Apr	64	90	199	60	430	590
15-Apr	90	140	300	100	650	860
1-May	130	215	480	170	1000	1300
15-May	430	290	690	300	1500	1940
1-Jun	1160	320	790	440	1500	2220
15-Jun	1160	320	790	440	1500	2220
1-Jul	500	292	694	390	1500	2150
15-Jul	180	110	240	130	500	800
1-Aug	75	70	153	58	325	480
15-Aug	32	47	100	27	220	300
1-Sep	32	47	100	27	220	300
15-Sep	32	47	100	27	220	300

Table 3. Difference between daily streamflow and state regulatory base flow for WY 1993-2002.

Methow River above Goat Creek	319 cfs[1]
Chewuch River at Winthrop	287 cfs
Methow River at Winthrop	917 cfs
Twisp River near Twisp	153 cfs
Methow River at Twisp	855 cfs
Methow River near Pateros	781 cfs

[1]cubic feet per second

Table 4. Annual net volume of streamflow in excess of WA regulatory base flows. Negative values indicate that annual streamflow was less than regulatory base flow.

Water Year	Methow River above Goat Creek	Chewuch River at Winthrop	Methow River at Winthrop	Twisp River near Twisp	Methow River at Twisp	Methow River near Pateros
			thousands of acre feet			
1992	159	80	443	51	360	244
1993	89	118	403	44	297	199
1994	73	122	362	31	263	156
1995	293	300	859	168	880	801
1996	365	302	951	218	998	946
1997	391	339	1000	200	1003	999
1998	292	288	844	135	820	844
1999	443	374	1065	170	1036	1088
2000	227	160	586	101	556	501
2001	-24	-8	124	-6	-22	-124

Table 5. Number of days each Water Year (WY) when streamflow exceeded regulatory base flows.

Water Year	Methow River above Goat Creek	Chewuch River at Winthrop	Methow River at Winthrop	Twisp River near Twisp	Methow River at Twisp	Methow River near Pateros
1992	179	321	366	312	324	216
1993	106	196	337	211	130	116
1994	94	286	365	158	157	89
1995	198	285	365	335	234	220
1996	321	365	366	366	366	358
1997	193	365	365	365	361	333
1998	250	365	365	354	354	364
1999	189	365	365	365	310	325
2000	247	350	366	354	351	353
2001	26	85	326	152	66	15
Median	189	321	365	335	310	220

Table 6. Annual volume of streamflow in excess of regulatory base flow for days when streamflow exceeded regulatory base flows.

Water Year	Methow River above Goat Creek	Chewuch River at Winthrop	Methow River at Winthrop	Twisp River near Twisp	Methow River at Twisp	Methow River near Pateros
			thousands of acre feet			
1992	174	81	444	55	362	259
1993	122	127	408	53	347	301
1994	105	124	362	41	279	215
1995	308	301	859	169	894	826
1996	370	303	953	218	1001	949
1997	403	339	1000	200	1003	1001
1998	297	288	844	135	821	844
1999	460	374	1065	170	1039	1090
2000	232	160	588	101	558	503
2001	25	9	133	12	55	32

Table 7. Sites investigated for potential artificial aquifer recharge.

	Site	Landscape feature	Soils
1	Methow River above Early Winters Creek	Floodplain	Not available[2]
2	Methow River at Fawn Creek	Floodplain	Xerofluvents, Boesel fine sandy loam, and riverwash[1]
3	Twisp River at War Creek	Floodplain	Not available[2]
4	Big Twin Lake, Winthrop	Glacial terrace	Owhi extremely stony fine sandy loam[1]
5	Elbow Coulee, Twisp River below Newby Creek	Glacio-fluvial valley-fill deposit	Newbon gravelly loam[1]
6	Terrace southeast of Twisp, Methow River above Beaver Creek	Glacio-lacustrine terrace	Newbon gravelly loam, Winthrop gravelly loamy sand, Newbon loam[1]

[1] Source: Okanogan County Soil Survey (Soil Conservation Service, 1980).

[2] Not included in the Okanogan County Soil Survey, but likely to have riverwash and Boesel fine sandy loam.

Table 8. Maximum recharge rates for sites based on total acreage and representative infiltration rate for soil types.

Site	Acres	Infiltration rate[1] (inches per day)	Maximum recharge rate for site (acre ft per day)
Methow River above Early Winters Creek	44.5	3	267
Methow River at Fawn Creek	61.7	3	370
Twisp River at War Creek	49.8	3	299
Big Twin Lake, Winthrop	77.6	4	621
Elbow Coulee, Twisp River	85.6	1.3	222
Terrace southeast of Twisp, Methow River above Beaver Creek	54.6	5	546

[1] Source: Okanogan County Soil Survey (Soil Conservation Service, 1980).

Table 9. Dimensions of side channels at sites 1-3.

Site	Maximum length (ft)	Median width of channels at bank (ft) with number of cross-sections in [ ]	Area covered by side channels (acres)
Methow River above Early Winters Creek	3900	83 [3]	7.5
Methow River at Fawn Creek	5600	65 [6]	8.3
Twisp River at War Creek	3300	144 [3]	10.9

Table 10. List of wells near sites with top elevations of land surface and potential low-permeability layers. Datum for all elevations is NAVD 1988.

Local well numbers[1]	Land surface (ft)	Principal lithology	Top elevation of potential low-permeability layers (ft)
Methow River above Early Winters Creek			
36N/19E 22C [E-12]	2205	Boulders, sand, gravel	Unconsolidated sediments not differentiated
36N/19E-15L02	2214	Gravel, clay, hardpan, sand	2200 (clay), 2191 (hardpan), 2168 (hardpan)
36N/19E-15K [MW-1B]	2208	Sandy cobbles, gravel	2163 (silt)
36N/19E-22J01	2179	Gravel, boulders, silt, sand	2160 (silt)
36N/19E-22J02	2179	Silt, gravel, hardpan, sand	2158 (hardpan)
36N/19E-23E02 [EW19]	2197	Boulders, sand, gravel	None
36N/19E-23E03 [EW19A]	2197	Sand, gravel, boulders	None
Methow River at Fawn Creek			
36N/20E-04N [E-10]	1999	Not differentiated	Unconsolidated sediments not differentiated
35N/20E-04N01	2010	Cobbles, sand, gravel, silt	1978 (silt and gravel)
35N/20E-10E01	1974	Clay, sand, and gravel	1969 (clay)
Twisp River at War Creek			
33N/20E-07N01	2408	Sand, gravel, and boulders	2306 (river sand and blue clay), 2291 (clay and sandstone)
Twin Lakes			
34N/21E-15B01	1894	Sand, gravel, clay	1825 (clay)
34N/21E-15R01	1886	Till, sand, gravel	1886 (till)
34N/21E-15E01	1954	Clay, gravel, hardpan, bedrock	1938 (clay)
34N/21E-14D01	1844	Sand, gravel, bedrock	None
34N/21E-14E01	1853	Silt, sand, cobbles, gravel	1838 (cemented silt), 1818 (clay like)
34N/21E-14N01	1864	Clay, sand, gravel, silt, bedrock	1864 (clay), 1822 (silt)
34N/21E-14P01	1864	Sandy clay, gravel, bedrock	1821 (bedrock)
Elbow Coulee			
33N/21E-09D01	1974	Sand, gravel, clay	1962 (clay)
33N/21E-09D02	2004	Gravel, silt, cobbles, boulders, clay, bedrock	1974 (clay)
33N/21E-09D03	1969	Gravel, hardpan, clay	1969 (clay and gravel)

Table 10 continued.

Local well numbers[1]	Land surface (ft)	Principal lithology	Elevation of potential low-permeability layers (ft)
Terrace southeast of Twisp			
33N/21E-16P01	1584	Silty sand, cobbles, gravel	1554 (sand, silty; tight clay-like)
33N/21E-16R03	1673	No well log	No well log
33N/21E-16R	1673	Sand, gravel, cobbles, boulders, clay	1632 (fine to medium sand, abundant clay)
33N/21E-16R	1657	Gravel, cobbles, boulders, sand, bedrock	None

[1] Local well numbers are the Township, Range, Section, and a letter identifying the quarter-quarter section of the well described in the text. If the well has been inventoried by USGS, then a 2-digit sequence number follows the quarter-quarter section identifier. Other agency codes for wells are listed in [ ].

