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River-Aquifer Exchanges in the Yakima River Basin, Washington

Scientific Investigations Report 2011–5026

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

Cover: Photograph of Clark Well No. 1, located on the north side of the Moxee Valley in North Yakima, Washington. The well is located in township 12 north, range 20 east, section 6. The well was drilled to a depth of 940 feet into an artesian zone of the Ellensburg Formation, and completed in 1897 at a cost of $2,000. The original flow from the well was estimated at about 600 gallons per minute, and was used to irrigate 250 acres in 1900 and supplied water to 8 small ranches with an additional 47 acres of irrigation. (Photograph was taken by E.E. James in 1897, and was printed in 1901 in the U.S. Geological Survey Water-Supply and Irrigation Paper 55.)

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By J.J. Vaccaro

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KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2011

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
inch per day (in/d)	0.0254	meter per day (m/d)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8\times°C)+32$$

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Conversion Factors, Datums, and Abbreviations and Acronyms—Continued

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Altitude, as used in this report, refers to distance above the vertical datum.

Abbreviations and Acronyms

BCD	Benton Conservation District
BLM	Bureau of Land Management
CRBG	Columbia River Basalt Group
CTD	conductivity-temperature depth probe
DTW	depth-to-water
ESA	Endangered Species Act
FLBL	Flathead Lake Biological Laboratory
GDE	groundwater-dependent ecosystem
GMWL	Global Meteoric Water Line
GPS	Global Positioning System
RM	river mile
Reclamation	Bureau of Reclamation
SOAC	Systems Operations Advisory Committee
SWA	Status Wildlife Area
TIR	thermal infrared
TU	tritium unit
TWSA	total water supply available
USGS	U.S. Geological Survey
VHG	vertical hydraulic gradient
WaDOE	Washington State Department of Ecology
WIP	Wapato Irrigation Project
YN	Yakama Nation

Well-Numbering System

The USGS assigns numbers to wells and springs in Washington that identify their location in a township, range, and section. Well number 20N/15E-26N01 indicates, successively, the township (T.20 N.) and the range (R.15 E.) north and east of the Willamette baseline and meridian. The first number following the hyphen indicates the section (26) within the township and the letter following the section number (N) gives the 40-acre subdivision within the section. The number (01) following the letter is the sequence number of the well within the 40-acre subdivision. An 'S' following the sequence number indicates that the site is a spring, a 'D1' after the sequence number indicates that the original reported depth of the well has been changed once and successive numbers indicate the number of changes in the well depth. An 'R' following the sequence number indicates the well has been reconditioned. A 'P1' or an 'A' after the sequence number indicates a group of nested piezometers, with successive numbers or letters assigned to each piezometer in the group. In the illustrations of this report, wells are identified individually by only the section and 40-acre tract, such as 34F02; township and range are shown on the map borders or are referenced to sequential numbers in a table.

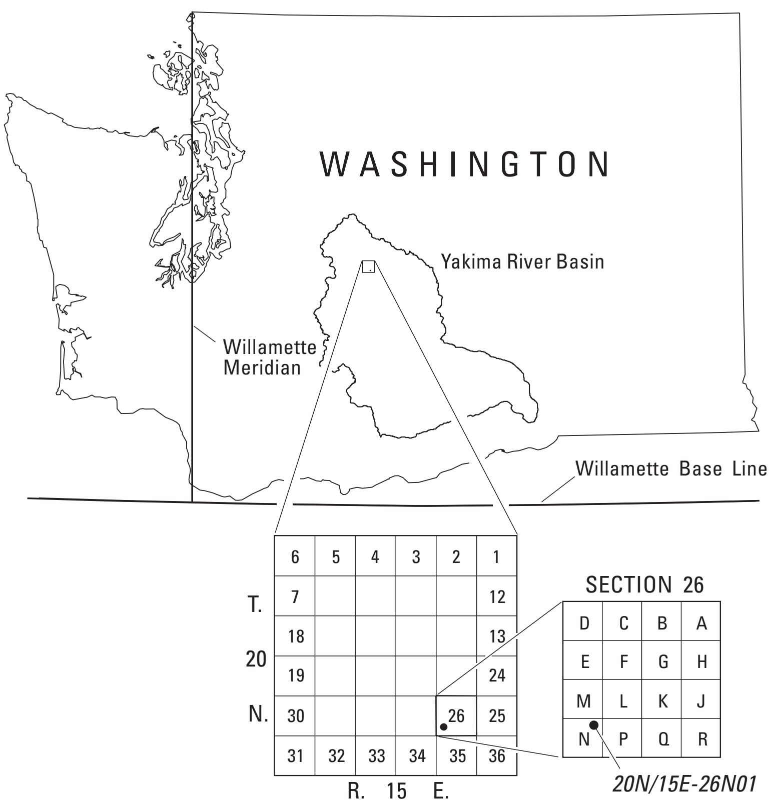


Diagram of well numbering system in the State of Washington.

River-Aquifer Exchanges in the Yakima River Basin, Washington

By J.J. Vaccaro

Abstract

Five categories of data are analyzed to enhance understanding of river-aquifer exchanges—the processes by which water moves between stream channels and the adjacent groundwater system—in the Yakima River basin. The five datasets include (1) results of chemical analyses of water for tritium (^{3}H, a radioactive isotope of hydrogen) and the ratios of the stable isotopes of hydrogen ($^{2}H/^{1}H$) and oxygen ($^{18}O/^{16}O$), (2) series of stream discharge measurements within specified reaches (seepage investigations or "runs"), (3) vertical hydraulic gradients (between stream stage and hydraulic heads the underlying aquifer) measured using mini-piezometers, (4) groundwater levels and water temperature in shallow wells near stream channels, and (5) thermal profiles (continuous records of water temperature along river reaches). Exchanges are described in terms of streamflow, vertical hydraulic gradients, groundwater temperature and levels, and streamflow temperature, and where appropriate, the exchanges are discussed in terms of their relevance to and influence on salmonid habitat.

The isotope data shows that the ultimate source of surface and groundwater is meteoric water derived from atmospheric precipitation. Water from deep wells has a different isotopic composition than either shallow groundwater or surface water, indicating that the deep groundwater system contributes, at most, only a small component of the surface-water discharge. The isotope data confirms that river-aquifer exchanges involve primarily modern streamflow and modern, shallow groundwater.

Net exchanges of water for 46 stream sections investigated with seepage runs ranged from nearly zero to 1,071 ft^3/s for 28 gaining sections, and -3 to -242 ft^3/s for 18 losing sections. The magnitude of the upper 50 percent of the net gains is an order of magnitude larger than those for net losses. The sections have a normalized net exchange (as absolute value) that fully ranged from near 0 to 65.6 $(ft^3/s)/mi$. Gaining-section values ranged from about 0.1 to 65.6 $(ft^3/s)/mi$, and losing section values ranged from about -0.1 to -35.4 $(ft^3/s)/mi$. Gains are much more vigorous than the losses with 55 percent being larger than 3.0 $(ft^3/s)/mi$, whereas, only 6 percent of the negative net exchanges were larger than 3.0 $(ft^3/s)/mi$. Gains and losses for 167 measured reaches within the 46 sections ranged from about 70 to -75 $(ft^3/s)/mi$, and ranged more than 5 orders of magnitude. The median values for the gains and losses were 5.1 and -4.4 $(ft^3/s)/mi$, respectively. The magnitude of the gains was larger than the losses; more than 40 percent of the gains were greater than 10 $(ft^3/s)/mi$, and only about 25 percent of the losses were greater than 10 $(ft^3/s)/mi$. Reaches with large gains are identified and these reaches represent potentially important areas for various life stages of salmonids and possibly for preservation or restoration of that habitat.

Ninety-nine measurements of vertical hydraulic gradients (VHGs) were made using mini-piezometers. The median for the measurements was -0.35 ft/ft (negative values indicate downward flow), and in terms of absolute values, the median was 0.05 ft/ft. The VHGs tended to be small. Seventy VHG values were negative (indicating streamflow losses), and 29 were positive (indicating streamflow gains). VHGs vary more than 4 orders of magnitude, and in terms of magnitudes, 65 percent were less than 0.1 ft/ft. The negative VHG values are not only more prevalent but are larger than the positive values. The magnitudes of almost 50 percent of the negative VHGs are greater than 0.05 ft/ft and only 33 percent of the positive VHGs are greater than 0.05 ft/ft. The percentile distribution of the VHG data, which is similar to the shape of the seepage data distribution, shows that beyond the 80th percentile, the positive values become much larger, indicating that the largest VHGs have a different controlling mechanism. The VHGs were formulated in terms of fluxes per unit area and the negative VHGs ranged from 0.005 to 24 in/d and 96 percent are less than 3 in/d. These fluxes are determined to be "reasonable," and river losses could support such values. Fluxes per unit area for the 29 positive VHGs ranged from 0.01 to 19.3 in/d, and 86 percent are less than 2.3 in/d. Formulating the values in terms of normalized discharge $[(ft^3/s)/mi]$ and comparing these values to the seepage data shows that the very large positive VHGs are not the controlling factor for exchanges and that other mechanisms, such as lateral inflow (groundwater discharge is not vertical), dominate the hydrologic exchange process.

Data from the near bank and flood plain monitoring sites display highly variable characteristics that reflect complex relations between groundwater levels and temperature, and water quality of the shallow system and streamflow,

surface-water bodies, the flow in alluvial aquifers, and irrigation. In many cases, groundwater levels mimic river stage at both gaining and losing sites and show the effects of river-stage pressure on the shallow groundwater flow system. These effects may raise groundwater levels to the extent they intercept the land surface in depressions and sloughs. Groundwater temperature thermographs can be clearly delineated by the magnitude of the annual amplitude as to whether they are surface-water or groundwater dominated. Amplitudes are as large as 16°C and as small as 1°C, and depending on the physical setting and type of climatic year, the annual maximum temperature of groundwater lagged that of streamflow by less than a month to more than two months. At sites with streamflow losses, temperature effects in shallow groundwater are attenuated in as little as 50 ft from the river. The temperature data show that bank storage is not as important as wetting-up side channel and sloughs for supplying cool water to the shallow groundwater system. The magnitude of streamflow is an important control on exchanges, with rain-on-snow runoff events being more important than the seasonal spring runoff because the former can produce higher discharges than the latter. Groundwater levels and temperatures differ distinctively between wet and dry years, and the differences show the importance of the type of year on exchanges throughout the Yakima River basin. The increased releases from the Naches River arm reservoirs beginning in September resulted in detectable changes in both groundwater temperature and levels downstream of the reservoirs. Vertical variations of water levels, temperature, and water quality in the shallow system occur over distances as small as 10 ft.

The longitudinal temperature gradient of the water in 16 reaches within some 160 river miles were recorded in thermal profiles. Reaches ranged in length from about 5 to 14 mi, and stream gradient ranged from 0.0002 to 0.0055 ft/ft. The profiles exhibit inter- and intra-profile variations that integrate the factors controlling the temperature of a parcel of water as it moves downstream. Such longitudinal variations previously had not been documented in a riverine system. Thermal gradients range from as small as 0.00002 to as large as 0.004°C per mile per minute, and unexpectedly, the smaller gradients are not confined to the upper parts of the basin. Effects of river-aquifer exchanges and surface-water inflows are clearly displayed in the profiles. The profiles document the riverine systems' temperature templet or longitudinal (environmental) gradient that defines a physical habitat templet, which provides for the overall biological community templet, including the different life stages and life history patterns of salmonids. The templet leads to a logical progression of the longitudinal gradient of fish assemblages, and invertebrate and algal community structure. The longitudinal gradient, overlaid with the distribution of temperature patches, compose a continuum from the headwaters to the mouth, along which habitat, and thus, species, are arranged.

Introduction

Surface water in the Yakima River basin in south-central Washington (fig. 1) is under adjudication. The amount of surface water available for appropriation is unknown, but there are increasing demands for water for municipal, fisheries, agricultural, industrial, and recreational uses. These demands must be met by groundwater withdrawals and (or) by changes in the way water resources are allocated and used. On-going activities in the basin for enhancement of fisheries and obtaining additional water for agriculture may be affected by groundwater withdrawals and by rules implemented under the Endangered Species Act for salmonids that have been either listed or were proposed for listing in the late 1990s. An integrated understanding of the groundwater flow system and its relation to the surface-water resources is needed in order to implement most water-resources management strategies in the basin. In order to gain this understanding, a study of the Yakima River basin aquifer system began in June 2000. The study is a cooperative effort of the U.S. Geological Survey (USGS), Bureau of Reclamation (Reclamation), the Yakama Nation (YN), and the Washington State Department of Ecology (WaDOE).

The overall objectives of the study are to describe the groundwater flow system and its interaction with and relation to surface water, and to provide baseline information for a management tool—a numerical model of the system. The conceptual model of the flow system and the results of the study can be used to guide and support actions that may be taken by management agencies with respect to groundwater availability and to provide information to other stakeholders and interested parties. The numerical model is being developed as an integrated tool to assess short-term to long-term management activities, including the testing of the potential effects of alternative management strategies for water development and use.

The study includes three phases. The first phase includes (1) project planning and coordination, (2) compiling, documenting, and assessing available data, and (3) initial data collection. The second phase consists of data collection to support the following Phase 2 work elements: (1) mapping hydrogeologic units, (2) estimating groundwater pumpage, (3) developing estimates of groundwater recharge, (4) assessing groundwater-surface water interchanges, and (5) constructing maps of groundwater levels. Together, these five elements provide the information needed to describe the groundwater flow system, develop the conceptual model, and provide the building blocks for the hydrogeologic framework. In the third phase, a regional-scale numerical model of the groundwater flow system will be constructed in order to integrate the available information. The numerical model will be used to enhance understanding of the flow system (including a water budget for the aquifer system) and its relation to surface water, and to test the potential effects of alternative management strategies.