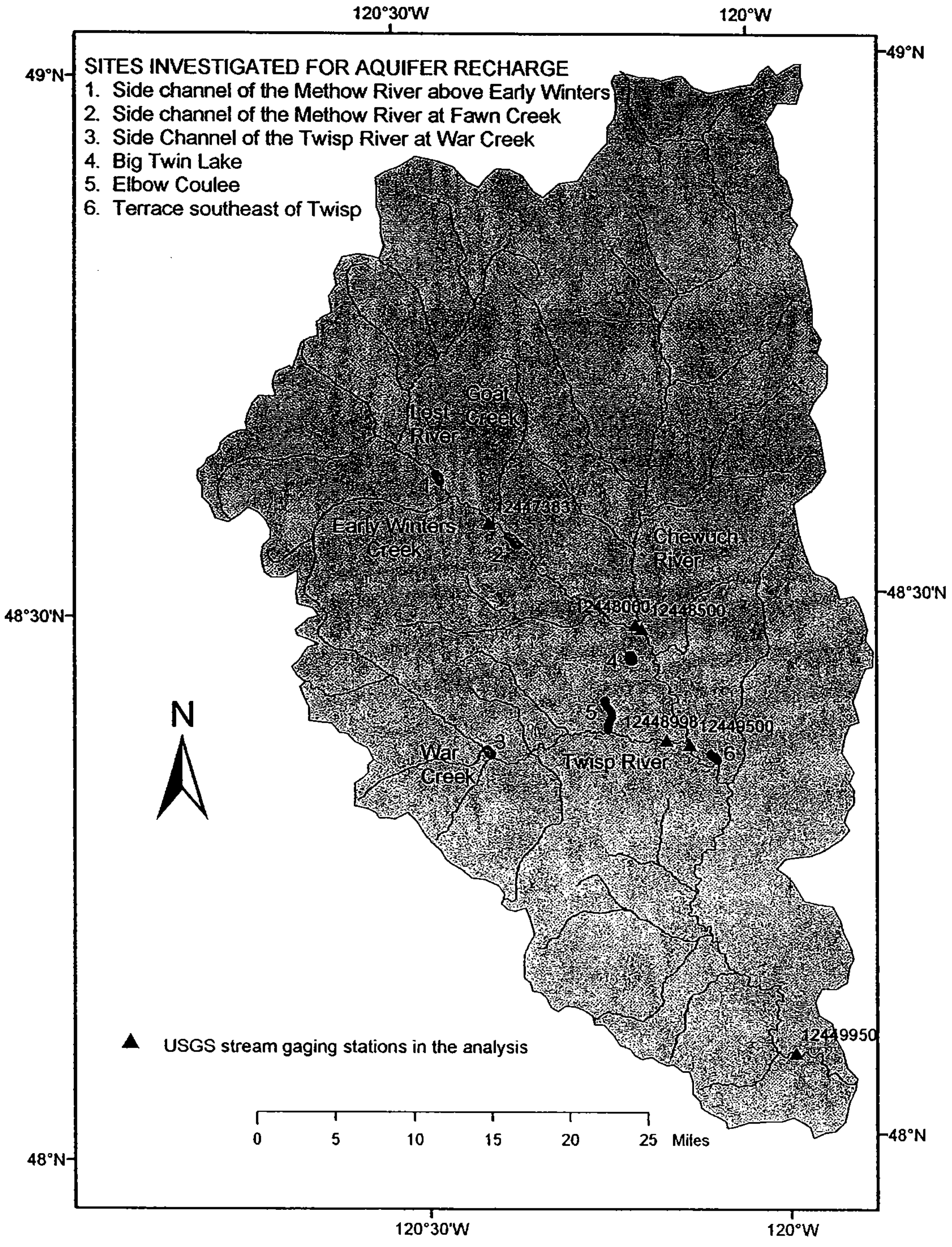
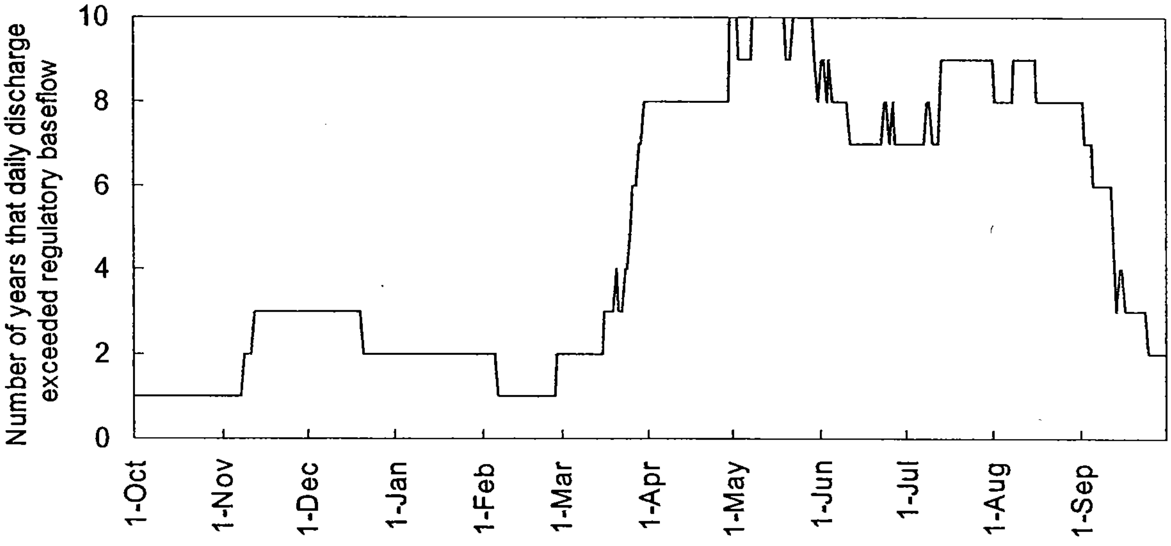
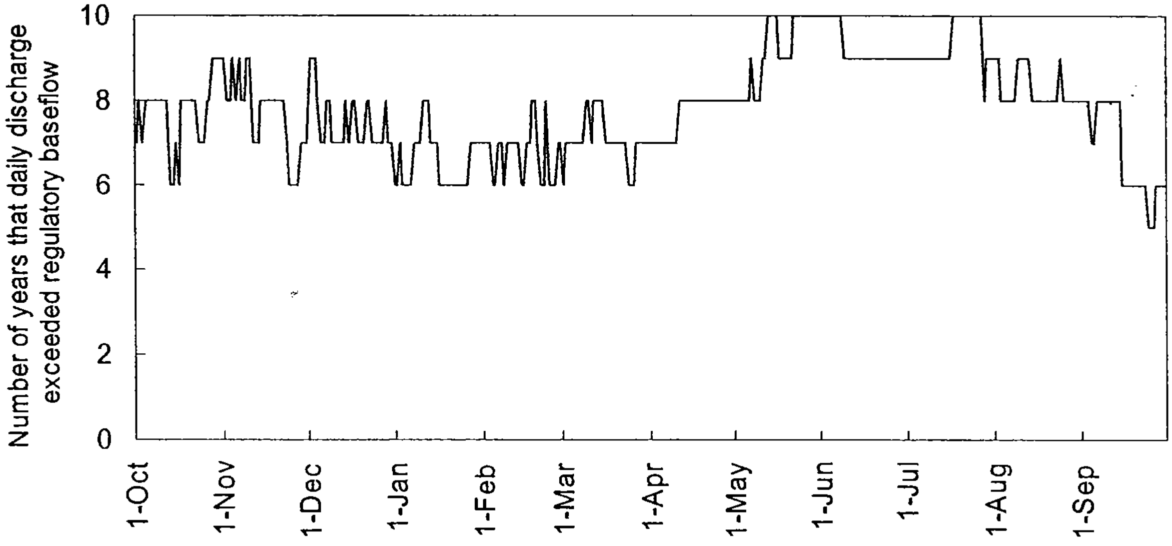


Figure 1. Methow River Basin with selected USGS stream gaging stations and sites investigated for artificial aquifer recharge.

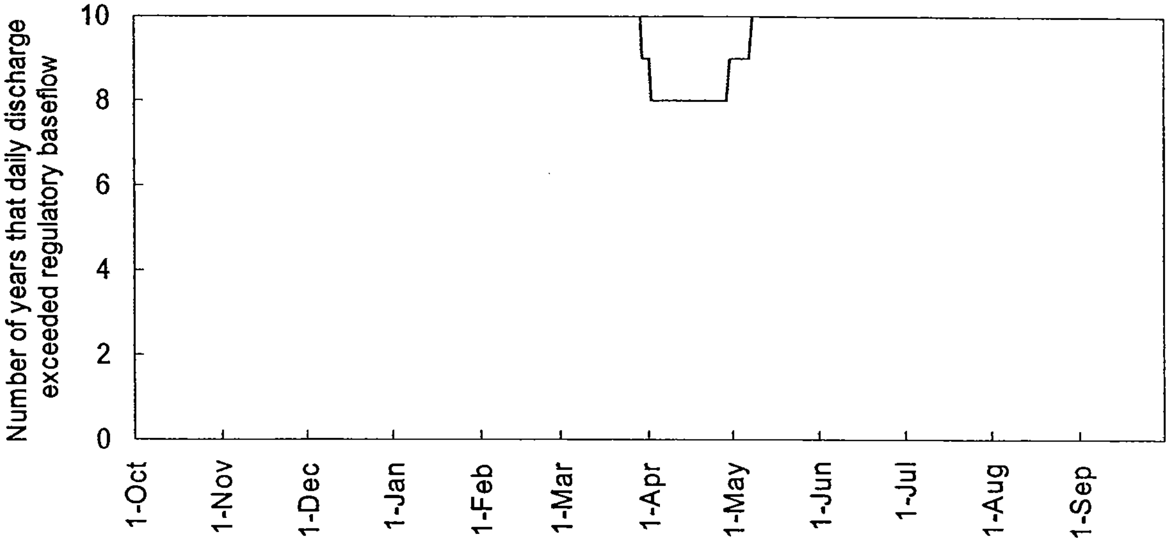


a. Methow River above Goat Creek (USGS station 12447383)

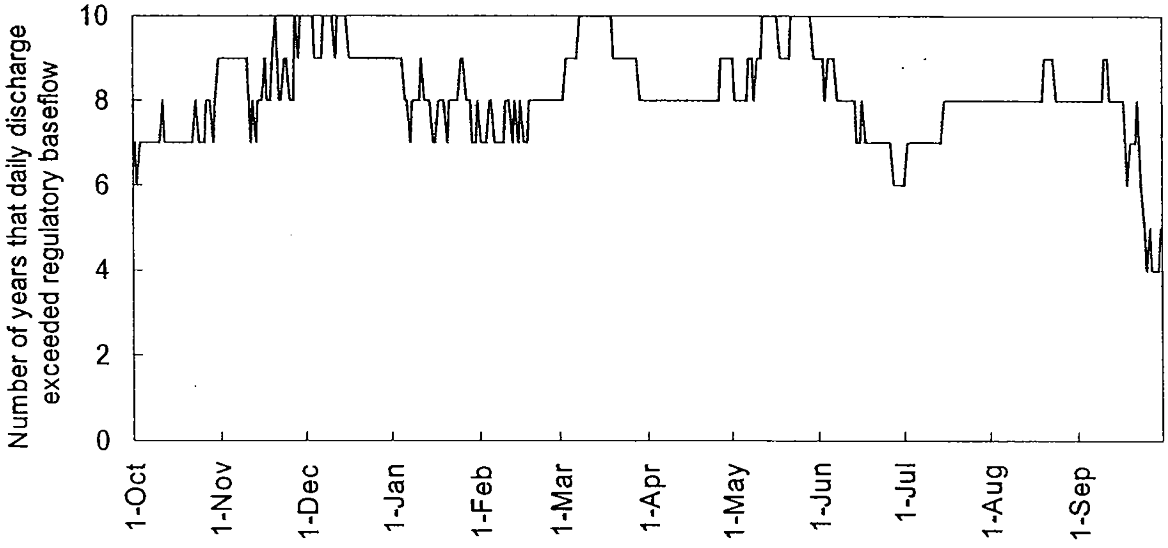


b. Chewuch River at Winthop (USGS station 12448000)

Figures 2a and 2b. Frequency that daily discharge exceeded regulatory base flows at the Methow River above Goat Creek and the Chewuch River at Winthrop for Water Years 1993 to 2002.

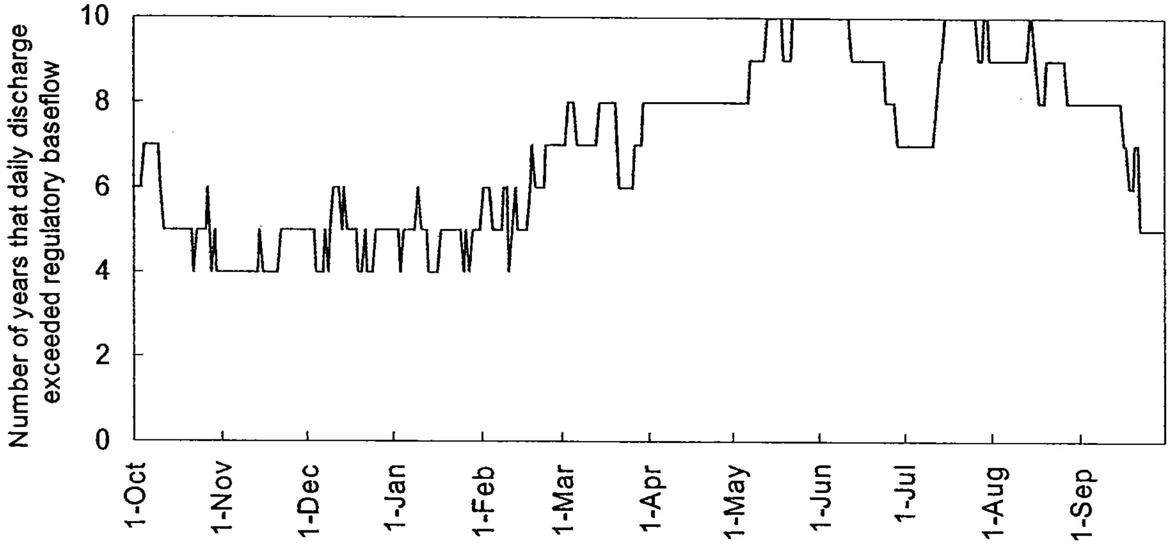


c. Methow River at Winthrop (USGS station 12448500)

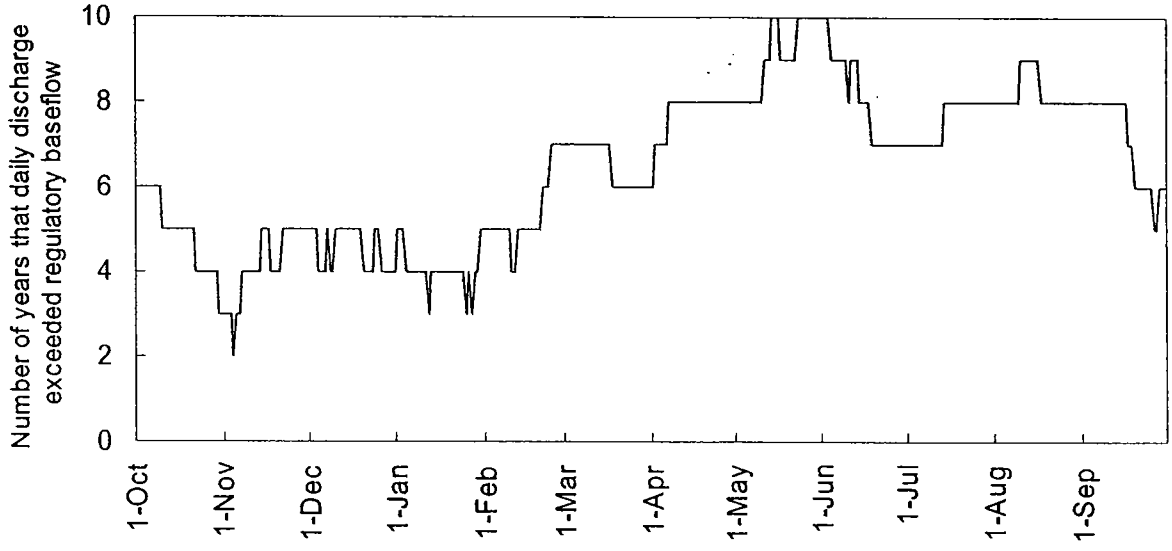


d. Twisp River near Twisp (USGS station 12448998)

Figures 2c and 2d. Frequency that daily discharge exceeded regulatory base flows at the Methow River at Winthrop and the Twisp River near Twisp for Water Years 1993 to 2002.



e. Methow River at Twisp (USGS station 12449500)



f. Methow River near Pateros (USGS station 12449950)

Figures 2e and 2f. Frequency that daily discharge exceeded regulatory base flows at the Methow River at Twisp and the Methow River near Pateros for Water Years 1993 to 2002.

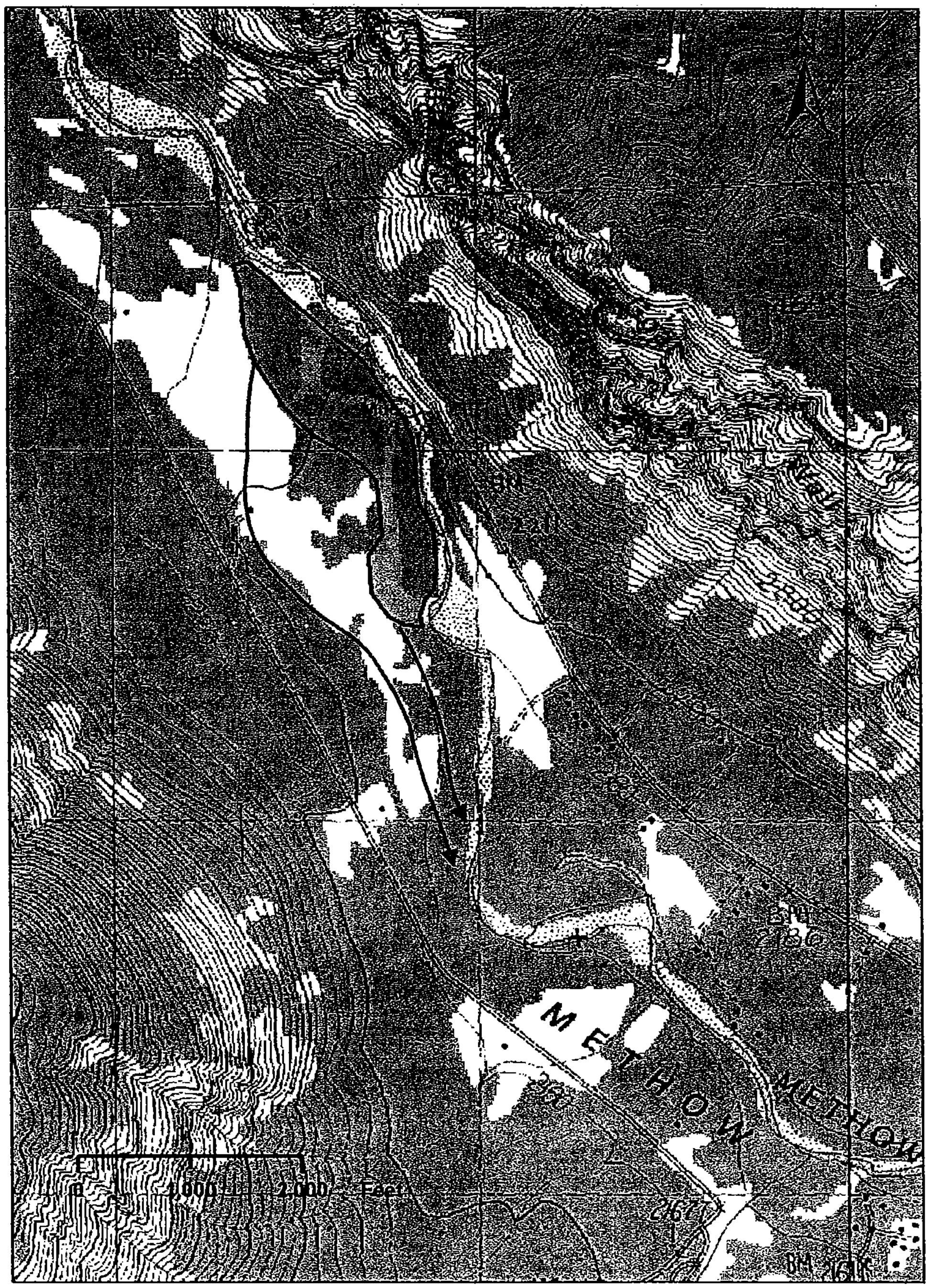


Figure 3. Methow River above Early Winters Creek with side-channel area (shaded), valley cross-section, and ground-water flow paths (lines with arrow ends).

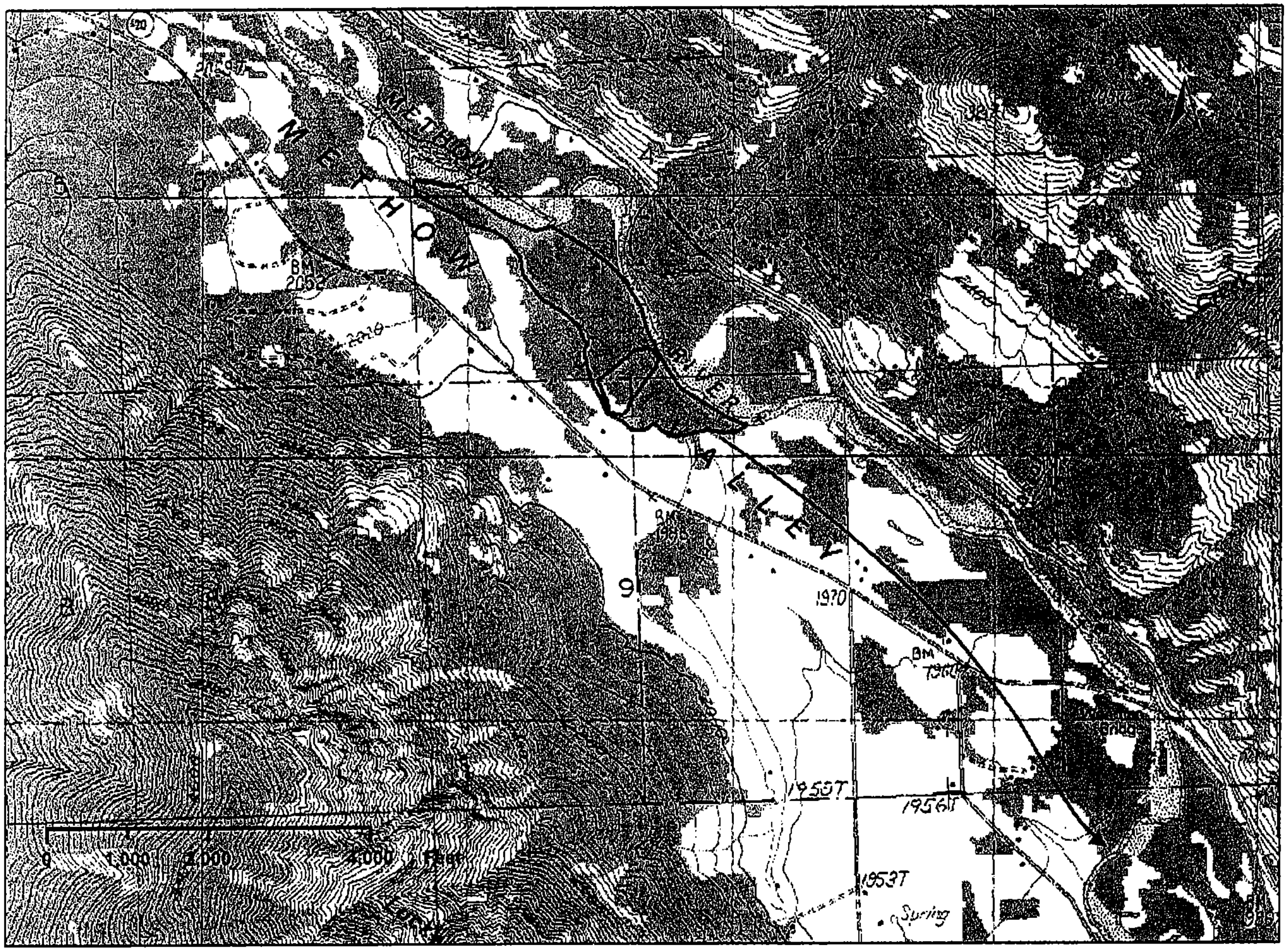


Figure 4. Methow River at Fawn Creek with side-channel area (shaded), valley cross-section (line), and ground-water flow paths (lines with arrow ends).