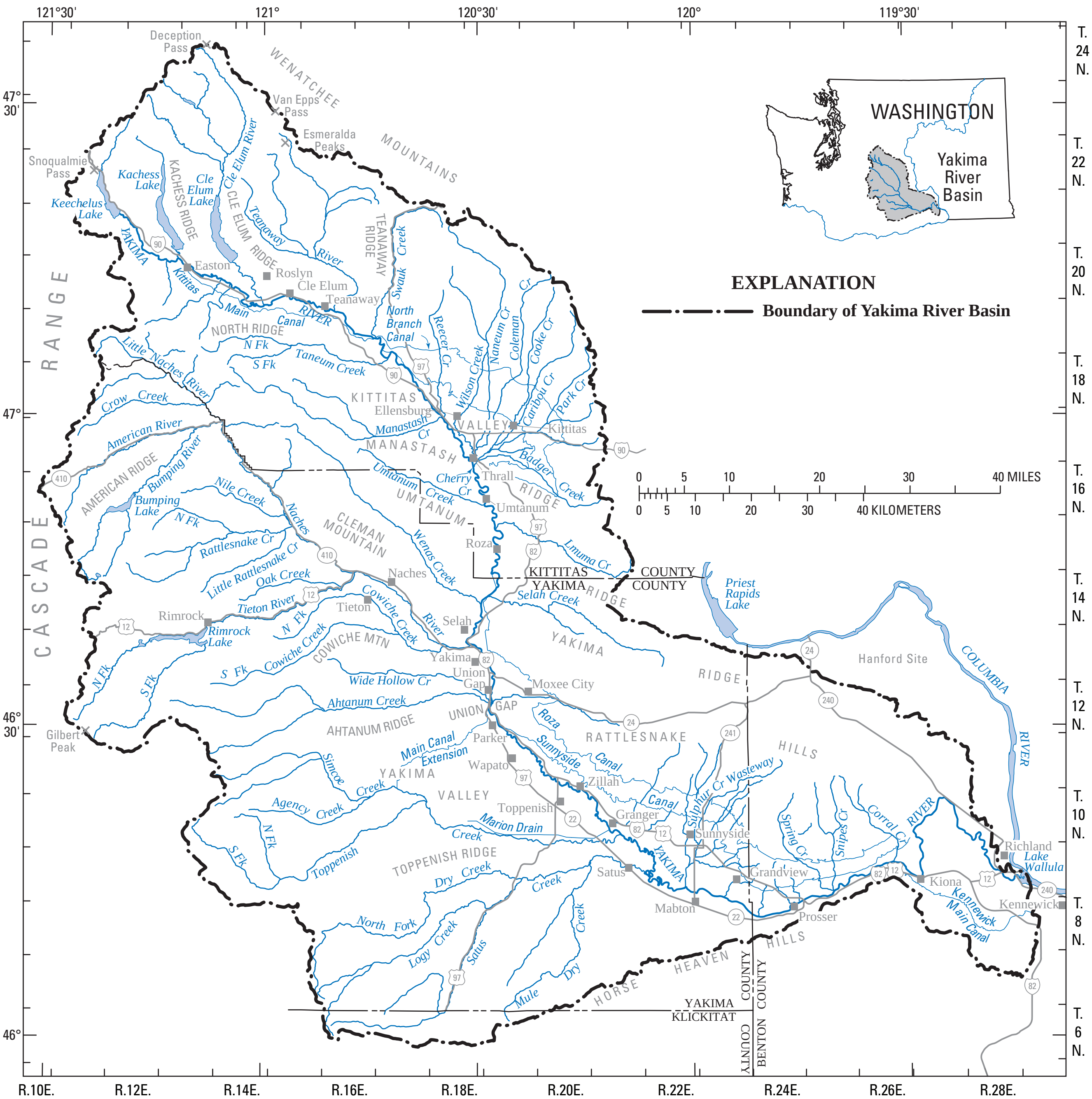


Figure 1. Yakima River basin, Washington.

The results of selected work elements of this study have been described in a series of reports: (Jones and others, 2006; Vaccaro and Maloy, 2006; Vaccaro and Sumioka, 2006; Vaccaro, 2007; Vaccaro and Olsen, 2007a, b; Jones and Vaccaro, 2008; Keys and others, 2008; Vaccaro and others, 2008; Vaccaro and others, 2009).

This report describes river-aquifer exchanges Yakima River basin. River-aquifer exchanges are important for understanding the potential effects of pumpage on groundwater discharge to streams and on the health of the aquatic ecosystem. These exchanges vary temporally and by physical setting and are more prevalent along stream reaches with an active flood plain.

Purpose and Scope

The purpose of this report is to improve the understanding of river-aquifer exchanges in the Yakima River basin. Exchanges in this report do not include hyporheic flow, which occurs ‘at the level of channel forms’ (Cardenas and others, 2004), because the exchanges described represent much longer flow-path lengths and a large magnitude of the net flow between a river and an aquifer. The report presents an analysis of exchanges along the flood plain based on data collected during this study and information collected and (or) described by others. The information is described in terms of streamflow, vertical hydraulic gradients, groundwater temperature and levels, and streamflow temperature. Where appropriate, the exchanges are discussed in terms of salmonid habitat. The data and information on which the discussions are based include isotopic composition of groundwater and streamflow; results of seepage investigations, which consist of a series of discharge measurements made at selected sites within a given reach or segment of a stream; hydraulic heads in the streambed and streams using mini-piezometers,; groundwater levels and temperature in shallow wells; and longitudinal profiles of streamflow temperature along reaches (thermal profiles).

Description of the Study Area

The location and setting of the Yakima River basin, a summary of the development of water resources in the basin, and an overview of the geology are presented to provide a general background for understanding the study area.

Location and Setting

The Yakima River basin encompasses about 6,200 mi^2 in south-central Washington (fig. 1). The basin produces a mean annual unregulated streamflow (adjusted for regulation and without diversions or returns) of about 5,600 ft^3/s (4.1 million acre-ft or about 0.9 [(ft^3/s)/mi^2]) and a regulated streamflow of about 3,600 ft^3/s (2.6 million acre-ft or about 0.6 [(ft^3/s)/ mi^2]). The basin includes three Washington State Water Resource Inventory Areas (WRIAs 37, 38, and 39), part of the Yakama Nation lands, and spans parts of three ecoregions (Cascades, Eastern Cascades, and Columbia Basin—Omernik, 1987; Cuffney and others, 1997). Almost all of Yakima County, more than 80 percent of Kittitas County, and about 50 percent of Benton County are in the basin. Less than 1 percent of the basin, principally an unpopulated upland area, lies within Klickitat County.

The headwaters of the basin are on the upper, humid eastern slope of the Cascade Range, where mean annual precipitation is more than 120 in. The basin terminates at the confluence of the Yakima and Columbia Rivers in a low-lying, arid area that receives about 6 in. of precipitation per year. Altitudes in the basin range from 400 to nearly 8,000 ft. Eight major rivers and numerous smaller streams are tributary to the Yakima River (fig. 1), the largest of which is the Naches River. Most of the precipitation in the basin falls during the winter months as snow in the mountains. The mean annual precipitation over the entire basin is about 27 in. (about 12,300 ft^3/s or 8.9 million acre-ft). The spatial pattern of mean annual precipitation resembles the pattern of the basin’s highly variable topography. The difference between the mean annual precipitation and mean annual unregulated streamflow is 6,700 ft^3/s (about 4.8 million acre-ft). On the basis of this difference and the simplifying assumptions of only small net groundwater inflow to or outflow from the basin and negligible changes in groundwater storage within the basin, about 55 percent of the precipitation is consumed by evapotranspiration under natural conditions.

The basin is separated into several broad valleys by east-west trending anticlinal ridges. The valley floors slope gently towards the Yakima River. Few perennial tributary streams traverse these valleys. Most of the population and economic activity occurs in these valleys.

Irrigated agriculture is the principal economic activity in the Yakima River basin. The average annual surface-water demand met by Reclamation’s Yakima Project is about 2.5 million acre-ft; an additional 336,000 acre-ft of demand in the lower part of the basin is separate from the demand met by the Project. Additional surface-water demand that is not met by Reclamation occurs in smaller tributaries and on the large rivers; this demand is based on State appropriated water. More than 95 percent of the surface-water demand is for irrigation of about 500,000 acres in the low-lying semiarid to arid parts of the basin (fig. 2). The demand is partly met by storage of nearly 1.1 million acre-ft of water in five Reclamation reservoirs. The major management point for Reclamation is the streamflow gaging station at the Yakima River near Parker at river mile 103.7 (USGS station number 12505000, fig. 3); this site is just below the Sunnyside and Wapato (main) canal diversions. Just upstream of this site, at about river mile 106.8, is the location that is considered the dividing line between the upper (mean annual precipitation of 7 to 145 in.) and lower (mean annual precipitation of 6 to 45 in.) parts of the Yakima

River basin. About 45 percent of the water diverted for irrigation is eventually returned to the river system as surface-water inflows and groundwater discharge, but at varying time-lags (Bureau of Reclamation, 1999). During low-flow periods, these return flows account, on average, for about 75 percent of the streamflow below the gaging station near Parker. Most of the surface-water demand in the basin below Parker is met by these return flows and not by the release of water from the reservoirs. As a result of water use in the basin, the difference between mean annual unregulated (5,600 ft^3/s) and regulated (3,600 ft^3/s) streamflow is about 2,000 ft^3/s, suggesting that some 1.4 million acre-ft of water, or about 17 percent of the precipitation in the basin, is consumptively used—principally through evapotranspiration from irrigated crops.

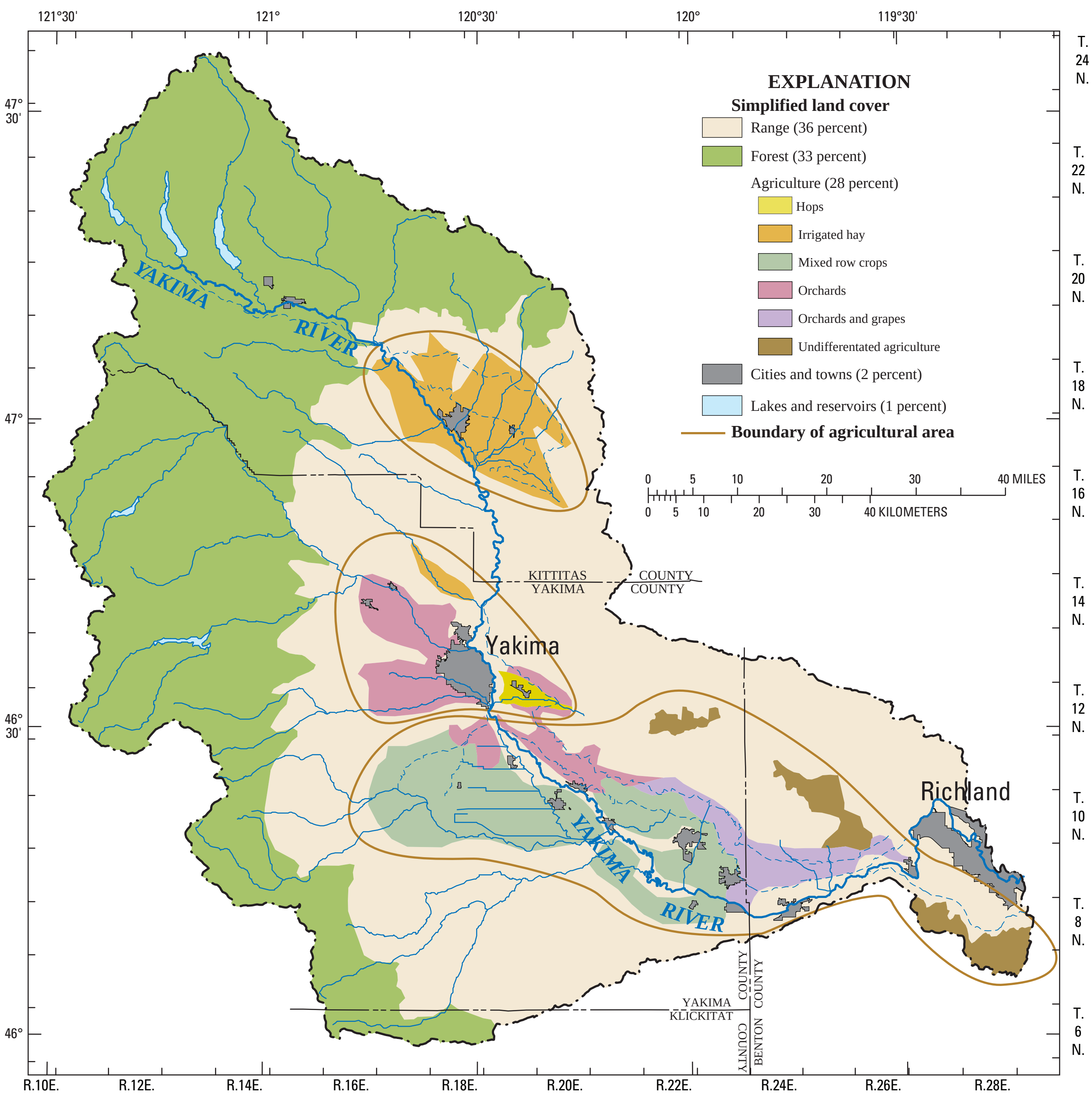


Figure 2. Land use and land cover, Yakima River basin, Washington, 1999.

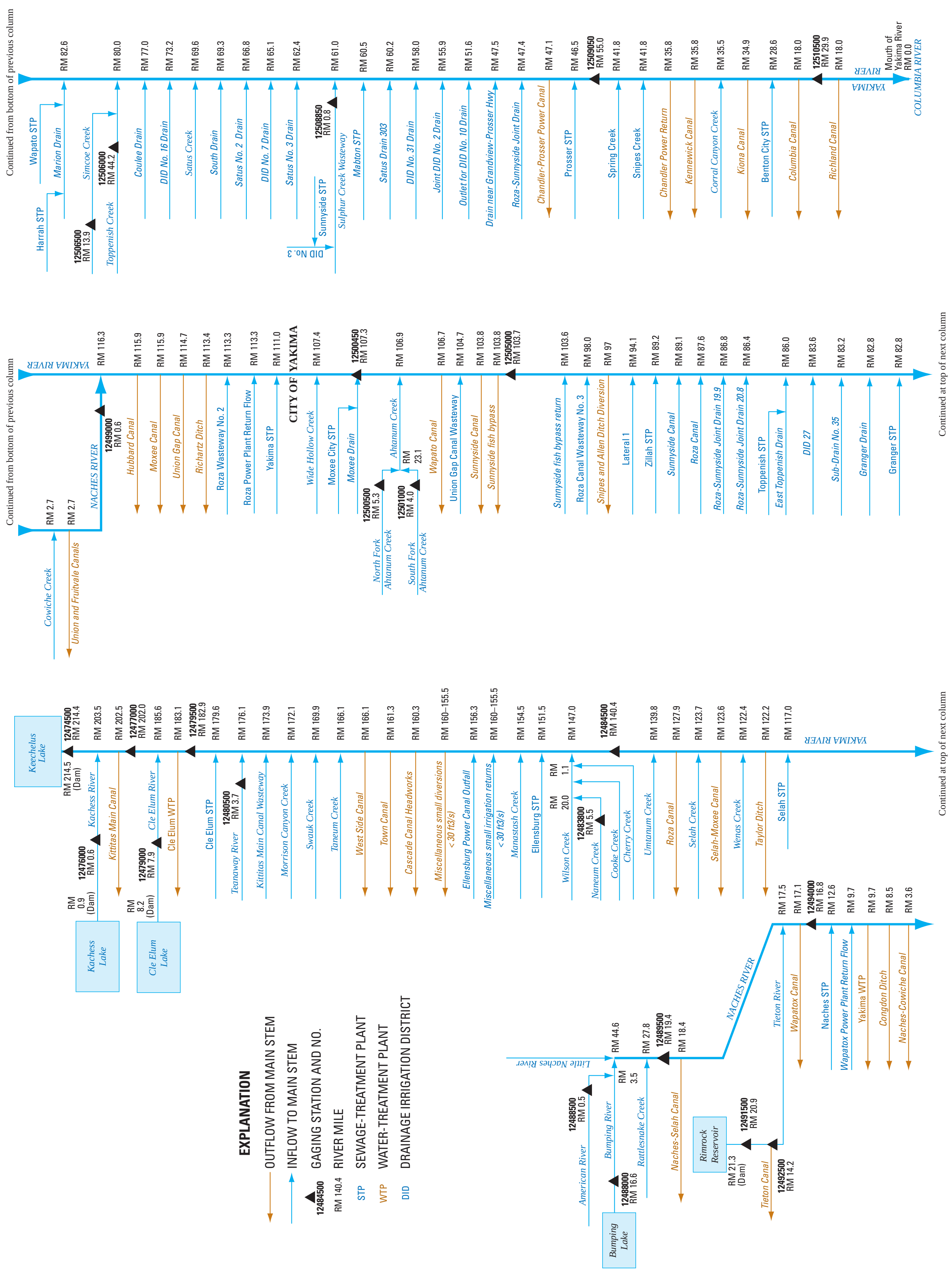


Figure 3. Selected tributaries, diversion canals, return flows, and stream-gaging stations, Yakima River basin, Washington.

Development of Water Resources

Missionaries arrived in the Yakima River basin in 1848 and established a mission in 1852 on Atanum (now Ahtanum) Creek. They were some of the first non-Indian settlers to use irrigation on a small scale. Miners and cattlemen immigrated to the basin in the 1850s and 1860s, which resulted in a new demand for water. With increasing settlement in the mid-1860s, irrigation of the fertile valley bottoms began and the outlying areas were extensively used for raising stock. One of the first known non-Indian irrigation ditches was constructed in 1867 to divert water from the Naches River (Parker and Storey, 1916; Flaherty, 1975). Private companies later delivered water through canal systems built between 1880 and 1904 for the irrigation of large areas. The development of irrigated agriculture was made more attractive by the construction of the Northern Pacific Railway that reached Yakima in December 1884 and provided a means to transport agricultural goods to markets; two years later, the completion of the railway to the Pacific coast provided new and easily accessible markets for agricultural products. The State of Washington was created in 1889, spurring further growth in the basin, especially because the cities of Ellensburg and Yakima were in contention for being the state capital. By 1902, about 120,000 acres were under irrigation, mostly by surface-water, (Parker and Storey, 1916; Bureau of Reclamation, 1999).

The Federal Reclamation Act of 1902 enabled the construction of Federal water projects in the western United States in order to expand the development of the West. In 1905, the Washington State Legislature passed the Reclamation Enabling Act, and the Yakima Federal Reclamation Project was authorized to construct facilities to irrigate about 500,000 acres. As part of the 1905 authorization and extensions, all forms of further appropriation of unappropriated water in the basin were withdrawn (Parker and Storey, 1916). Six dams were constructed as part of the Yakima Project: Bumping Dam in 1910, Kachess Dam in 1912, Clear Creek Dam in 1914, Keechelus Dam in 1917, Tieton Dam (Rimrock Lake) in 1925, and Cle Elum Dam in 1933. The six reservoirs have a total capacity of about 1.07 million acre-ft, about 78 percent of which is stored in the upper arm of the Yakima River and 22 percent is stored in the Naches River arm. The construction of the dams and other irrigation facilities resulted in an extremely complicated surface-water system (fig. 3). These Federal reservoirs provide storage to meet water requirements of the major irrigation districts during the period of the year when the natural streamflow from unregulated streams can no longer meet demands; the onset of this period is referred to as the ‘storage control’ date. Releases from several of the reservoirs also provide instream flows during the winter to support the incubation of salmon eggs in redds (gravel spawning nests).

Legal challenges to water rights resulted in the 1945 Consent Decree (U.S. District Court, 1945) that established the framework of how Reclamation operates the Yakima Project to meet water demands. The Decree established three classes of rights—nonproratable (priority dates of pre-May 1905), proratable (priority date of May 1905 when Reclamation obtained the unappropriated water), and junior (post-May 1905 priority dates). When the total water supply available (or TWSA, defined as current available storage in the reservoirs, forecasted estimates of unregulated flow, and other sources that are principally return flows) is not sufficient to meet all three classes of rights, the proratable rights are decreased according to the quantity of water available defined by the TWSA, and junior users can be completely turned off. As of 2008, the years when proration levels were defined were 1973, 1977, 1979, 1987–88, 1992–94, 2001, and 2005. This legally mandated method of apportioning water, which was upheld in a 1990 court ruling, generally performs well in most years, but it success is dependent on the accuracy of the TWSA estimate. In some years, for example 1977, problems have arisen because of errors in the TWSA estimate (Kratz, 1978; Glantz, 1982). Additionally, numerous proratable users have obtained groundwater-water rights that allow them to pump supplemental water in the years that they receive prorated quantities of surface water. System management also accounts for defined instream flows at selected target points on the river, and for suggested changes in storage releases recommended by the Systems Operations Advisory Committee (SOAC)—the advisory board of fishery biologists representing the different stakeholders (Systems Operations Advisory Committee, 1999). The operations for meeting instream flows are most affected by a 1980 Federal circuit court decision and by Title XII of a Public Law that instituted (beginning in 1995) new instream flows for the former and target flows for the latter at two diversions dams (Sunnyside and Prosser). The 1980 decision resulted in lower reservoir releases from the Keechelus and Cle Elum reservoirs in mid-September to prevent spawning chinook salmon from building redds higher up in the channel. To meet demands after mid-September, releases from the Naches arm reservoirs are increased. This operational procedure is called ‘flip-flop’.

The drilling of numerous wells for irrigation was spurred by new (post-1945) well-drilling technologies, legal rulings, and the onset of a multi-year dry period in 1977 (Vaccaro, 1995, 2002). Population growth in the basin remains the driving force behind the increased drilling of shallow domestic wells as well as deeper public - supply wells, and currently there are more than 20,000 wells (fig. 4) in the basin. More than 70 percent of these wells are shallow, 10–250 ft deep, domestic wells. On the basis of the digital water-rights database provided by WaDOE (R. Dixon, Washington State Department of Ecology, written commun., 2001) and other information, there are 2,874 active groundwater rights are associated with wells in the basin

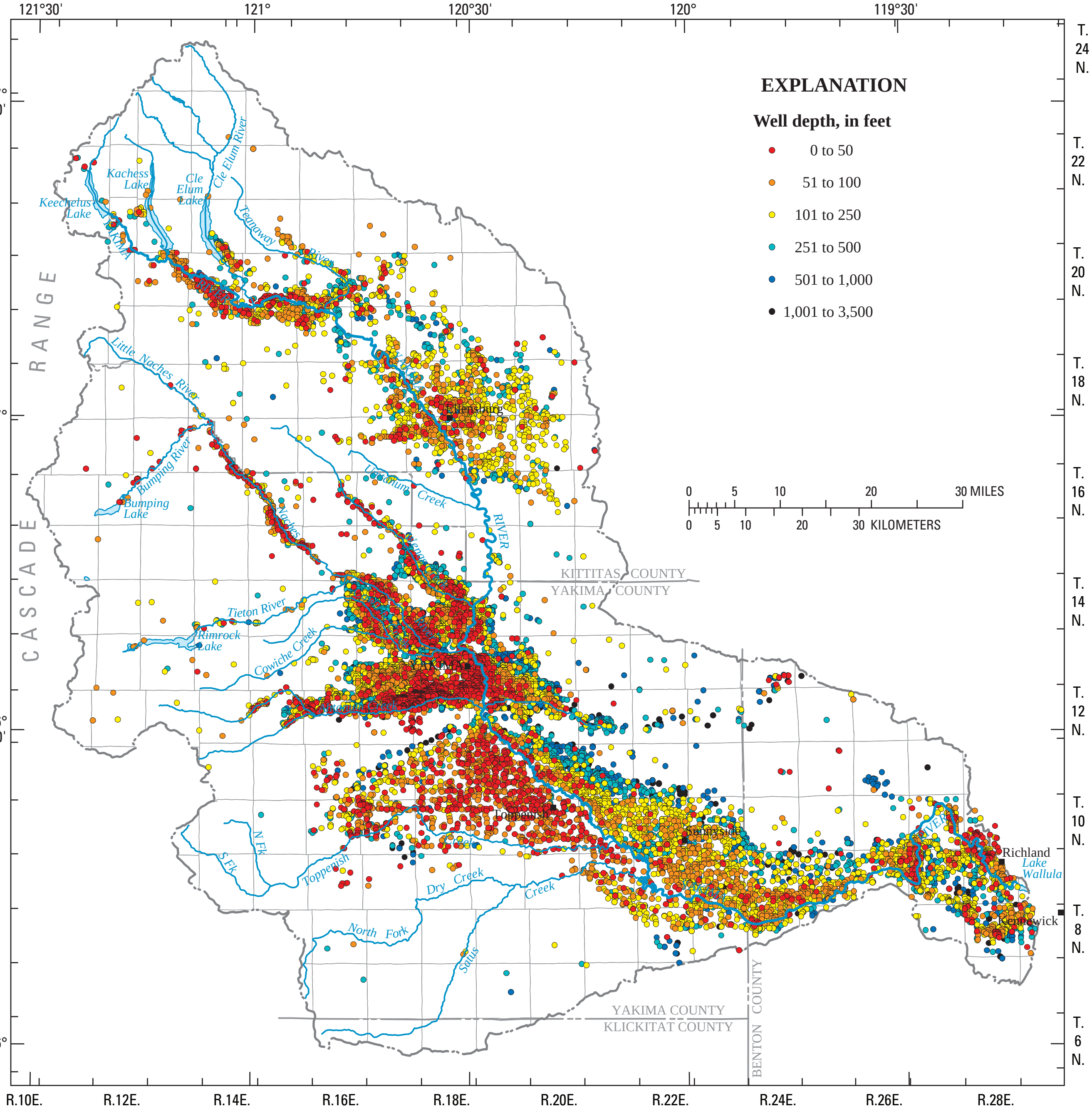


Figure 4. Distribution of depths of water wells, Yakima River basin, Washington.

that can collectively withdraw about 529,231 acre-ft during dry years. The irrigation rights are for the irrigation of about 129,570 acres. There are about 16,600 groundwater claims in the basin, for some 270,000 acre-ft of groundwater (J. Kirk, Washington State Department of Ecology, written commun., 1998). ‘A water right claim is a statement of claim to water use that began before the state Water Codes were adopted, and is not covered by a water right permit or certificate. A water right claim does not establish a water right, but only provides documentation of one if it legally exists. Ultimately, the validity of claimed water rights would be determined through general water right adjudications’ (Washington State Department of Ecology, 1998). A groundwater claim means a user claims that they were using groundwater continuously for a particular use, prior to 1945, when the State legislature enacted the Ground Water Code.

Overview of the Geology

The Columbia Plateau has been informally divided into three physiographic subprovinces (Meyers and Price, 1979). The western margin of the Columbia Plateau contains the Yakima Fold Belt subprovince and includes the Yakima River basin. The Yakima Fold Belt is a highly folded and faulted region, and within the study area it is underlain by various consolidated rocks ranging in age from Precambrian to Tertiary, and unconsolidated materials and volcanic rocks of Quaternary age. The simplified surficial geology of the Yakima River basin (Fuhrer and others, 1997) clearly shows the wide variety of rock materials present (fig. 5). The headwater areas in the Cascade Range include metamorphic, sedimentary, and intrusive and extrusive igneous rocks. The central, eastern, and southwestern parts of the basin comprise basalt lava flows of the Columbia River Basalt Group (CRBG) with some intercalated sediments that are discontinuous and weakly consolidated. The lowlands are underlain by unconsolidated and weakly consolidated valley-fill comprising glacial, glacio-fluvial, lacustrine, and alluvium deposits that in places exceed 1,000 ft in thickness (Drost and others, 1990). Wind-blown deposits, called loess, are present locally along the lower valley.

Valley-fill deposits and basalt lava flows are important for groundwater occurrence in the study area. The basalt comprises a series of flows erupted during various stages of the Miocene Age, from 17 to 6 million years ago. Basalt erupted from fissures located in the eastern part of the Columbia Plateau and individual flows range in thickness from a few feet to more than 100 ft. The total basalt thickness in the central part of the plateau is estimated to be greater than 10,000 ft (Drost and others, 1990) and the maximum thickness in the Yakima River basin is more than 8,000 ft. Unlike most of the Columbia Plateau, the CRBG in the Yakima Fold Belt is underlain by sedimentary rocks. The valley-fill deposits were eroded from the Cascade Range and from the east-west-trending anticlinal ridges that were formed by the buckling of the basalt sequence during mid- to late-Miocene time. Most of these deposits are part of the Ellensburg Formation. This formation underlies, intercalates, and overlies the basalts along the western edge, and constitutes most of the thickness of the unconsolidated deposits (informally called the overburden; Drost and others, 1990) in the basins. The basins are narrow to large open synclinal valleys between the numerous anticlinal ridges.

The deposition of a thick, upper sequence of sand, gravel, and some fine-grained material is the result of erosion by glacial ice and transport by meltwater streams. Damming of large lakes by glacial ice during the Pleistocene epoch resulted in the deposition of silt and clay beds in parts of the uplands. When the lakes drained, the fine sediments were exposed, subsequently eroded by wind, and deposited over the lower, eastern parts of the study area. Thus, the unconsolidated materials in the basins abutting and interbedded with the basalts range in age from Miocene to Holocene.