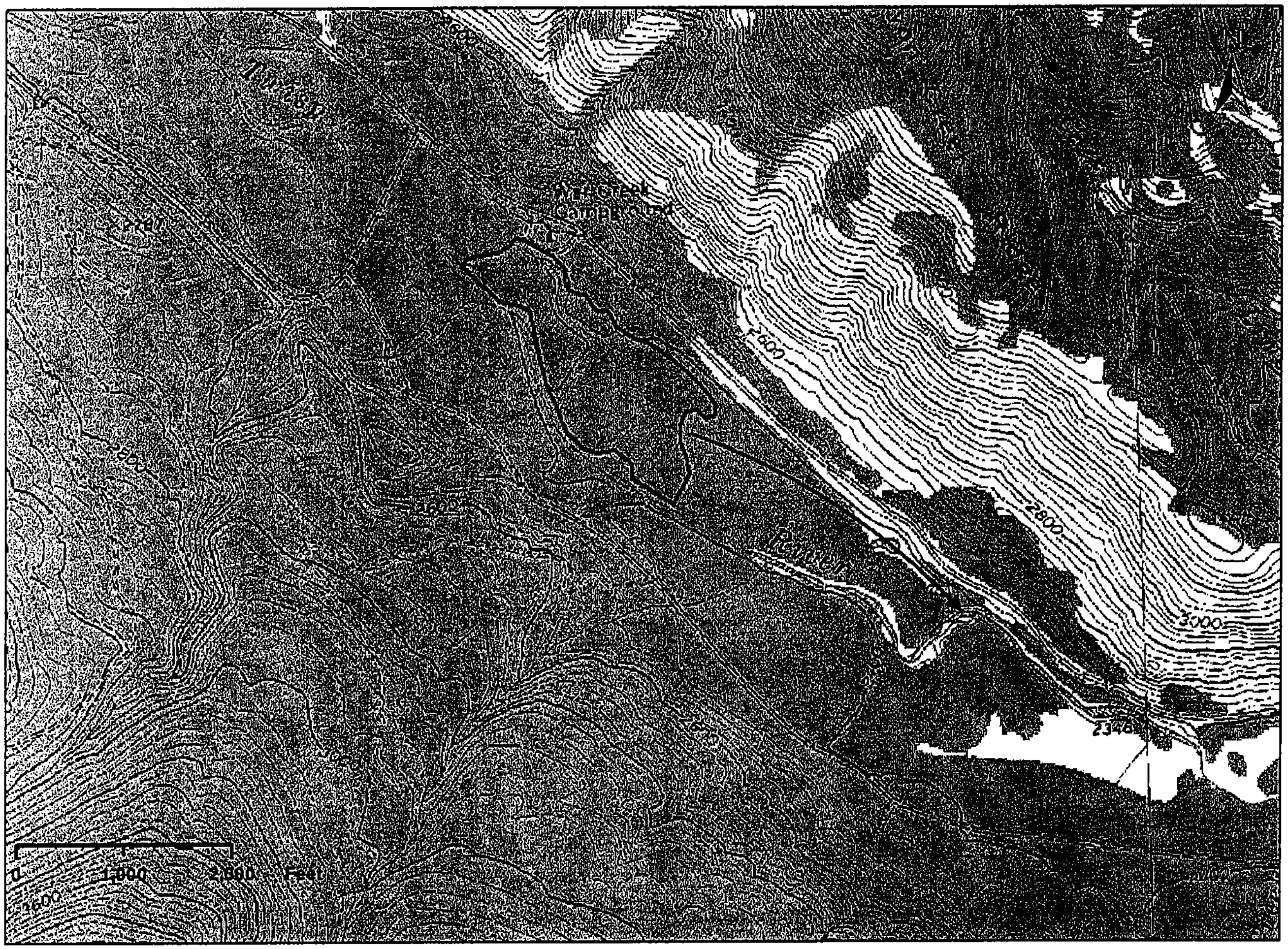


Figure 5. Twisp River at War Creek with side-channel area (shaded), valley cross-section (line), and ground-water flow paths (lines with arrow ends).

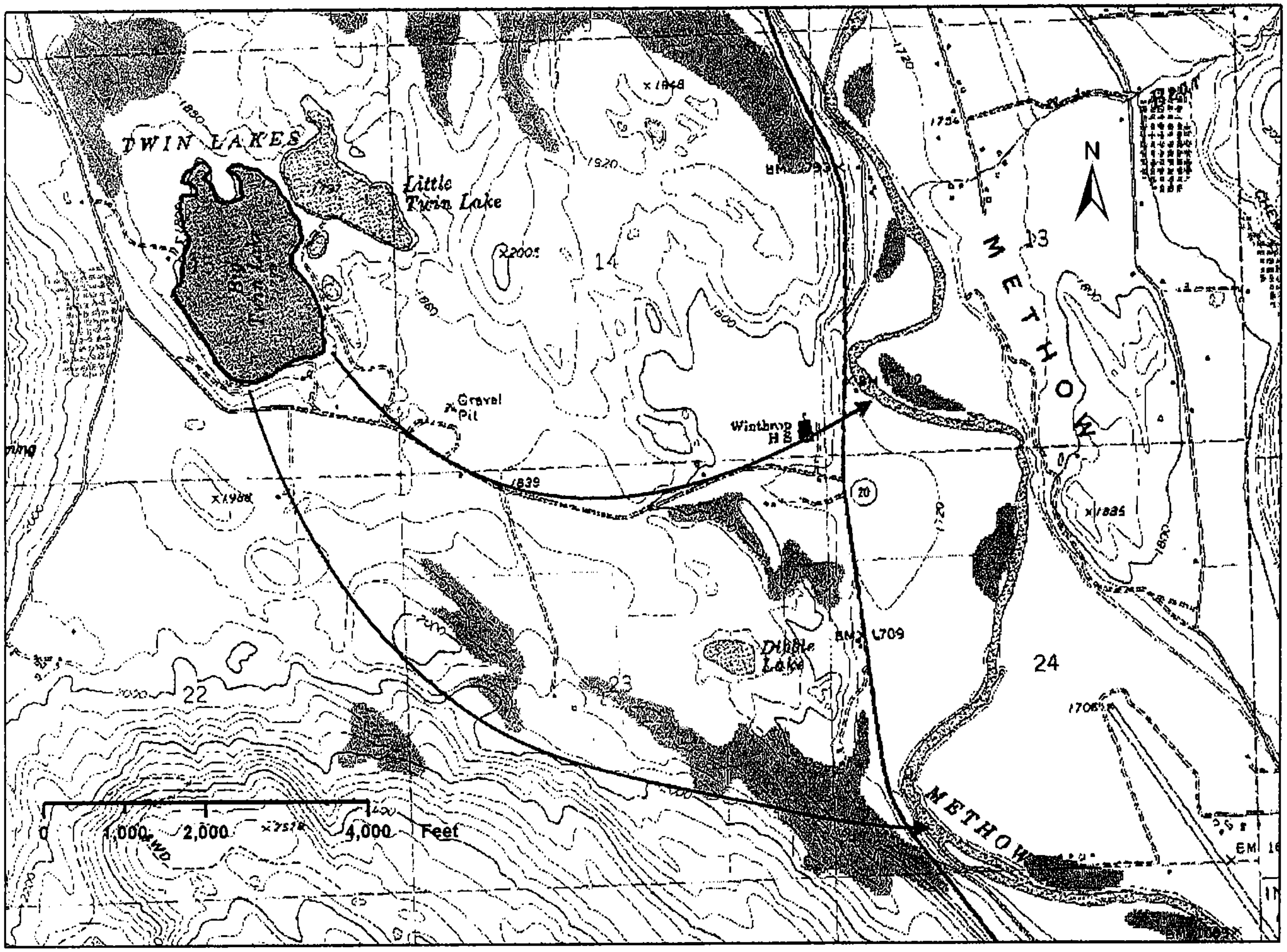


Figure 6. Big Twin Lake (shaded), valley cross-section (line), and ground-water flow paths (lines with arrow ends).

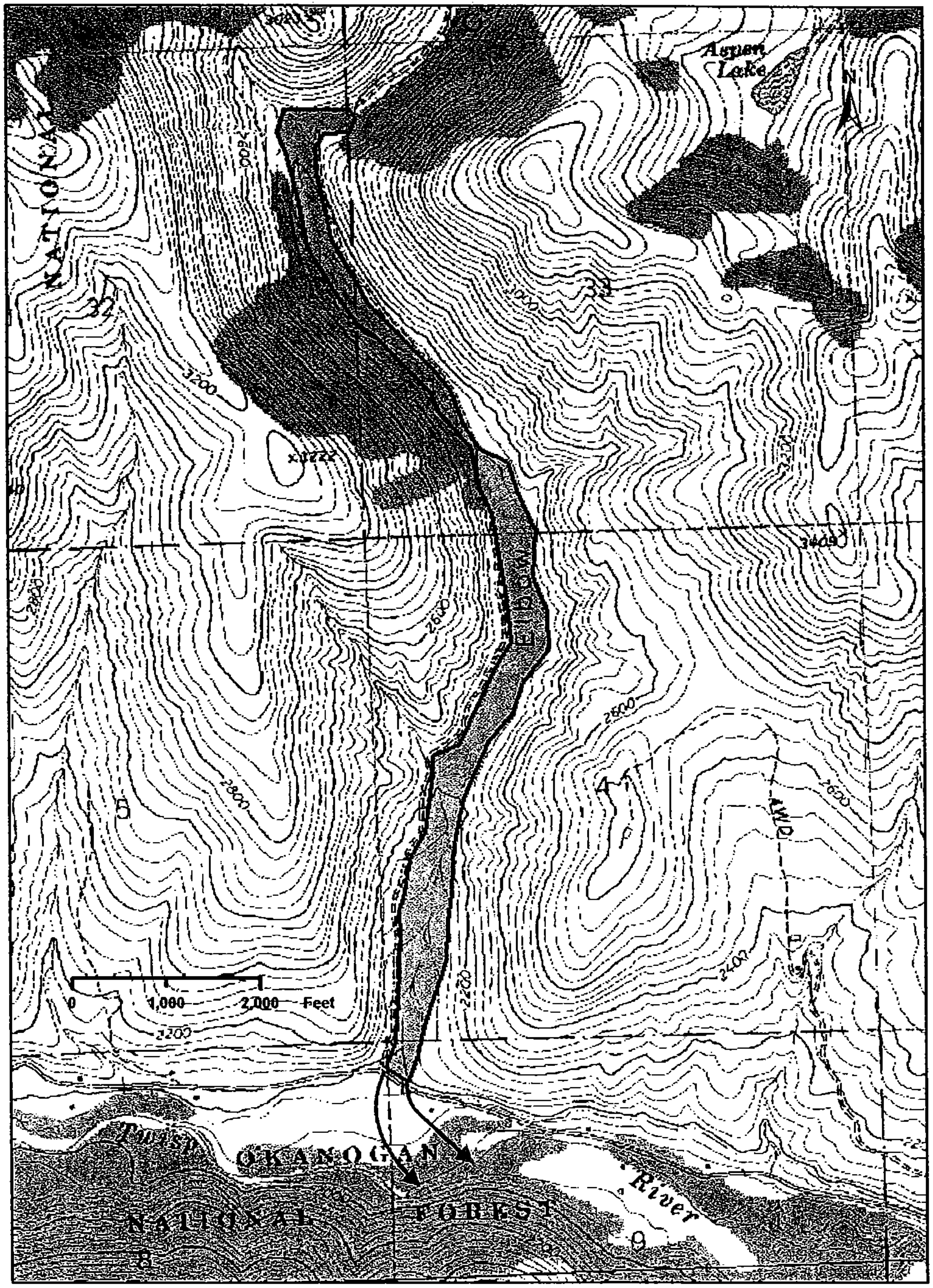


Figure 7. Elbow Coulee (shaded), valley cross-section (line), and ground-water flow paths (lines with arrow ends).

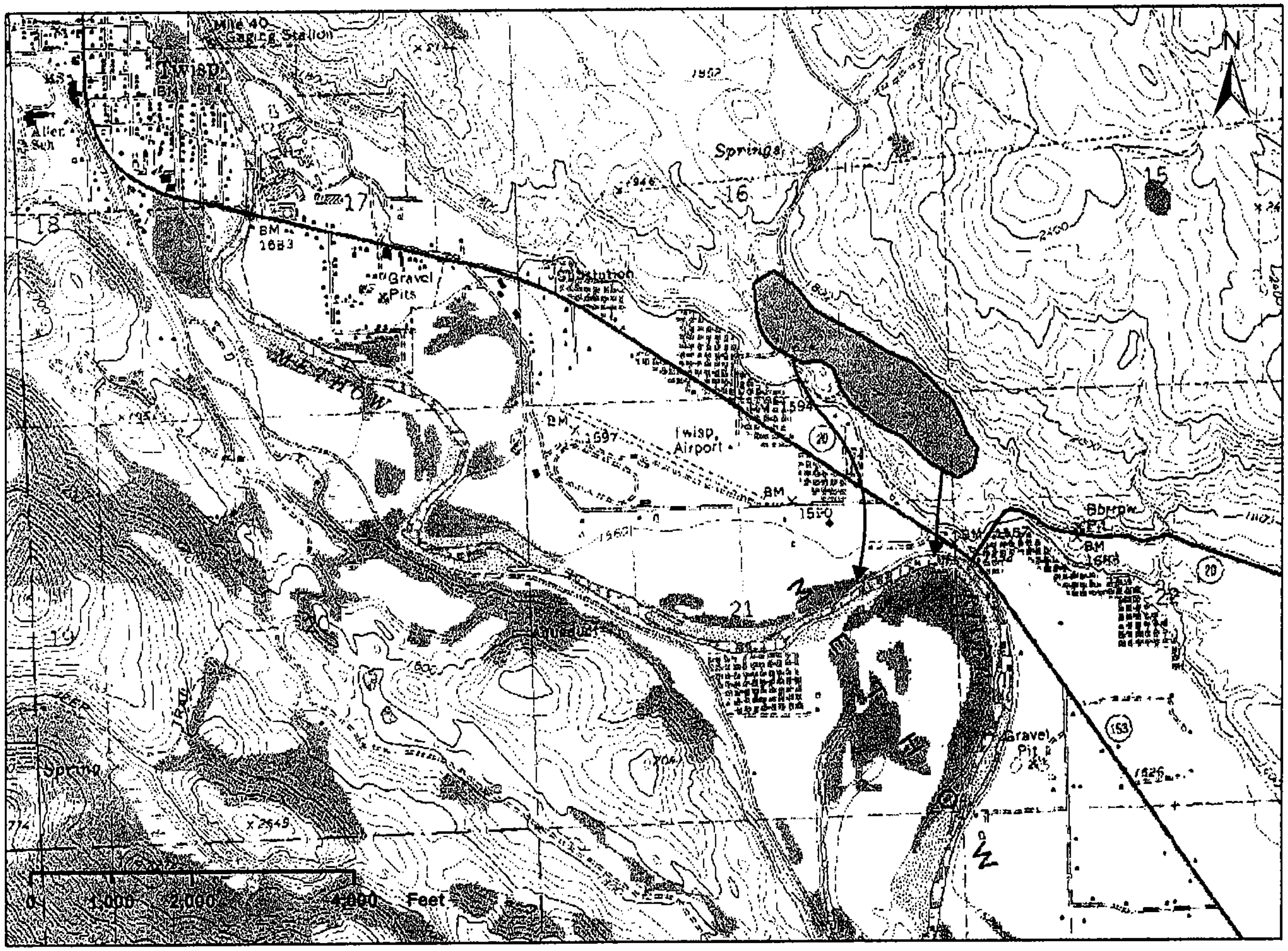


Figure 8. Terrace southeast of Twisp (shaded), valley cross-section (line), and ground-water flow paths (lines with arrow ends).

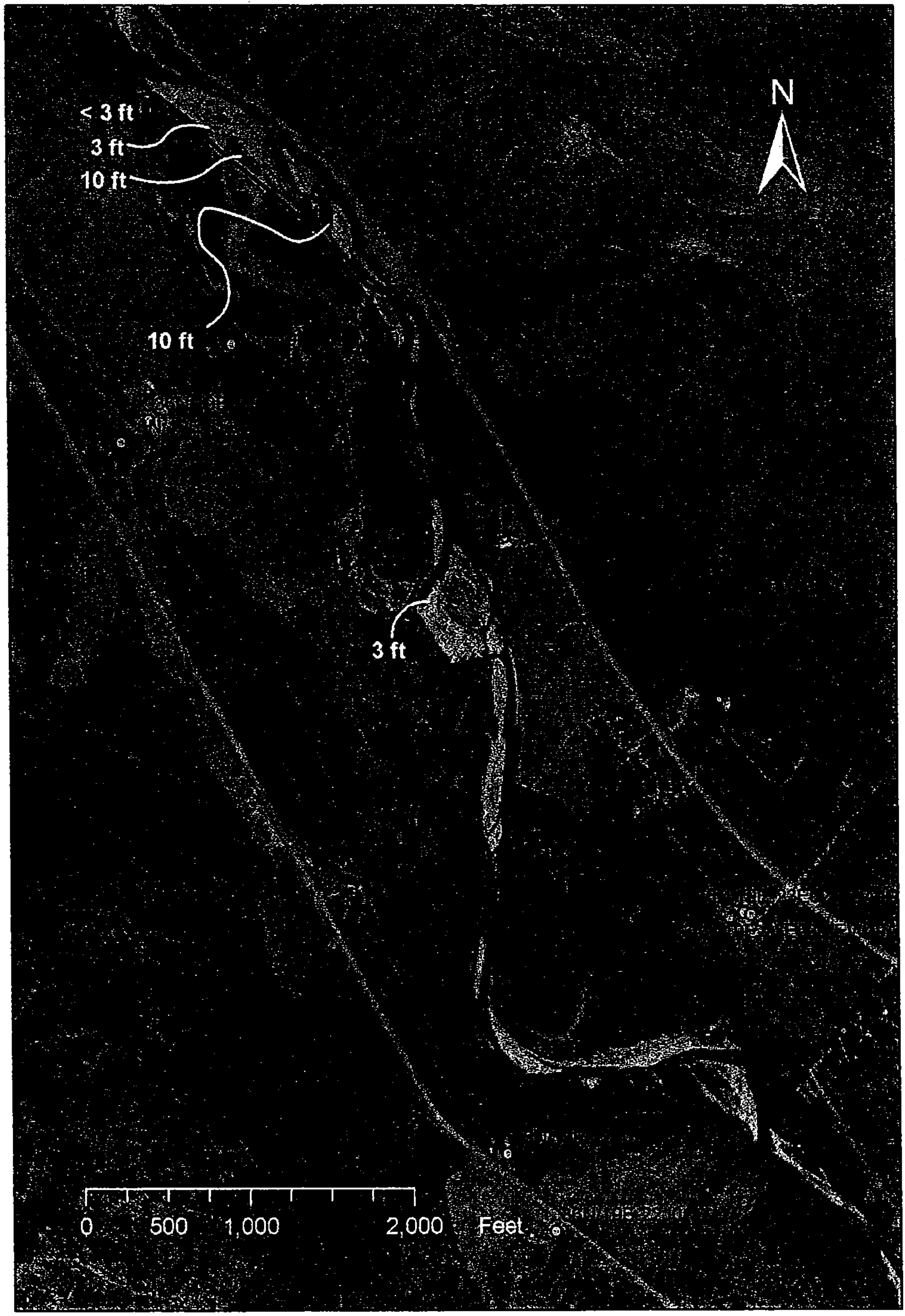


Figure 9. Side channel of the Methow River above Early Winters Creek with estimated depth to ground water. Digital orthophoto source: U.S. Forest Service, 1998a.