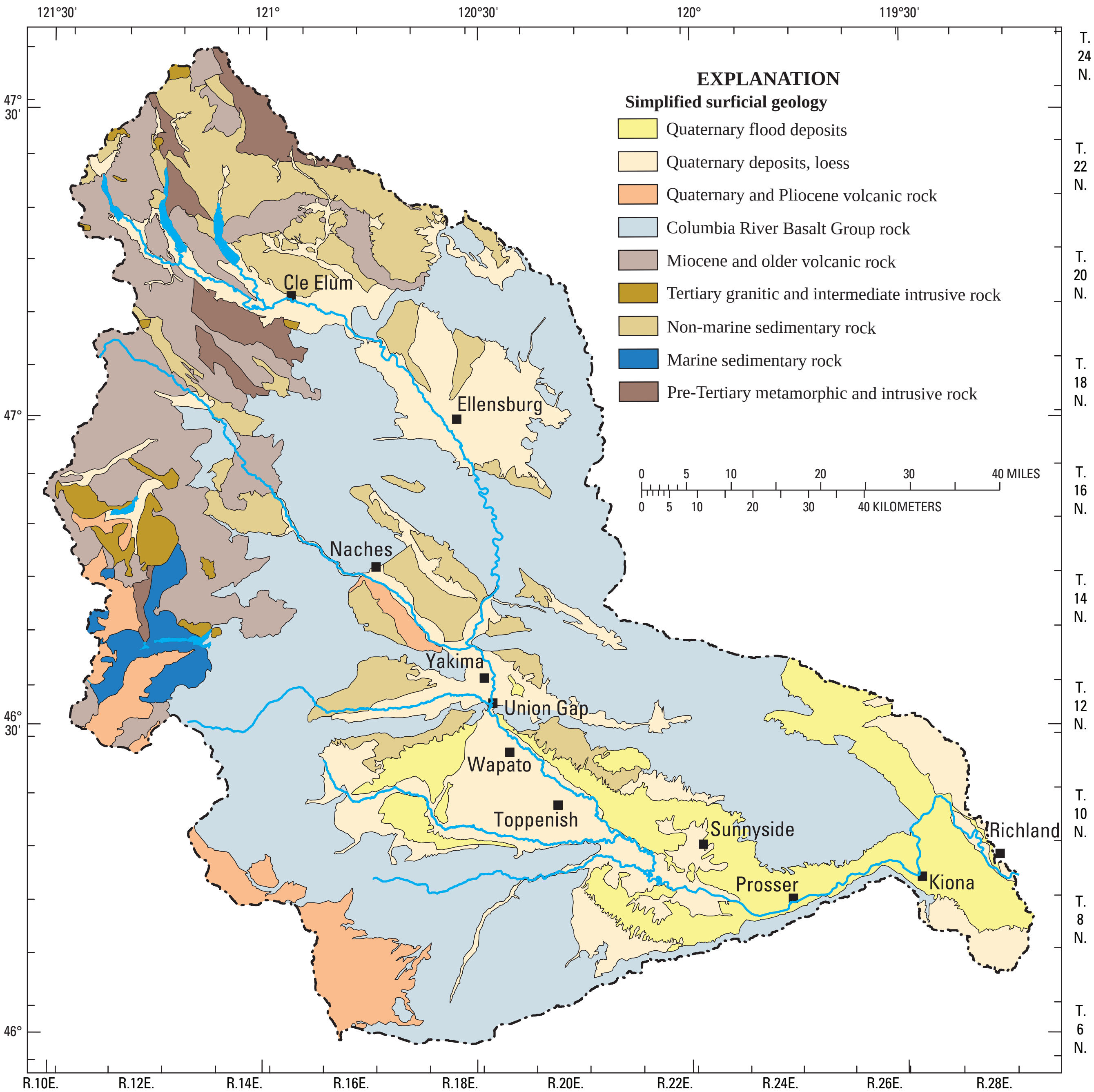


Figure 5. Simplified surficial geology, Yakima River basin, Washington.

Importance of River-Aquifer Exchanges

Groundwater discharge, including that discharged from the hyporheic zone, provides preferred thermal structure and habitat for different species and stocks of fishes at different life-history stages (Power and others, 1999), and is an important abiotic variable of the aquatic ecosystem that is basic to the ecological function of riverine systems (Hynes, 1983; Stanford and Simons, 1992; Stanford and Ward, 1993; Brunke and Gonser, 1997). The groundwater and surface-water interface is a unique ecotone (transition zone or area) and is similar to other ecotones that are the most productive and diverse habitats (Wetzel, 1990). Most of the year, streamflow in the Yakima River basin is largely baseflow or groundwater that has discharged to the stream channel; therefore, the quality and availability of surface water are largely influenced by groundwater. Perennial streams are supported by groundwater and constitute a groundwater-dependent ecosystem (GDE) (Hatton and Evans, 1998; Eamus and Froend, 2006). Riparian habitat, and algal, invertebrate, and fish communities therefore are, to some extent, dependent on groundwater discharge to perennial streams. An overview of the current understanding of the interaction between groundwater and surface water is presented in Winter and others (1998), and methods for estimating exchanges are described in Rosenberry and La Baugh (2008).

Lateral and vertical hydraulic exchanges between groundwater and surface water in both natural and modified river systems are important components of ecosystem dynamics (Hynes, 1983; Stanford and Ward, 1993; Ward and others, 1999), and the locations of such exchanges represent areas that salmonids either use or avoid (Power and others, 1999; Rieman and Dunham, 2000). Groundwater discharge locations provide refugia, the preferred salmonid habitat during summer when river temperatures are otherwise warm and during winter in colder regions when rivers may freeze or water temperatures stay less than 1°C for some period (these refugia are species/stock dependent). For example, groundwater discharge areas are the preferred winter habitat for trout (Brown and Mackay, 1995). Salmonids seek out and take advantage of this habitat. Magnuson and others (1979) suggest that fish and other aquatic ecosystem components compete for such habitat. The longitudinal gradient of exchanges along a river corridor, overlaid with the distribution of localized patches of exchanges, composes a continuum from the headwaters to the mouth, along which habitat and species are arranged (Vannote and others, 1980). Groundwater discharge and the connectivity of exchanges along the river corridor therefore facilitate the movement and sustainability of salmonids during their various life-history stages; the importance of groundwater discharge for such salmonid habitat has long been recognized (Benson, 1953).

Groundwater discharge is a significant form of thermal flux in many river systems. In turn, water temperature is one of the most important abiotic characteristic of the riverine system because it influences dissolved oxygen concentrations, the metabolic rates of aquatic organisms, decomposition rates of organic material, and many other ecosystem processes. Thus, the bioenergetics of riverine GDEs is ultimately determined by the thermal regime. The presence of long and short temporal variations in the temperature regime is functionally related to groundwater discharge. These variations lead to increased biodiversity (Magnuson and others, 1979), including that of fish (Brett, 1956; Beschta and others, 1987), insects (Vannote and Sweeney, 1980), and macrophytes (Haslam, 1978; White and others, 1987). The long and short temporal variations increase with the size of a basin and attendant variations in climatic regimes and landscape characteristics.

Groundwater discharge at salmonid redds (gravel spawning nests), such as for bull trout, is important for incubation of eggs (Combs and Burrows, 1957; Combs, 1965; Alderdice and Velsen, 1978) and affects egg survival for salmonid species (Sowden and Power, 1985; Woessner and Brick, 1992; Curry and others, 1995), including wild bull, rainbow, steelhead, and kokanne trout in the Yakima River basin. For example, the Endangered Species Act (ESA)-listed bull trout require temperatures below 8–9°C for spawning initiation, 2–4°C for optimal egg incubation (egg survival can be reduced by 75 percent for temperatures above 7.8°C), and 4–10°C for juvenile rearing (note that initial rearing occurs near the bottom of the natal stream, where groundwater discharge generally enters the channel) (http://ecos.fws.gov/ecos/indexPublic.do and http://www.fws.gov/pacific/bulltrout/).

The above factors are important to the health and survival of salmonids in the Yakima River basin. On-going activities to enhance water availability for increasing in-stream flows for salmonids and providing more secure supplies of irrigation water under the Yakima River basin Water Enhancement Project (Bureau of Reclamation, 1999) directly relate to river-aquifer exchanges. Indeed, the Yakima groundwater study was initiated to assess whether groundwater pumping results in a decrease in groundwater discharge, and therefore, streamflow. Further, WaDOE activities in 2008 related to domestic exempt-well usage were initiated because groundwater pumping may alter river-aquifer exchanges—possibly affecting senior surface-water rights. The Yakima Basin Fish and Wildlife Recovery Board's long-term salmon recovery plan for steelhead in the basin addresses the need for complex exchanges in the river system and protection of areas with good habitat, many of which are associated with groundwater discharge (http://www.ybfwrb.org). The YN in conjunction with the Washington State Department of Fish and Wildlife, National Oceanographic and Atmospheric Administration, and other parties are undertaking large-scale restoration projects, habitat management, and fish enhancement/supplementation activities, many of which are oriented to improving river-aquifer exchanges because of their importance to the aquatic ecosystem in general, and survival and recovery of ESA-listed salmonids in particular (http://ykfp.org). Areas of complex and active exchanges therefore are prime areas for preservation and restoration (Reeves and others, 1991) because they are important components of a GDE and provide connectivity through the river corridor.

Data Used to Assess River-Aquifer Exchanges

Several types of data, either compiled from previous studies or collected as part of this study, were identified for assessing river-aquifer exchanges. Those data were separated into five categories.

The first category consists of isotope data for streams and groundwater (fig. 6). This data provided information on the source of water in the streams and groundwater system, and in particular, the part of the groundwater system dominates the exchanges. The second category encompasses seepage investigations using discharge data (seepage runs) for streams or farm-drains (fig. 7). Data include previously published seepage investigations and information collected or compiled

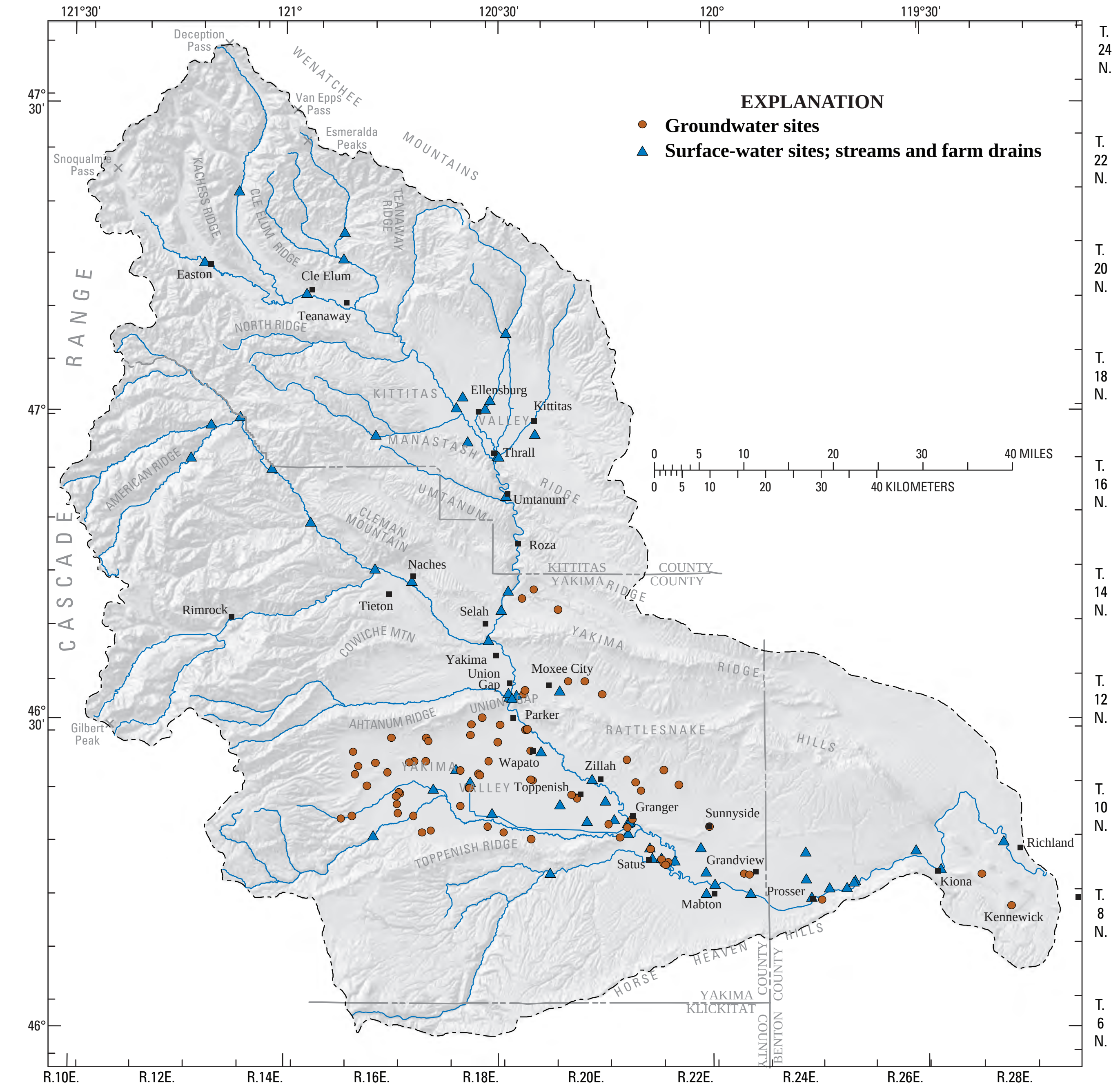


Figure 6. Location of measuring sites with isotope data, Yakima River basin, Washington.

during this study (Carey, 2006; J. Kardouni, Washington State Department of Ecology, written commun., 2006; D. Lind and S. Ladd, Yakama Nation, written commun., 2008, 2009; Magirl and others, 2009); and information collected or compiled during this study (Magirl and others, 2009). Mini-piezometer data comprise the third category; the data were collected by USGS, WaDOE (Carey, 2006), and Flathead Lake Biological Lab (FLBL) (Stanford and others, 2002) (fig. 8). The fourth category was groundwater levels and (or) temperatures from shallow monitoring wells that generally were located in the flood plain (fig. 9); the monitoring wells include a set of nine wells located across a broad range of physical settings. The fifth category comprises thermal profiles collected by USGS along 12 reaches of the Yakima and Naches River (fig. 8; Vaccaro and Maloy, 2006; Vaccaro and others, 2008), and profiles collected by the Benton Conservation District (BCD) along 5 reaches of the lower Yakima River (M. Appel, Benton Conservation District, written commun., 2009).

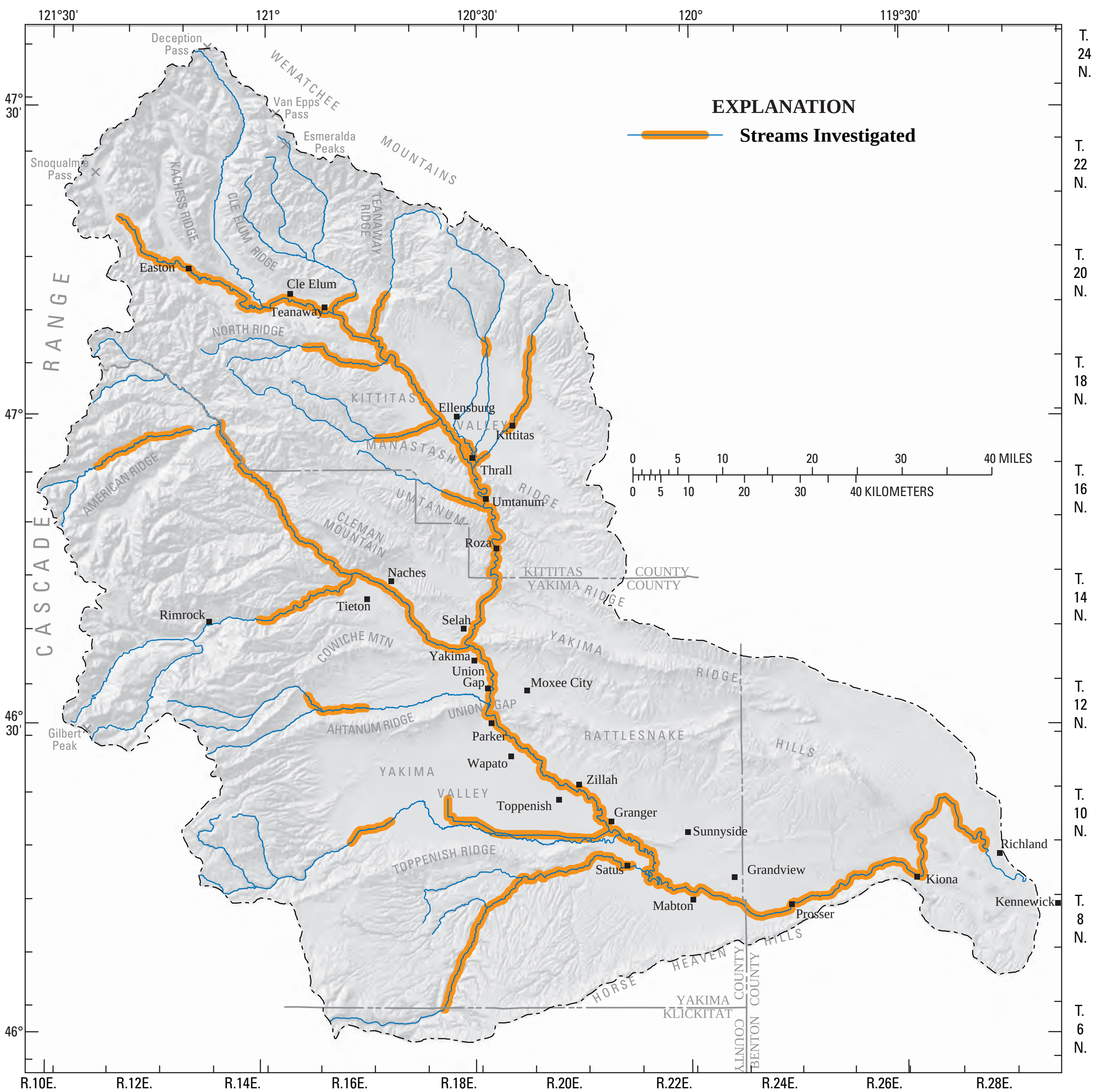


Figure 7. Location of streams with seepage investigations, Yakima River basin, Washington.

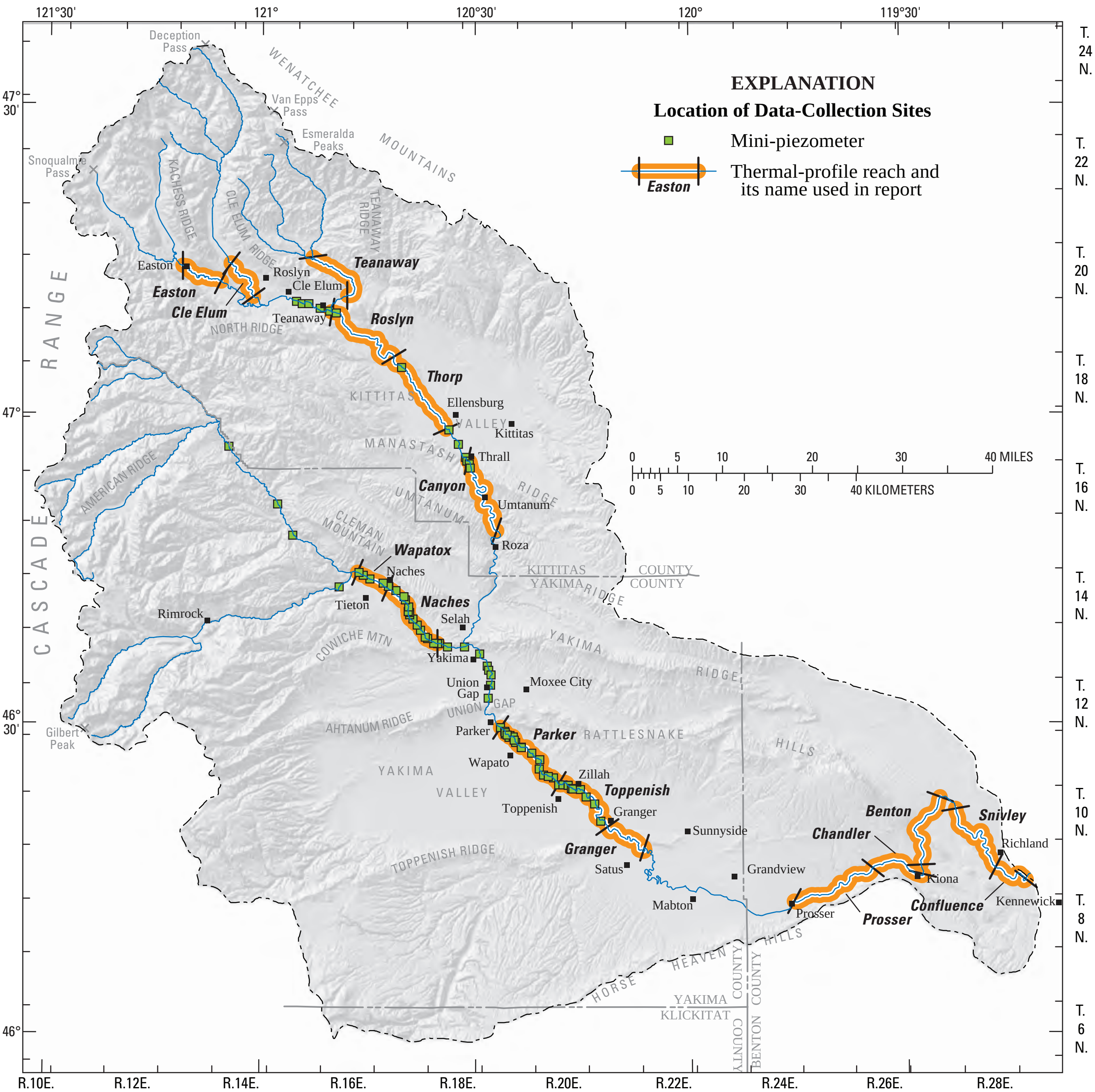


Figure 8. Location of mini-piezometer measuring sites and thermal-profile reaches, Yakima River basin, Washington.

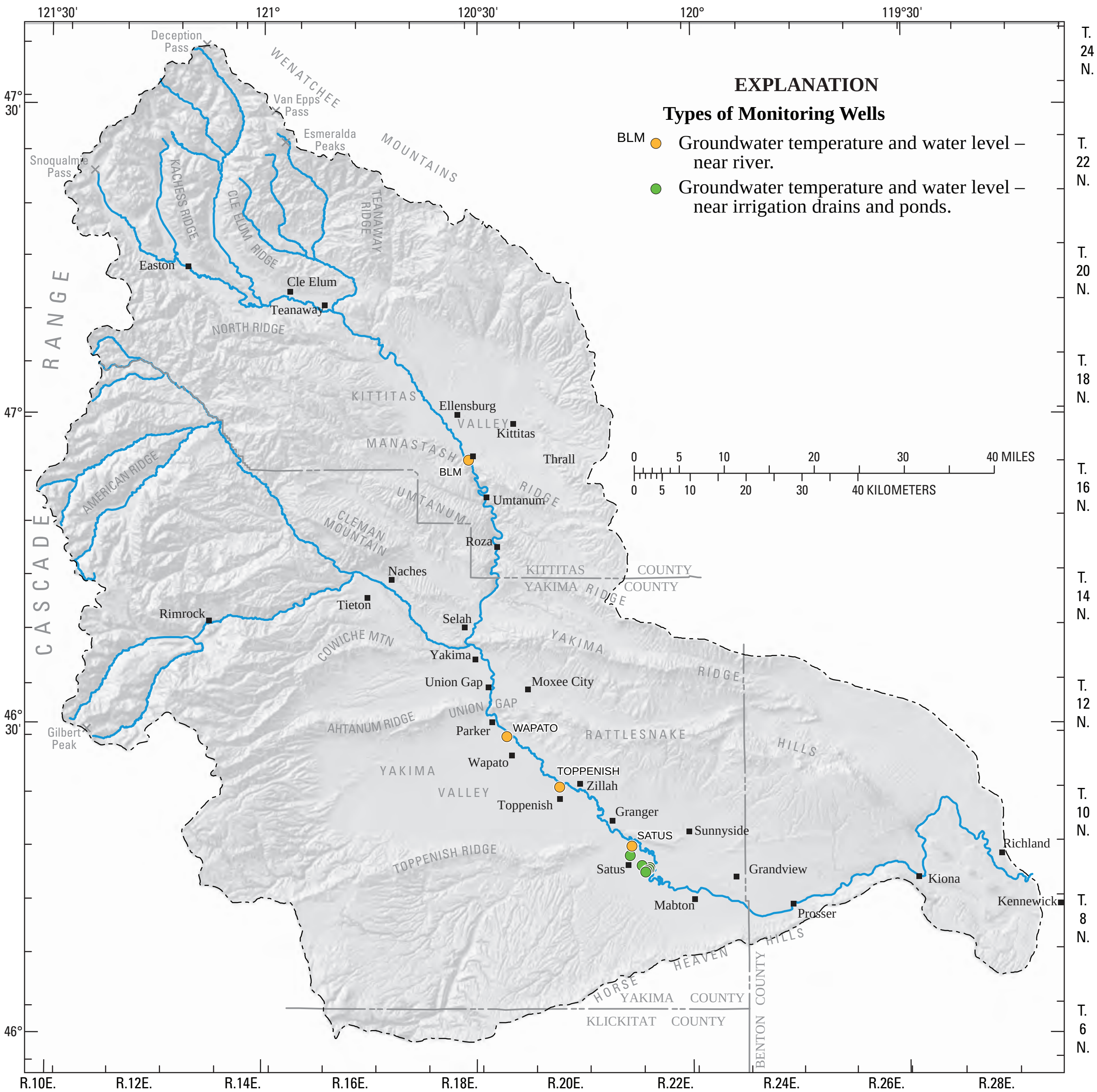


Figure 9. Location of monitoring wells, Yakima River basin, Washington.

Description of River-Aquifer Exchanges by Data Category

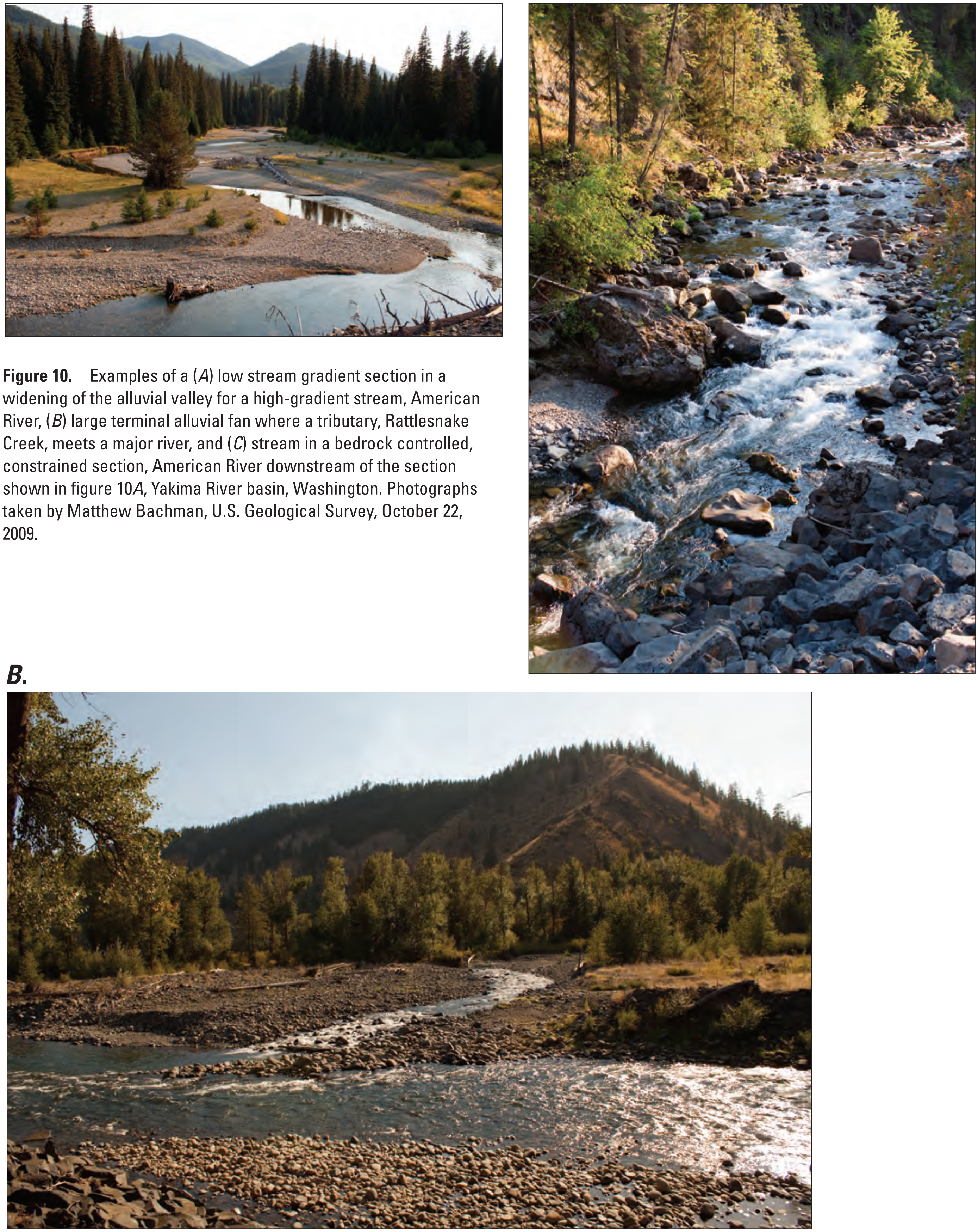
The processes by which water is exchanged between streams and the groundwater system in the Yakima River basin are complex and highly variable. Basin-wide spatial patterns of exchanges provide an overall templet for smaller spatial-temporal patterns. For the basin as a whole, perennial streams with incised channels in the humid uplands are supported by groundwater discharge throughout the year. Some segments of these high-gradient upland streams may lose water to the underlying aquifer, however, where they leave a narrow, bedrock-controlled channel and enter a wider valley that is underlain by unconsolidated glacial or alluvial deposits, with a concomitant decrease in stream gradient. Figure 10*A* shows an example of a high-gradient stream (American River) just downstream of a bedrock-controlled reach; locally, the river assumes a progressively lower gradient in a widening alluvial valley with a complex braided channel system. Overall, these upland streams have a large net gain from groundwater discharge and supply the surface water that ultimately enters the mainstem of the Yakima and Naches Rivers. Streamflow from the larger upland streams generally occur where the streams flow out onto a valley floor, usually at the proximal (upstream) end of the alluvial fan that is typically present at their mouths or on a valley floor (Nelson, 1991; Woodward and others, 1998; Konrad, 2006). This hydrologic process is referred to as mountain-front or focused recharge (Stonestrom and others, 2007). For example, seepage investigations on Taneum and Manastash Creeks show losses where the creeks flow out onto the valley floor (Magirl and others, 2009), and shallow groundwater monitoring wells near where Toppenish Creek emerges onto the valley floor show water-level rises concurrent with streamflow increases that indicate streamflow losses, which are consistent with seepage investigation results. Most tributaries that enter the valleys (especially the major structural basins) have large alluvial fans that were formed during the latter part of the Pleistocene and early Holocene, when the glaciers were receding, the climate was wetter, and the rivers had more energy to transport sediment, including coarse-grained material such as cobbles and boulders. Figure 10*B* shows an example of a large (about 0.2-mi wide) terminal alluvial fan at the mouth of Rattlesnake Creek (mean annual discharge of about 350 ft^3/s [Mastin and Vaccaro, 2002]) where it enters the Naches River; other tributary fans in the basin range in width from about 0.05 to 2 mi. Under present-day conditions, the rivers either do not have enough energy to erode down into these fans or they are in the process of eroding through the fans, and thus, they either 'skirt' the fan near one of its sides or flow atop/across the top of the fans at elevations above the groundwater table (Woodward and others, 1998). In some cases, the streams gain water across the distal (downstream) end of these alluvial fans (Woodward and others, 1998), and thus exchanges can be large and complex across the fans—suggesting their potential ecological importance for salmonid habitat, especially for rearing juvenile fish, near the mouth of these streams. For example, figure 10*B* shows a large backwater eddy pool at the mouth of Rattlesnake Creek that receives cold groundwater discharge.