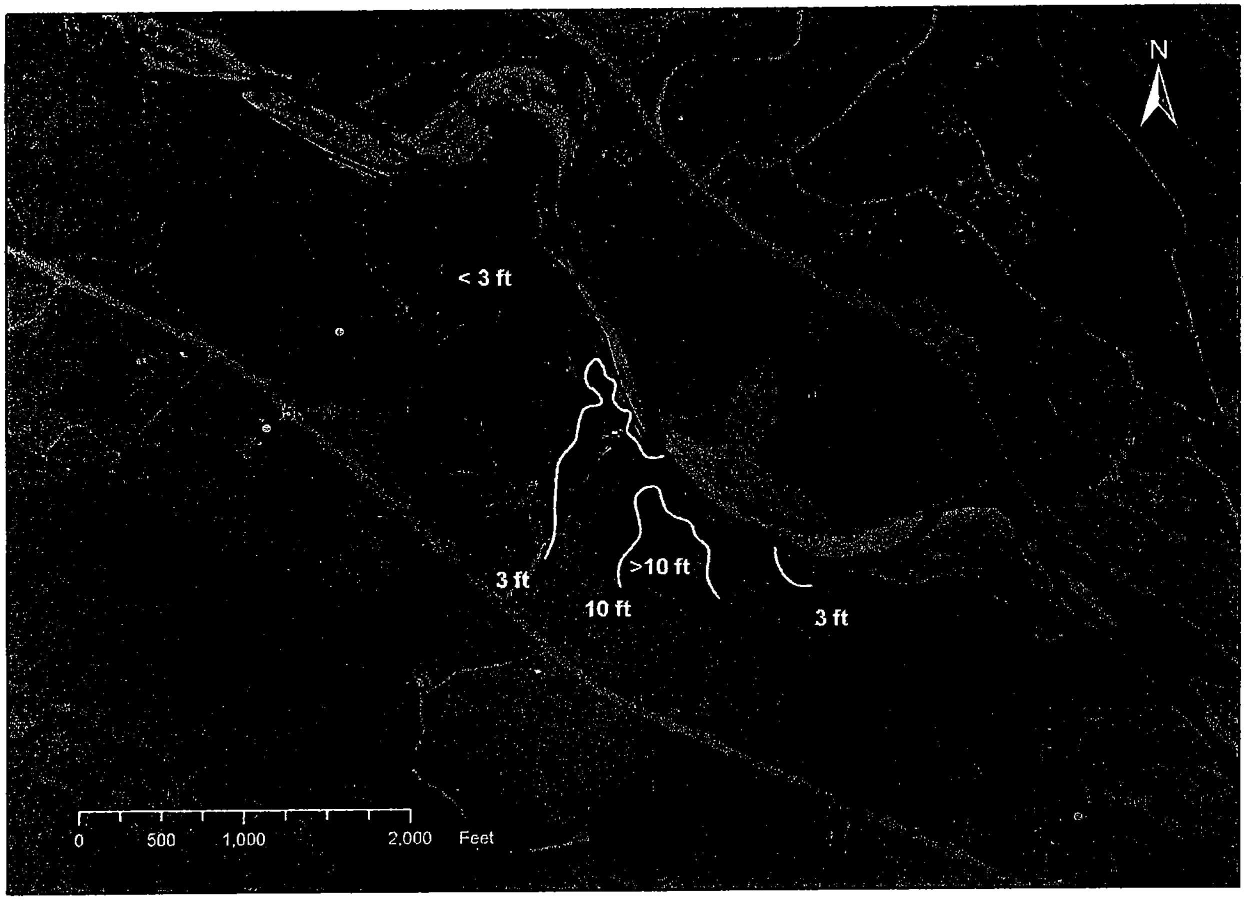


Figure 10. Side channel of the Methow River at Fawn Creek with estimated depth to ground-water. Digital orthophoto source: U.S. Forest Service, 1998b.

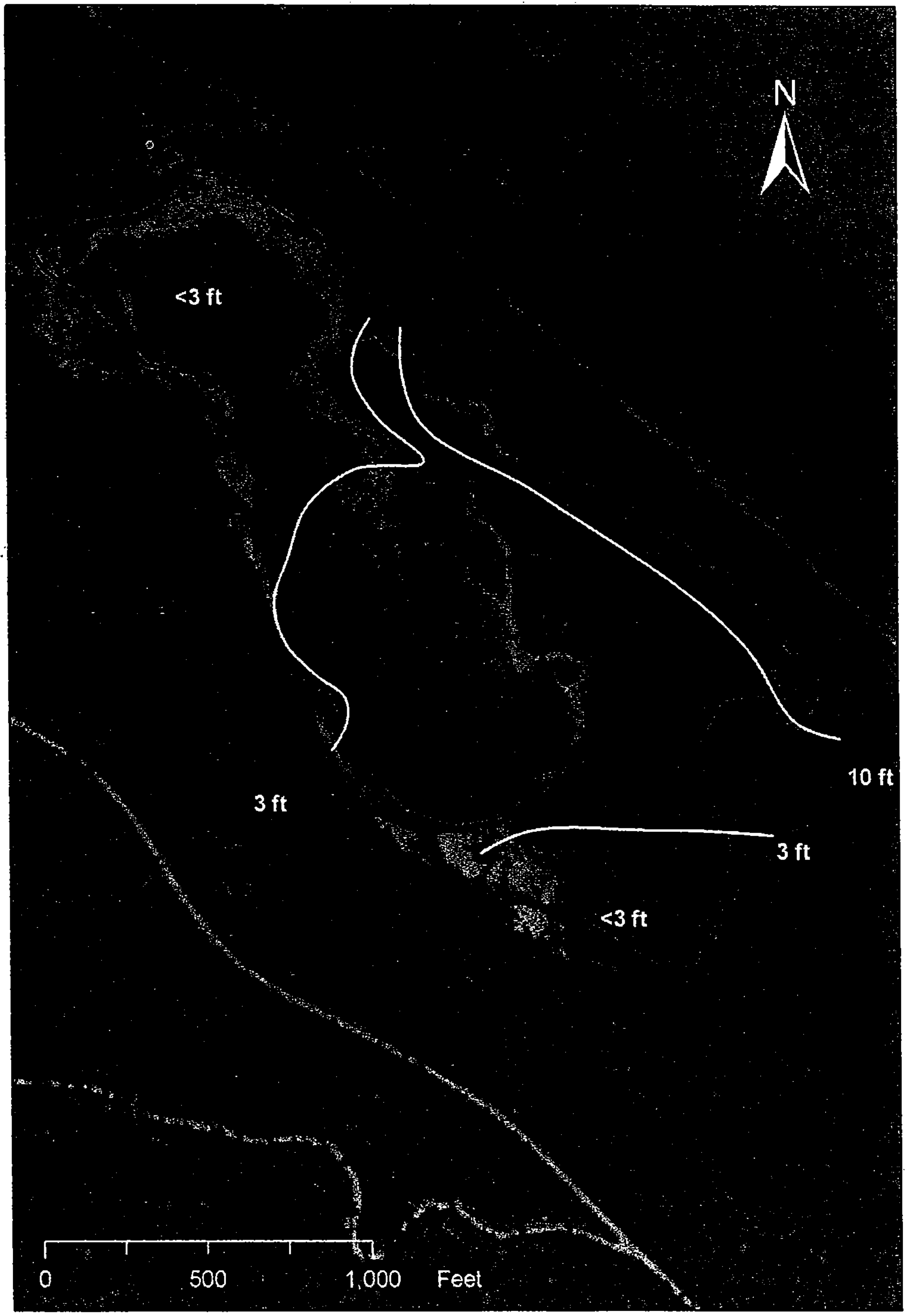


Figure 11. Side channel of the Twisp River at War Creek with estimated depth to ground water. Digital orthophoto source: U.S. Forest Service, 1998c.

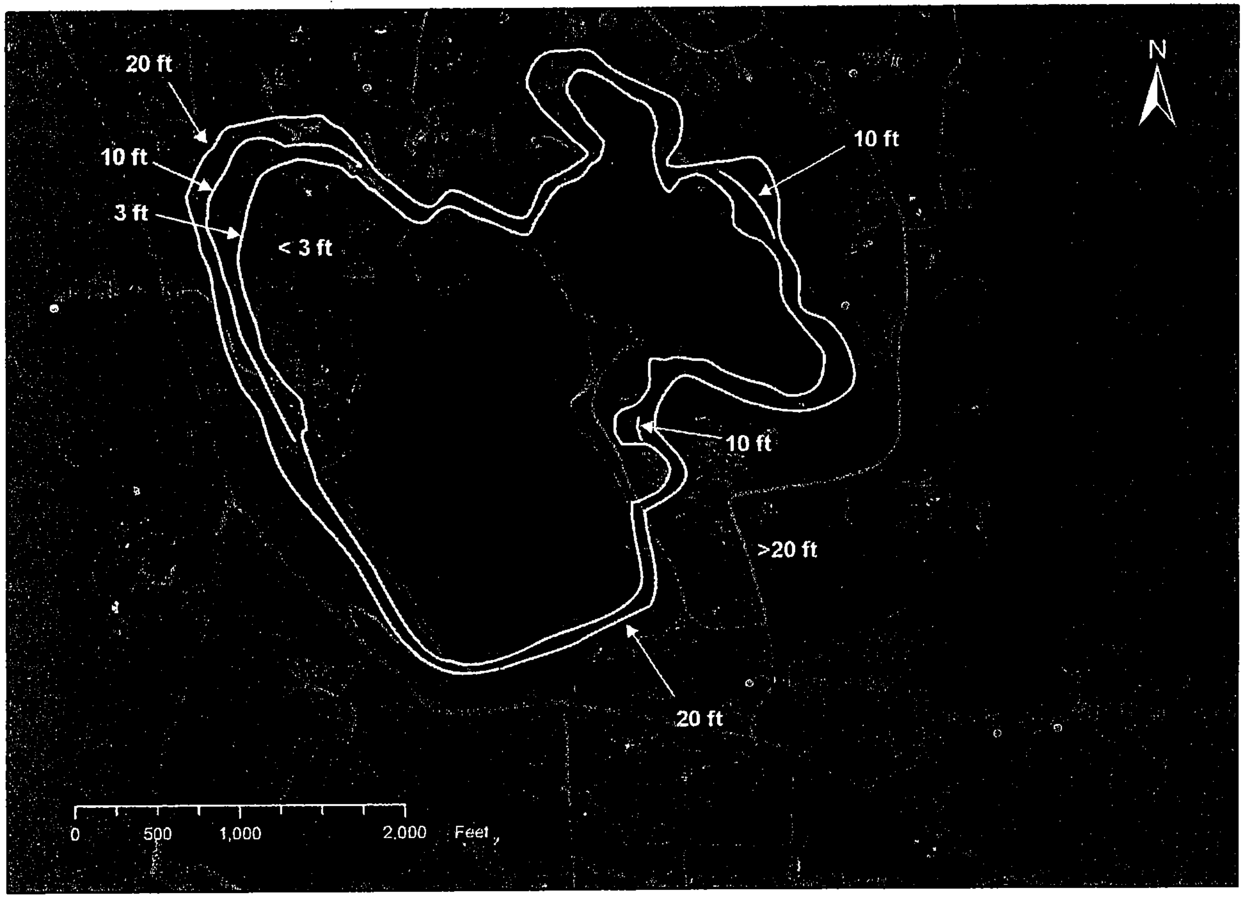


Figure 12. Big Twin Lake, Winthrop with estimated depth to ground water. Digital orthophoto source: U.S. Forest Service, 1998d.