Downstream of the humid uplands, broad-scale river-aquifer exchanges for the remaining part of the river system (typically where the average stream gradient is less than about 0.005 ft/ft or having a Strahler stream order generally greater than three) can occur in two ways: losses in flow within the flood plain where a river enters a structural basin, and gains in flow further down-valley, especially near the terminus of a basin (Kinnison and Sceva, 1963; Vaccaro and others, 2009). Within these structural basins, the delivery and application of surface-water to croplands has raised groundwater levels, and the canal and drainage systems, which are both parallel and perpendicular the streams, now receive groundwater discharge that naturally would discharge to the streams. The construction of levees, revetments, and rip-rap banks; suburban/urban development; and railroad and road embankments in the flood plain also have locally altered the natural exchanges by eliminating large parts of the flood plain or "disconnecting" them from the main stream channel. Thus, the natural river-aquifer exchanges have been greatly modified throughout large areas as a consequence of human activities and actions, and as a result, the remaining reaches and or segments with functional river-aquifer exchanges are important.

Overlain on this basin-wide templet from the humid uplands to the large structural basins are complex relations between river-aquifer exchanges that are controlled by various factors. For example, water-level contours for the unconfined (water-table) aquifer in the structural basins indicate that groundwater moves towards the Yakima River along many 0.1 to 30-mi long reaches (Vaccaro and others, 2009). However, groundwater entering the alluvial aquifer (typically defined by the flood plain) also moves longitudinally downgradient in the aquifer (generally parallel to the river), and exchanges (manifested as streamflow gains and losses) are controlled by differences in streambed/water-surface elevation, elevation of the water table, variations in the lateral and vertical extent of the aquifer, lithology contrasts, and channel complexity and orientation (Konrad, 2006). An example of how groundwater can move in the alluvial aquifer for the Parker reach (see fig. 8 for location of reach) was presented in Stanford and others (2002). Variations in the extent of an alluvial aquifer are one of the major controls on exchanges between the aquifer and adjacent stream channels. For example, where the aquifer diminishes, groundwater discharges to a stream, and the predominant condition for this is upgradient from a bedrock-controlled reach. Conversely, a stream typically begins to lose water downgradient from a bedrock controlled reach where the stream flows out into an alluvial valley. Figure 10*C* shows an example of a bedrock controlled reach of a stream; this photograph was taken on the American River just downstream of the wide valley shown in figure 10*A*. Channel orientation also is an important influence on river-aquifer exchanges.

A.

C.



B.

Figure 10. Examples of a (*A*) low stream gradient section in a widening of the alluvial valley for a high-gradient stream, American River, (*B*) large terminal alluvial fan where a tributary, Rattlesnake Creek, meets a major river, and (*C*) stream in a bedrock controlled, constrained section, American River downstream of the section shown in figure 10*A*, Yakima River basin, Washington. Photographs taken by Matthew Bachman, U.S. Geological Survey, October 22, 2009.

Where a stream traverses the alluvial aquifer, the channel sides and bottom are available for intercepting groundwater in the aquifer; thus the closer to perpendicular the orientation of the stream is to groundwater flow paths, the higher the opportunity and probability of intercepting groundwater. In such cases, gains would be derived predominantly from lateral groundwater flow and not vertical flow through the streambed. Changes in the orientation of streams may be due to changes in the underlying geology, such as the presence of a bedrock high, which in turn can increase groundwater discharge as the streambed intersects the water table.

In the following discussion, river-aquifer exchanges are described relative to both large and small spatial scales. Most of the discussion applies primarily to summer, or low-flow conditions, when the exchanges (in terms of water quantity and temperature) are important for both in-stream and out-of-stream uses. Temporal variations in the exchanges are discussed primarily on the basis of analysis and interpretation of data collected at shallow-monitoring wells.

Isotope Data

The ratios of the stable isotopes of hydrogen ($^{2}H/^{1}H$) and oxygen ($^{18}O/^{16}O$) of meteoric waters, which vary as atmospheric precipitation moves farther away from its source area in the Pacific Ocean, can be used to identify the source of water in streams and groundwater in the Yakima River basin. The isotope ratios are expressed in delta (δ) notation, as δD and $\delta^{18}O$, and are reported in units of per mille (parts per thousand, or ‰) as differences from a standard. Waters with ratios greater than the standard have positive delta values and are referred to as “heavy” or “enriched” relative to the standard. Conversely, waters with ratios less than the standard have negative values and are referred to as “light” or “depleted.” Values of δD and $\delta^{18}O$ in the waters of Washington State typically are negative, or depleted relative to the standard (Kendall and Coplen, 2001 Vaccaro and others, 2009).

Tritium (^{3}H) is a radioactive isotope of hydrogen that has a half-life of about 12.4 years. It is found in groundwater that was recharged during or after the period of above-ground testing of thermonuclear weapons, from 1952 to 1963. During this period, large amounts of ^{3}H were injected into the atmosphere. Groundwater with ^{3}H concentrations greater than about 0.5 tritium units (TU) are categorized as modern, whereas groundwater with values less than 0.5 TU are categorized as pre-modern (recharged prior to weapons testing—pre 1952).

A total of 494 paired δD and $\delta^{18}O$ values were compiled for 84 groundwater sites and 66 surface-water sites in the Yakima River basin (fig. 6). The groundwater data were collected by the USGS from 2000 through 2005 and by the YN in 1990 and 1991 (Hendry and others, 1992). Several of the groundwater samples were from wells just outside the basin (on Horse Heaven Hills, not shown in figure 6) that were completed in basalt at depths ranging from 220 to 345 ft. Isotopic analyses of these samples were used to determine whether the waters in wells of about the same depth completed in basin-fill materials and basalt had similar isotopic signatures. Surface-water samples were collected by the USGS and processed for isotopic analyses by Tyler Coplen (U.S. Geological Survey, written commun., 2009). Isotope data also were available from the YN for five precipitation collection sites in the Toppenish Basin that ranged in altitude from 937 to 5,720 ft (Hendry and others, 1992). Tritium (^{3}H) data also were available for 68 of the wells (fig. 11); 21 samples were collected by the USGS and the remaining samples (from the Toppenish Basin) by the YN (Hendry and others, 1992). The data collected by the USGS are available from the USGS National Water Inventory System, and data from wells sampled by YN, as well as the USGS groundwater data, were published in Vaccaro and others (2009).

The δD and $\delta^{18}O$ values for groundwater and surface water (fig. 12*A*) plot near the Local Meteoric Water Line (LMWL) for Washington State (Coplen and Kendall, 2000; Kendall and Coplen, 2001), and the Global Meteoric Water Line (GMWL) of Craig (1961) and Rozanski and others (1993). The slope of a regression line fitted to all the groundwater and surface-water data is 8.6 (the LMWL for this data set), which closely approximates the 8.17 slope of the GMWL from Rozanski and others (1993). The 8.6 slope is similar to the slope of 8.9 from Hendry and others (1992) for groundwater in the Toppenish Basin. The groundwater data had a slope of 8.8 and the surface-water data had a slope of 7. Together, the isotope data shows that the source of surface water and groundwater in the Yakima River basin is meteoric water derived from atmospheric precipitation.

The stable isotope data (fig. 12*A*) indicates that shallow groundwater (from wells less than 100-ft deep) is the isotopically most similar to surface water in comparison to water from deeper wells (those greater than 100-ft deep). The slopes of regression lines fitted to the data for wells less than 100-ft deep was 7.9 and for wells less than 200-ft deep the slope was 8.2. Water from wells deeper than 200 ft (slope of 8.7) tends to have a different isotopic composition (isotopically lighter) than both shallower groundwater and surface water; water from wells completed in basalt and basin-fill aquifers at about the same depth generally had similar isotopic composition. A comparison of average isotope values for groundwater and surface water (fig. 12*B*) demonstrates the above relationship (fig. 12*B*) , and indicates that surface water in the Yakima River basin contains, at most, only a small component of discharge from the deeper flow system.

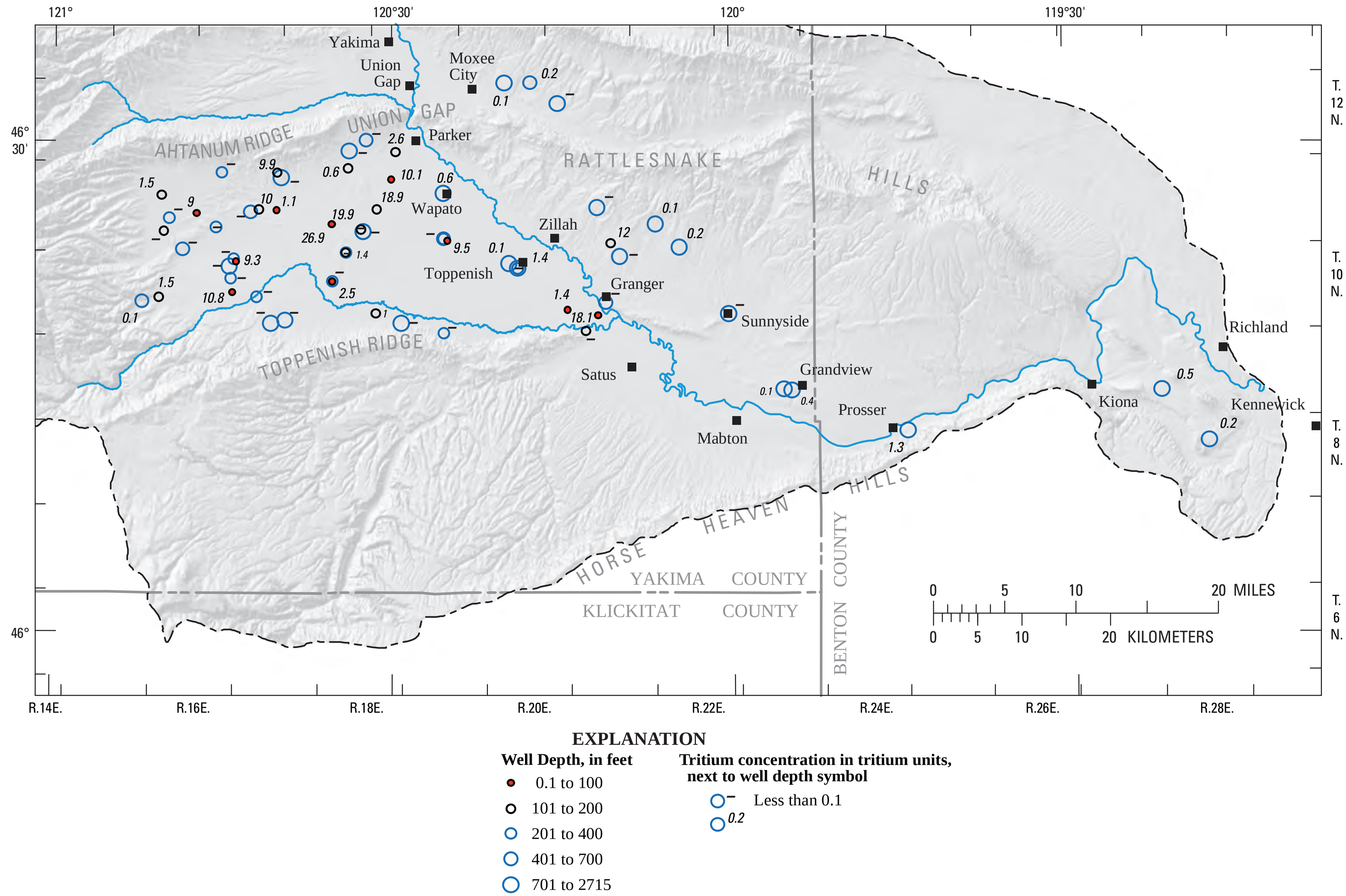


Figure 11. Location of wells with tritium data and tritium concentrations, Yakima River basin, Washington.

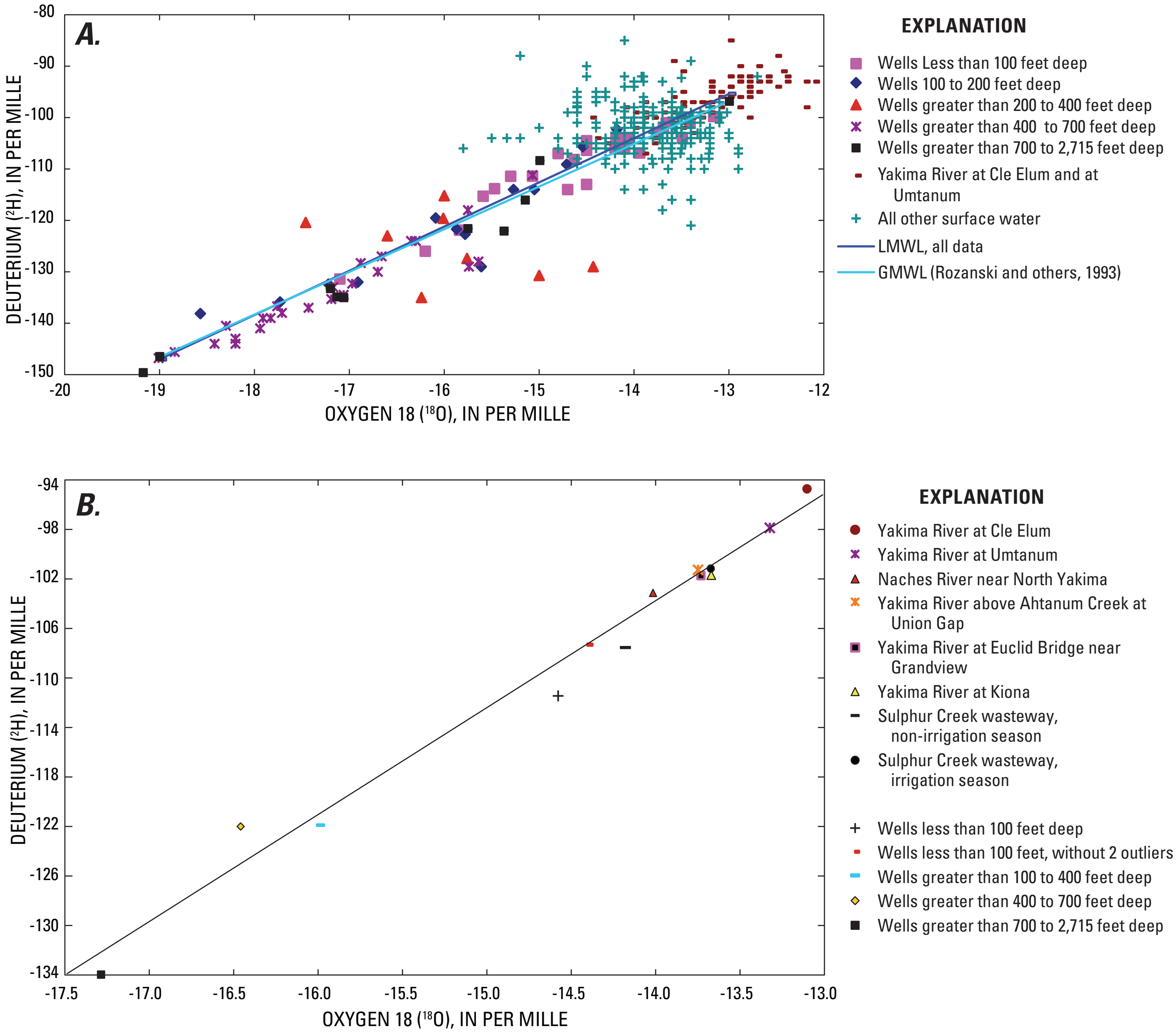


Figure 12. Relation between (*A*) stable isotope data for groundwater and surface water and their relation to the Global Meteoric Water Line (GMWL) and Local Meteoric Water Line (LMWL), and (*B*) averaged stable isotope data for groundwater and surface water, Yakima River basin, Washington.

Most surface water in the basin originates as snowmelt in the humid uplands of the upper arms of the Yakima and Naches Rivers (Mastin and Vaccaro, 2002), and it has a distinct isotopic signature of enrichment of heavier isotopes (fig. 12*B*). Mastin and Vaccaro (2002) also show that the partitioning of surface water is predominantly (80–95 percent) between shallow subsurface flow (water that has moved below the root zone) and groundwater flow, and thus, to a much smaller extent, direct surface runoff. The partitioning further indicates that the perennial streams in the humid uplands are supported by shallow river-aquifer exchanges throughout the year.

There is a distinct isotopic difference between the waters originating from the Naches and upper Yakima River drainages (figs. 12*B* and 13). The Naches River drainage contains a greater proportion of high-altitude lands (average altitude of about 4,400 ft compared to 2,700 ft for the upper headwaters of the Yakima River) and thus is colder and retains its snowpack longer, which results in an isotopically more depleted (rain-like) snowmelt component. The depletion of δD in the Naches River compared to that in the upper Yakima River at Cle Elum clearly shows this aspect (fig. 13). The seasonal variation in δD shows that streamflow emanating from the upper Yakima River becomes more depleted as it moves downstream, and by the time it reaches Union Gap the isotopic signature of the water in the Yakima River is similar to that in the Naches River (fig. 14). Further depletion occurs by Kiona due to retention time and the mixing of return-flow waters (surface and groundwater) with mainstem Yakima River water. The averaged surface-water data (fig. 12*B*) also indicates a relatively small difference in the isotopic composition of streamflow in the lower basin, with the three lower basin sites clustering within a 1-percent range. Runoff from rain-on-snow events that produces elevated streamflows shows depleted isotope values during these events. The depleted *δ*D values measured in March 1989 (fig. 14) is an example.

About 4,400 ft^3/s of streamflow is diverted for delivery to agricultural croplands in the Yakima River basin (Vaccaro and others, 2009). Of this total, about 1,700 ft^3/s recharges the shallow groundwater system in the surface-water irrigated areas (Vaccaro and Olsen, 2007a) and has raised water levels more than 80 ft in some areas (Jayne, 1907; Parker and Storey, 1916). Excluding the humid uplands, the irrigation-derived recharge and subsequent discharge overwhelms the quantity of recharge that would have occurred under natural conditions in the structural basins; most of these basins receive less than 8 in/yr of precipitation, and mean annual recharge under natural conditions was estimated to be less than 0.5 in. (Vaccaro and others, 2009). As a result, most of the groundwater discharging from the active part of the aquifer system to streams and drains from about the Kittitas Basin for the Yakima River and the City of Naches for the Naches River to the mouth of the Yakima River is 'recycled' surface water, particularly during the irrigation season. After the irrigation season, the excess irrigation recharge discharges (typically to drains) from the shallow groundwater system until the beginning of the next irrigation season, with most of the post-irrigation season drainage occurring from late October through January. The stable isotope data for Sulphur Creek wasteway near Sunnyside clearly shows the presence of 'recycled' recharge (fig. 12*B*). During the irrigation season, its isotopic composition is similar to that of the lower Yakima River, while during the non-irrigation season, its isotopic composition is more like that of the shallow groundwater. During the non-irrigation season, however, the wasteway still retains a signature of surface water due to mixing of the two water sources. USGS nitrate data for Granger drain at Granger (see, for example, Kimbrough and others [2003]) also clearly shows the water in the drain changing from surface-water dominated (lower nitrate concentrations) to groundwater dominated (higher nitrate concentrations) during the non-irrigation season. The more depleted groundwater also would discharge to surface-water features (for example, Wilson, Wide Hollow, and Sulphur Creeks) in the surface-water irrigated areas during the non-irrigation season.

Data for 68 of the wells that were sampled for analysis of tritium (^3H) can be used to infer groundwater age, or the length of time between when groundwater was recharged and when it was collected for analysis. There is a distinct relation between well depth and tritium concentration (fig. 15). Of the 26 samples with values greater than 0.5 TU, 11 (42 percent) were from wells less than 100 ft deep, and 10 (38 percent) were from wells between 100 and 200-ft deep (Hendry and others, 1992; Vaccaro and others, 2009). The average tritium concentrations for these two groups of wells were 10.8 and 5.9 TU, respectively, showing the more modern component of shallow groundwater. The spatial distribution of tritium in groundwater samples also indicates that tritium concentrations are more a function of well depth rather than location in the basin (fig. 11). The tritium data further indicate that river-aquifer exchanges are represented by the exchange of modern streamflow and modern, shallow groundwater. Prior to human activities in the basin, it is likely that exchanges also were dominated by modern water. However, much of the groundwater component of streamflow would have been derived from the flood plain aquifers that were recharged (1) during high overbank flows, (2) from tributary losses where they emanate out onto the flood plain, and (or) (3) as bank-storage during the snowmelt-runoff period and rain-on-snow events. Otherwise, the groundwater component would have been derived from recharge of precipitation in bedrock-controlled reaches that are typically incised river channels in valleys. In these types of reaches—for example, the Prosser reach (fig. 8)—groundwater moves along short to medium length flow paths before discharging to the streams (Vaccaro and others, 2009).

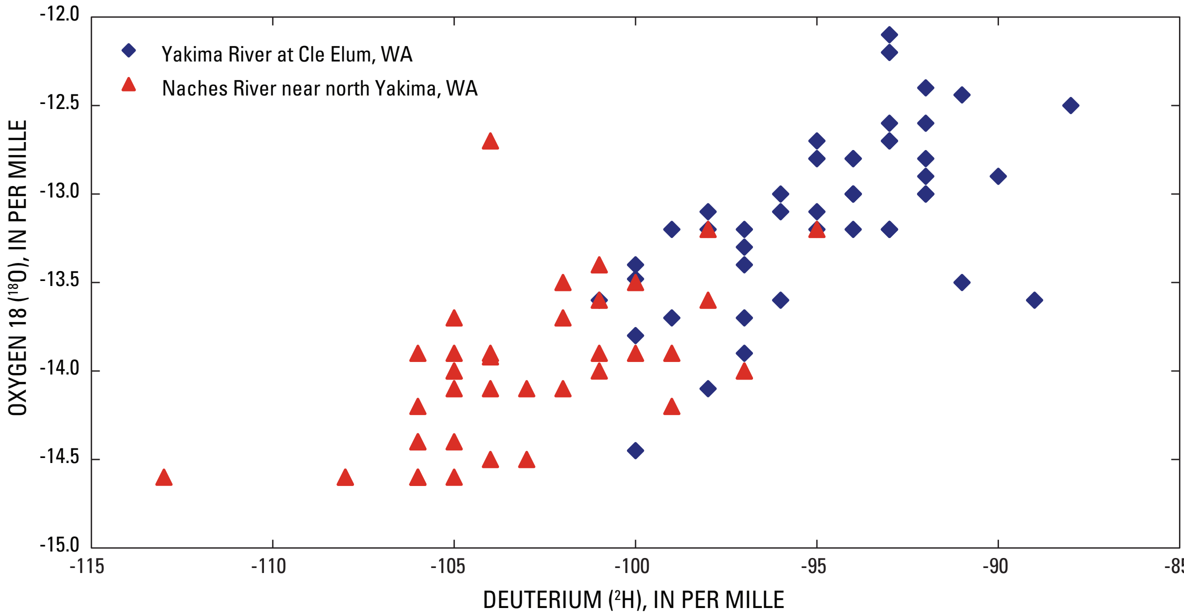


Figure 13. Relation between stable isotopic composition (deuterium and oxygen-18) samples for the Naches River near North Yakima and the Yakima River at Cle Elum, Yakima River basin, Washington.

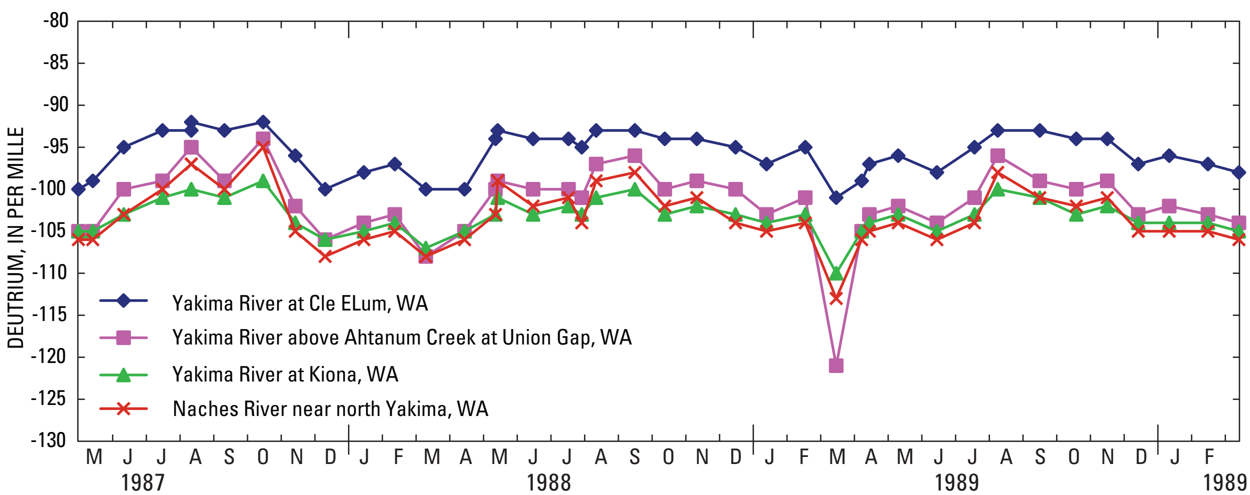


Figure 14. Seasonal variations in deuterium for selected streamflow sites, Yakima River basin, Washington.