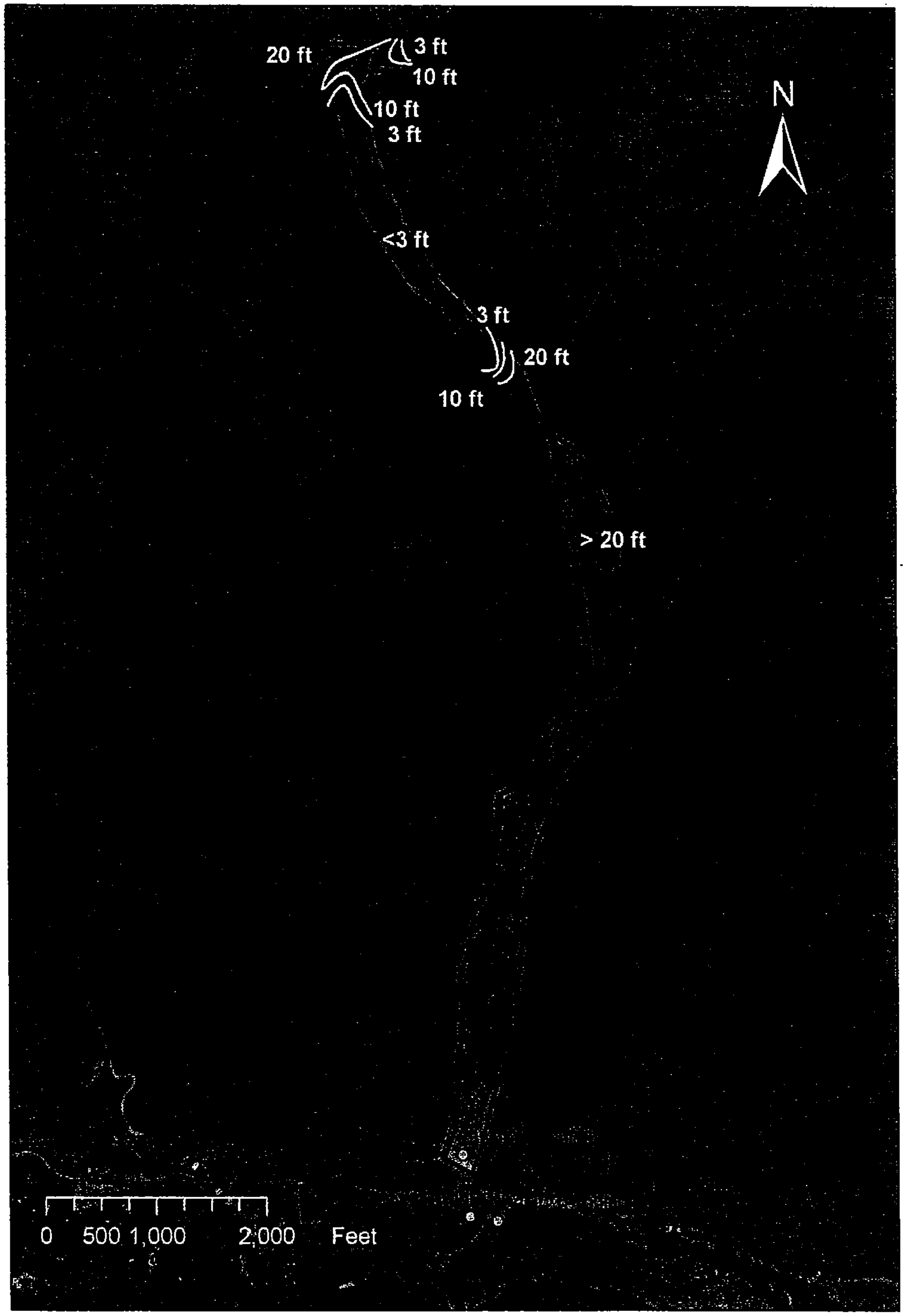


Figure 13. Elbow Coulee, Twisp River with estimated depth to ground water. Digital orthophoto source: U.S. Forest Service, 1998d.

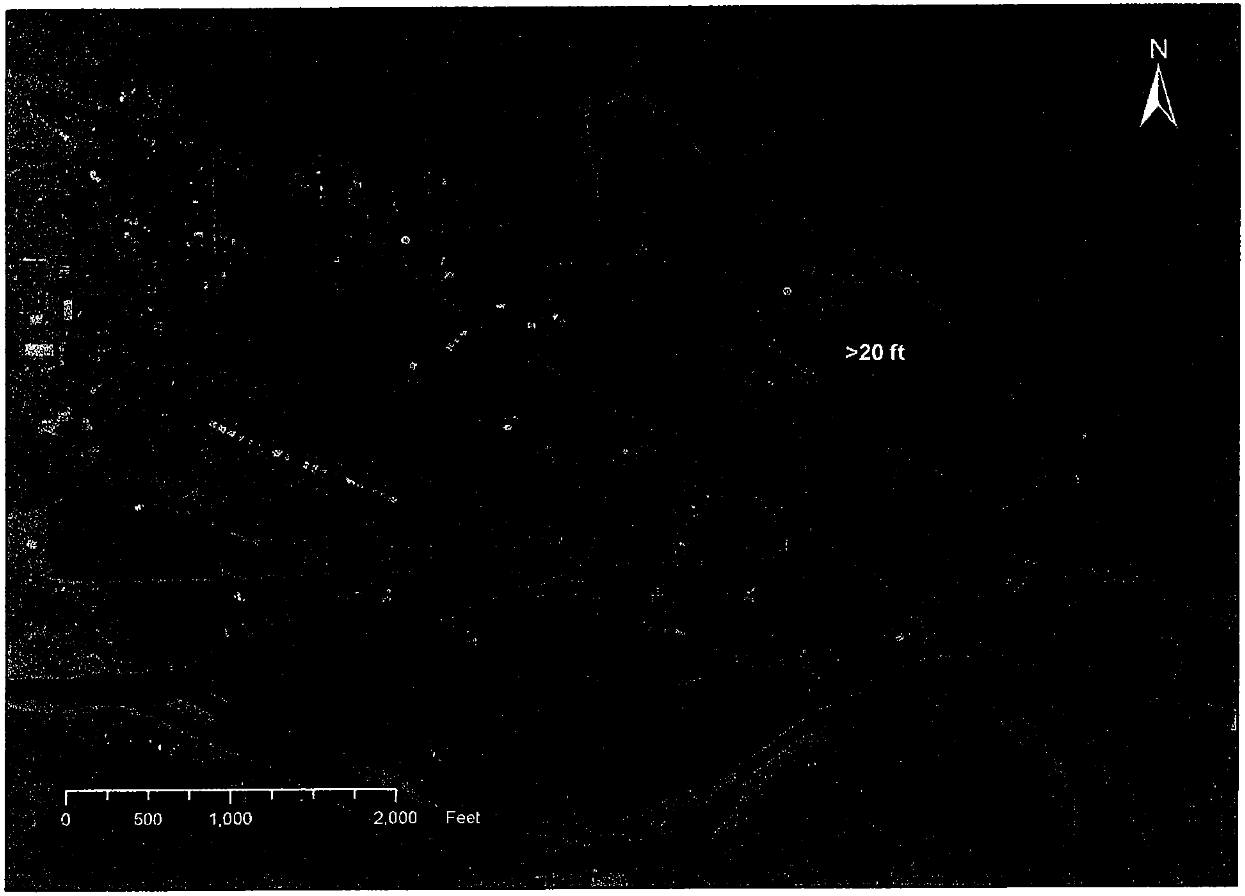


Figure 14. Terrace southeast of Twisp, Methow River above Beaver Creek with estimated depth to ground water. Digital orthophoto source: U.S. Forest Service, 1998e.

Table 20. Measurements of discharge from irrigation canals in the Methow River Basin, Okanogan County, Washington, June 2001 and May-July 2002

[**Latitude and longitude**: Latitude and longitude at station, in degrees, minutes, and seconds referenced to NAD27]

Description of discharge measurement location	Latitude	Longitude	Township Range	Section	Quarter-quarter section	Date	Discharge (ft^3/s)
Batie Canal							
50 feet downstream from fish screen, 4.2 miles northeast of Twisp	48 23 49.0	120 02 38.0	T34N R22E	35	SW SE	05-09-02	3.1
0.35 mile downstream from diversion	48 23 38.0	120 02 42.5	T33N R22E	2	NW NE	05-09-02	2.9
0.4 mile downstream from diversion	48 23 54.4	120 02 44.8	T33N R22E	2	NW NE	05-09-02	2.3
0.8 mile downstream from diversion	48 23 19.3	120 02 40.7	T33N R22E	2	NW NE	05-09-02	2.6
30 feet downstream from #4	48 23 17.6	120 02 40.8	T33N R22E	2	NW NE	05-09-02	1.9
1.05 miles downstream from diversion	48 23 01.8	120 02 39.1	T33N R22E	2	SE SW	05-09-02	1.8
150 feet downstream from # 6	48 23 00.9	120 02 40.0	T33N R22E	2	SE SW	05-09-02	1.5
End of diversion, 850 feet downstream of # 7	48 22 54.0	120 02 33.5	T33N R22E	2	SE SW	05-09-02	1.2
Chewuch Canal							
50 feet downstream from headgate, 6.2 miles north of Winthrop	48 34 0.6	120 10 36.8	T35N R21E	2	NW NE	06-20-01	41.9
						05-08-02	25.3
						07-16-02	27.9
0.3 mile upstream from Ramsey Creek, on East Chewuch Road	48 33 39.6	120 10 31.7	T35N R21E	2	SE SW	06-20-01	41.0
						05-08-02	24.7
						07-16-02	29.6
0.2 mile downstream from Ramsey Creek, on East Chewuch Road	48 33 13.3	120 10 46.4	T35N R21E	11	NW NW	06-14-01	36.4
						05-08-02	22.0
						07-16-02	26.0
Downstream from culvert on East Chewuch Road, 3.6 miles north of Winthrop	48 31 43.7	120 10 45	T35N R21E	14	SW SE	06-20-01	31.7
						05-08-02	20.0
						07-16-02	23.8
On Red Dog Road, 10 feet upstream from siphons	48 30 56.3	120 10 50.4	T35N R21E	23	SW SW	06-20-01	28.7
						05-08-02	21.7
						07-16-02	21.8
On Red Dog Road, 10 feet downstream from siphons	48 30 55.1	120 10 49.3	T35N R21E	23	SW SW	05-08-02	19.9
Dempsey Drop, 1.7 miles north of Winthrop	48 30 5.4	120 10 28.5	T35N R21E	26	SE SW	05-08-02	20.4
						07-16-02	20.1
0.1 mile downstream from Lake Creek	48 29 38.8	120 10 36.4	T35N R21E	35	NW NE	06-20-01	22.2
						05-10-02	12.8
						07-16-02	16.8
Downstream from Pearrygin Lake, above Winthrop	48 29 00	120 10 38	T35N R21E	35	SW SE	06-20-01	17.4
						05-10-02	11.8
						07-16-02	15.0
On Eastside Road, 1.0 mile southeast of Winthrop	48 28 00	120 09 50.6	T34N R21E	12	NW NW	06-20-01	14.5
						05-10-02	11.5
						07-16-02	12.8
Upstream from Bear Creek spillway at Boesel Farm, 2.4 miles southeast of Winthrop	48 27 16.7	120 8 40.8	T34N R22E	18	NW NW	05-10-02	8.6
						07-16-02	8.7
Downstream from Bear Creek spillway at Boesel Farm, 2.4 miles southeast of Winthrop	48 27 16.4	120 8 39.7	T34N R22E	18	NW NW	06-20-01	10.1
						05-10-02	4.8
						07-16-02	8.1
0.6 mile downstream from Bear Creek, on Eastside Road	48 26 33.3	120 8 38.4	T34N R21E	13	SE SE	06-20-01	8.6
						05-10-02	3.6
						07-16-02	6.7
End of diversion, 1.4 miles downstream from Bear Creek	48 25 53.9	120 08 20.8	T34N R22E	19	NW SW	06-20-01	4.3
						05-10-02	2.0

Table 20. Measurements of discharge from irrigation canals in the Methow River Basin, Okanogan County, Washington, June 2001 and May-July 2002—*Continued*

Description of discharge measurement location	Latitude	Longitude	Township Range	Section	Quarter-quarter section	Date	Discharge (ft^3/s)
Foghorn Canal							
20 feet downstream from headgate, at National Fish Hatchery	48 28 22.2	120 11 24.4	T34N R21E	3	SE NE	05-07-02	24.4
						07-17-02	19.9
0.2 mile downstream from headgate at end of hatchery	48 28 19.5	120 11 11.3	T34N R21E	2	SW SW	07-17-02	18.6
Side lateral off Foghorn Ditch, 0.4 mile downstream from headgate	48 28 12.6	120 10 40.9	T34N R21E	2	SW SE	05-07-02	.6
						07-17-02	1.2
5 feet upstream from siphon, 1.0 mile downstream from headgate on Highway 20, 0.9 mile southeast of Winthrop	48 27 54.0	120 10 23.1	T34N R21E	11	NE NW	05-07-02	20.2
						07-17-02	15.2
5 feet downstream from siphon, 1.0 mile downstream from headgate on Highway 20, 0.9 mile southeast of Winthrop	48 27 53.1	120 10 22.5	T34N R21E	11	NE NW	05-07-02	16.9
						07-17-02	13.3
20 feet upstream from spillway on Highway 20, 0.3 mile upstream from Bear Creek	48 27 07.4	120 09 50.7	T34N R21E	13	NW NW	05-07-02	13.1
						07-17-02	11.1
20 feet downstream from spillway on Highway 20, 0.3 mile upstream from Bear Creek	48 27 03.6	120 09 48.6	T34N R21E	13	NW NW	05-07-02	10.6
						07-17-02	7.9
20 feet upstream from siphon at Twin Lakes Road and Highway 20	48 26 19.6	120 09 49.0	T34N R21E	24	NW NW	05-07-02	8.1
						07-17-02	5.9
20 feet downstream from siphon at Twin Lakes Road and Highway 20	48 26 18.2	120 09 48.7	T34N R21E	24	NW NW	05-07-02	6.3
10 feet upstream from second siphon, 1.0 mile downstream from Bear Creek	48 26 02.3	120 09 46.9	T34N R21E	24	NW SW	05-07-02	4.7
						07-17-02	5.1
20 feet downstream from second siphon, 1.0 mile downstream from Bear Creek	48 26 03.3	120 09 47.8	T34N R21E	24	NW SW	07-05-02	4.0
						07-17-02	4.2
End of diversion at Methodist Church	48 25 18.0	120 09 13.9	T34N R21E	25	NW NE	07-05-02	1.5
						07-17-02	1.4
Fulton Canal							
30 feet downstream from headgate, 0.4 mile north of Winthrop	48 28 58.6	120 10 54.6	T34N R21E	2	NW NW	06-19-01	16.2
						05-09-02	15.3
						07-18-02	17.5
0.21 mile downstream from headgate, upstream from siphon	48 28 57.5	120 11 10.5	T34N R21E	2	NW NW	06-19-01	14.5
						05-09-02	15.7
						07-18-02	17.3
Duck Brand Inn at Winthrop	48 28 38.3	120 10 56.5	T34N R21E	2	NW SW	06-19-01	13.6
						05-09-02	11.4
						07-18-02	12.7
At intersection of Washington Street and Castle Avenue in Winthrop	48 28 20.6	120 10 24.4	T34N R21E	2	SE SW	06-19-01	13.9
						05-09-02	11.8
						07-18-02	10.9
On Eastside Road, 1.0 mile southeast of Winthrop	48 27 51	120 09 50	T34N R21E	12	NW NW	06-19-01	11.2
						05-09-02	11.3
						07-18-02	11.4
0.4 mile upstream from Bear Creek	48 27 18.4	120 09 17.9	T34N R21E	12	SW SE	07-18-02	9.0
Upstream from spillway at Bear Creek Road	48 27 10.0	120 9 18.6	T34N R21E	13	NW NE	05-09-02	8.7
						07-18-02	6.3
Downstream from spillway at Bear Creek Road	48 27 10.0	120 9 18.6	T34N R21E	13	NW NE	06-19-01	5.9
						05-09-02	6.8
						07-18-02	4.6
At downstream weir, 0.5 mile downstream of Bear Creek	48 26 31.5	120 09 08.4	T34N R21E	13	SE SW	06-19-01	4.4
						05-09-02	5.9
						07-18-02	2.3

Table 20. Measurements of discharge from irrigation canals in the Methow River Basin, Okanogan County, Washington, June 2001 and May-July 2002—*Continued*

Description of discharge measurement location	Latitude	Longitude	Township Range	Section	Quarter-quarter section	Date	Discharge (ft^3/s)
Red Shirt Canal							
300 feet downstream from headgate, 3.6 miles northeast of Twisp	48 22 53.9	120 02 48.7	T33N R22E	2	SW SE	05-09-02	1.0
Upstream from Beaver Creek Road	48 22 42.8	120 02 36.3	T33N R22E	11	NE NW	05-09-02	.4
End of ditch	48 22 26.9	120 02 16.8	T33N R22E	11	NE SE	05-09-02	.5
Skyline Canal							
50 feet downstream from pipe, 3.4 miles north of Winthrop	48 31 37.8	120 11 26.6	T35N R21E	15	SE SW	05-10-02	5.8
						07-15-02	4.7
0.64 mile downstream from pipe	48 31 03.0	120 11 29.7	T35N R21E	22	SE NW	05-10-02	3.9
						07-15-02	3.0
End of unlined section, 0.9 mile downstream from pipe	48 28 22.2	120 11 24.4	T35N R21E	22	SE SW	05-10-02	2.8
						07-15-02	2.1
Stokes Canal							
Downstream from headgate, 3.7 miles northeast of Twisp	48 22 48.1	120 02 50.0	T33N R22E	2	SW SE	05-09-02	1.6
0.3 mile downstream of headgate	48 22 36.7	120 02 49.3	T33N R22E	11	NW SE	05-09-02	1.3
30 feet upstream from pipe	48 22 29.0	120 02 43.6	T33N R22E	11	NW SE	05-09-02	.9
Eight Mile Canal							
110 feet downstream of culvert	48 36 16	120 10 09	T36N R21E	23	SE NW	06-18-01	4.1
Upstream of 8 Mile Ranch turn-in	48 35 55	120 10 02	T36N R21E	26	NE NE	06-18-01	2.3
Foster Canal							
20 feet downstream of flume	48 35 09	120 22 30	T36N R20E	29	SW SE	06-18-01	4.8
200 feet -250 feet upstream of lake	48 35 02	120 23 13	T36N R20E	31	NE NW	06-18-01	3.7
McKinney Mtn Canal							
Below screen	48 33 16	120 20 51	T35N R20E	9	NE NW	06-21-01	2.3
End of dredged section	48 33 15	120 20 48	T35N R20E	9	NE NW	06-21-01	1.0
Near Highway 20	48 33 10	120 20 47	T35N R20E	9	SE SW	06-21-01	.7
Rockview Canal							
Below screen	48 32 22	120 19 03	T35N R20E	14	NW NW	06-20-01	9.0
Above turnout	48 32 15	120 18 47	T35N R20E	14	NW NW	06-20-01	7.6
Below turnout	48 31 58	120 18 19	T35N R20E	14	SE NW	06-20-01	5.4
Downstream point in hay field	48 31 46	120 17 45	T35N R20E	14	SE SE	06-20-01	5.4

Table 21. Measured seepage rates from irrigation canals in the Methow River Basin, Okanogan County, Washington

[**Total measured loss rate**: Mean values in bold for canals where multiple seepage runs were made]

Irrigation canal	Length of canal (miles)	Total measured loss rate (cubic feet per second)		Seepage rate (cubic feet per second per mile)	
		May to August	September to October	May to August	September to October
Twisp Valley Power and Irrigation Company	3.17	**4.6**	2.5	1.4	0.8
Methow Valley Irrigation District, west	3.13	**3.3**	1.8	1.0	.6
Eightmile	.44	1.8		4.1	
Foster	.56	1.1		2.0	
McKinney Mountain	.15	1.6		10.7	
Rockview	1.25	3.6		2.9	
Chewuch	10.0	**16.2**		1.6	
Fulton	3.23	**4.9**		1.5	
Skyline	1.03	**2.8**		2.7	
Foghorn	4.78	**12.4**		2.6	
Red Shirt	.48	.5		1.0	
Stokes	.62	.7		1.1	
Batie	1.12	1.6		1.4	
Totals	30.0	55.1			
Mean seepage rates				1.8	0.7