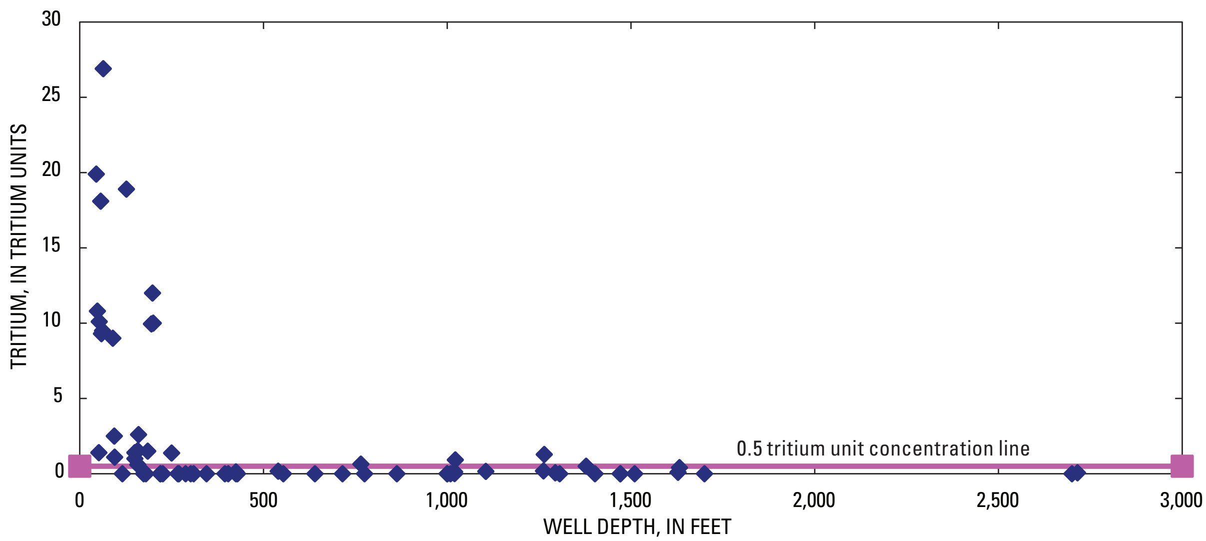


Figure 15. Relation between well depths and tritium concentrations, Yakima River basin, Washington.

Seepage Investigations

Discharge measurements can be used to estimate river-aquifer exchanges. A series of discharge measurements made along a part, or section, of a stream within a short period can be used to locate and estimate the magnitude of river-aquifer exchanges. Such "near simultaneous" measurements, called seepage investigations (or seepage runs), provide useful information on the net gain or loss for the part of a stream defined by bounding measuring sites at some particular time. Seepage investigations provide an integrated estimate of gaining and losing areas for part of a stream but do not provide information on the local, variable and complex relations between groundwater discharge and streamflow losses. The part of a stream in which a seepage investigation is completed is called a section in this report. The part of a stream within a section that has bounding measuring sites is called a reach. Seepage investigations in the basin range from sections with many reaches to a section that includes only one reach. For case in which a reach from one seepage investigation was subdivided into two or more reaches in another investigation, the terminology of segment is used and it refers to the part of a reach defined by the more detailed investigation.

The estimated (or calculated) gain or loss in flow for any particular section or reach of a seepage run is dependent on the streamflow conditions (for example, low- or high-flow conditions), time of year (non-irrigation or irrigation season), and the location and number of the measurement sites. For example, for discharge measurements with an accuracy of 5 percent and an estimated reach gain of 20 ft^3/s, the reach may be identified as neutral—neither gaining or losing—at a discharge of 500 ft^3/s (25 ft^3/s potential error), or gaining at a discharge of 100 ft^3/s (5 ft^3/s potential error). During the irrigation season, many more discharge measurements may be needed to define the inflows and (or) outflows to and from a stream section (see fig. 3). An outflow (diversion) may be as much as three times larger than the most-downstream, ending discharge measurement, resulting in large potential errors. Additionally, a reach may be gaining water during low-flow periods but losing water during high-flow periods. The selection of discharge measurement sites is generally based on access (ideally immediately upstream or downstream of a diversion or return flow) and a suitable channel condition for a measurement. The selection of a measurement site generally is not based on the concept of bounding, say, a known gaining segment, because identifying such segments is the purpose of the investigation. The site selection also depends on the magnitude of the discharge. For example, many locations are not suitable, or unsafe, for wading measurements at high flows, and the bounding ends of reaches would be further apart than during low-flow periods.

The U.S. Geological Survey has made many seepage investigations in the Yakima River basin (Magirl and others, 2009). Additionally, seepage investigations have been made by WaDOE personnel along the Naches and Tieton Rivers (Carey, 2006) and along parts of smaller creeks in Kittitas County (J. Kardouni, Washington State Department of Ecology, written commun., 2008), and the YN collected seepage information along selected reaches of Toppenish Creek and Marion drain in the Toppenish Basin (S. Ladd and D. Lind, Yakama Nation, written communs., 2008, 2009). The WaDOE and YN data also are documented in Magirl and others (2009). The seepage runs for the various investigations range from those in which discharge measurements were made only within a single, short reach and only at the upstream and downstream ends of the reach, to large-scale seepage runs encompassing many measurements along several reaches that constitute a stream section. More than 470 discharge measurements were made within 46 stream sections ranging in length from 0.4 to 206 mi (median 7.6 mi) that included about 167 reaches (Magirl and others, 2009). The reaches ranged in length from 0.1 to 31.9 mi, and typically were about 2 to 6-mi long (median 3.7 mi). Together, the seepage runs include most of the Yakima River and its principal tributary—the Naches River—as well as its major tributaries such as parts of the American and Tieton Rivers (fig. 7). Seepage investigations also were made on smaller tributaries, including parts of (in downstream order) Taneum Creek, Teanaway River, Swauk Creek, Naneum Creek, Cooke Creek, Manastash Creek, Wilson Creek, Cherry Creek, Umtanum Creek, Ahtanum Creek, Marion drain, Toppenish Creek, and Satus Creek. Discharge measurements were made on both inflows and outflows to a reach; those that were measured in at least one seepage run are shown on figure 3. The location, dates, measured discharge, and calculated change in discharge for each reach are available from Magirl and others (2009). Note that the change in discharge for a reach in Magirl and others (2009) is calculated from all the measurements between and including the bounding sites and may not be statistically significant.

In multiple seepage investigations that included the same part of a particular stream, discharge measurements were not necessarily made at the same sites. Additionally, a reach identified as being neutral (no gain or loss in flow) in one seepage investigation may include different segments identified as either gaining or losing flow in a different seepage investigation. Some investigations did not measure all the inflows and outflows between the bounding upstream and downstream measuring sites because they were limited by available resources. This is a typical problem in extensively modified basins such as the Yakima, in which ten or more inflows and (or) outflows—tributaries, diversions, return flows, and sewage-treatment plant outfalls—may occur within an 8- to 10-mi reach of a stream (fig. 3).

The spatial distribution of exchanges for the investigated reaches was shown by Magirl and others (2009) for four categories of change, expressed as a percent of the most downstream measured discharge: (1) -5–5 percent, (2) 5–10 percent, (3) 10–15 percent, and (4) greater than 15 percent, with negative values indicating losses in total flow. Where losses or gains were shown by Magirl and others (2009) to be between -5 and 5 percent, the reach generally is considered to be neutral because the calculated gain or loss may be less than the measurement error, which was assumed to be 5 percent. For reaches identified as neutral, there may be either a net gain or loss, or no net gain or loss but segments within the reach having about equal quantities of gains and losses.

Seepage investigation results are described in terms of: (1) net exchange in flow (cumulative total of gains and losses for the section of a stream being investigated that may include one or more reaches); (2) net gain and net loss (cumulative of the gains and losses, respectively, for a stream section); (3) reach gain or loss (calculated exchange for a reach bounded by upstream and downstream measurements); and (4) gain or loss for both sections and reaches normalized to their length (units of [(ft^3/s)/mi]).

Results of Seepage Investigations by Stream Sections

Net exchanges for the 46 stream sections ranged from nearly zero to 1,071 ft^3/s (average 155 ft^3/s) for 28 gaining (positive net exchange) sections, and -3 to -242 ft^3/s (average -25 ft^3/s) for 18 losing (negative net exchange) sections. In turn, the net exchange, expressed as a percent of the most downstream measured discharge, ranged from nearly 0 to about 590 percent. The magnitude of the net exchange was not significantly correlated to the percent change, but it was correlated to the total section length. The gaining sections ranged in length from 0.4 to 206 mi (median 12.7 mi), and the losing sections ranged in length from 4.9 to 37.6 mi (median 7.6 mi). The magnitude of the upper 50 percent of the positive net exchanges generally was an order of magnitude larger than those for negative exchanges (fig. 16); note that the two largest values shown on figure 16 are for the two longest sections, those for the Yakima River at Martin at River Mile (RM) 214.4 to near the mouth at RM 8.4, and the Yakima River at Cle Elum at RM 182.5 to Yakima River at Kiona at RM 29.9.For long sections, such as the above two, gains do not occur over the complete section length. For example, for the longer section (206 mi), about 55 percent of the gain occurred over about 35 percent of the total length. Net exchanges greater than about 30 ft^3/s were estimated for the Yakima and Naches Rivers and for two drains (Marion drain and Wilson Creek). The largest net exchanges for the rivers are predicated on large discharge quantities, and the largest net exchanges for the drains on the availability of groundwater inflow that originated as recharge of surface water that had been applied to agricultural fields.

The net exchange for a section was determined from a net gain plus a net loss; that is, some reaches in a section were gaining flow and some were losing flow. Of the 46 sections, 37 had reaches with gains and 27 had reaches with losses. Cumulative net gain for the 37 sections ranged from about 0.3 to 1,520 ft^3/s (average 155 ft^3/s), and cumulative net losses for the 27 sections that had at least one reach with a loss ranged from -0.3 to -553 ft^3/s (average -105 ft^3/s).

The sections had a normalized net exchange (as absolute value) that ranged from near 0 to 65.6 (ft^3/s)/mi (mean and median 5.1 and 1.9 [(ft^3/s)/mi], respectively). For the gaining sections, values ranged from about 0.1 to 65.6 (ft^3/s)/mi (mean and median 7.1 and 2.6 [(ft^3/s)/mi], respectively), and for the losing sections, values ranged from about -0.1 to -35.4 (ft^3/s)/mi (mean and median -2.0 and -0.8 [(ft^3/s)/mi], respectively). Similar to that described above, the gains (positive, normalized net exchanges) were more vigorous than the losses with 55 percent being larger than 3.0 (ft^3/s)/mi; whereas, only 6 percent of the negative net exchange was larger than 3.0 (ft^3/s)/mi.

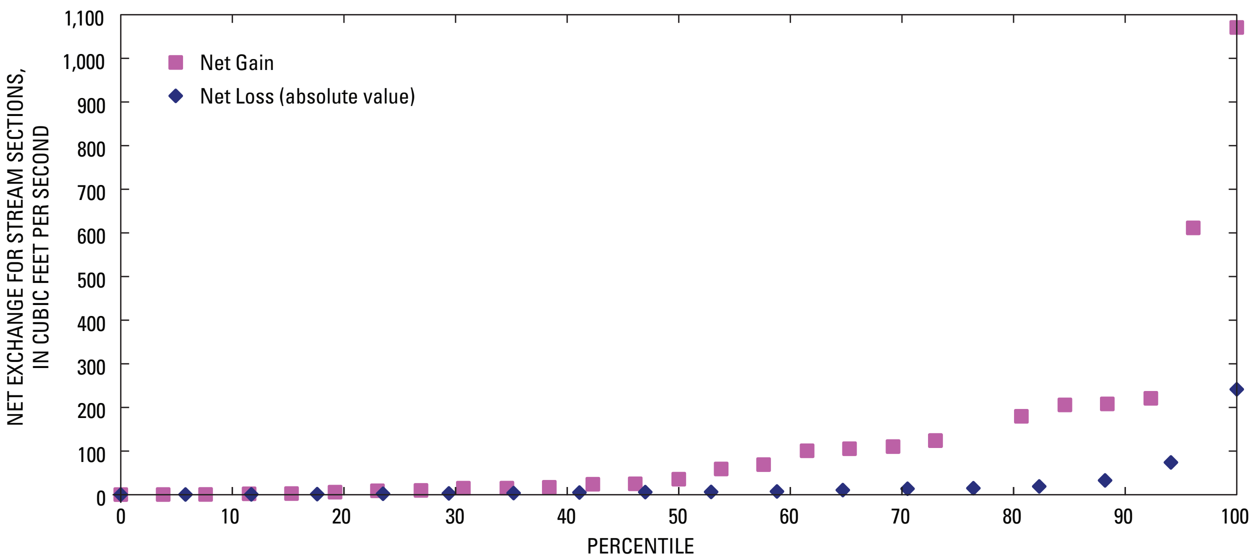


Figure 16. Percentile distribution of net gain and net loss for selected stream sections, Yakima River basin, Washington.

The seepage investigations encompassing long sections indicate a positive net exchange—a gain in flow—for the Yakima, Naches, and American Rivers. For the Tieton River, a July seepage investigation from RM 14 (7.3 mi below Rimrock Reservoir at Tieton Canal headworks) to RM 0.4 had a net gain (9 percent) and an August investigation from RM 14 to RM 2.3 had a net loss (8 percent); discharge for the two seepage runs at RM 14 was similar, 262 and 270 ft^3/s, respectively. It is unclear why the results for the two investigations differed. For all of the reaches for both Tieton River seepage runs, eight of the ten reaches had gains or losses less than 5 percent (the remaining two were each 6 percent), and seven were less than 4 percent. The difference between the results of the two investigations, therefore, may be due to measurement error. No seepage runs were made on long sections of the Cle Elum, Bumping, Little Naches, and Teanaway Rivers, or on Rattlesnake Creek. The Cle Elum, Little Naches, and Bumping Rivers, and Rattlesnake Creek likely have net gains in flow on the basis of: (1) their physical setting and their similarity to the American River, and (2) results of simulations made with watershed models (Mastin and Vaccaro, 2002). Both the Little Naches River and Rattlesnake Creek are ideal candidates for seepage investigations because of the presence of ESA-listed steelhead redds (G. Torretta, U.S. Forest Service, written commun., 2009). It is unknown if the Teanaway River would have either a net gain or loss, or a temporal variation in a net gain to a net loss because of its hydrogeologic setting. Watershed modeling results (calculated unregulated flows) for the Teanaway River indicate a slight gain (on the order of 10 ft^3/s) during low-flow periods, but it is known that parts of the lower Teanaway River lose water during low-flows.

Results of Seepage Investigations by Stream Reaches

In a seepage investigation, the net exchange of water between the stream channel and aquifer within a given section is the cumulative total of the gains (positives) and losses (negatives) in flow in the measured reach or reaches within that section. The net gains and losses for all reaches ranged from about 70 to -75 $(ft^3/s)/mi$, and varied over 5 orders of magnitude. The median values for the gains and losses were 5.1 and -4.4 $(ft^3/s)/mi$, respectively, and there were more gaining reaches/segments than losing ones. The magnitude of the gains was generally larger than the magnitude of the losses; for example, more than 40 percent of the gains were greater than 10 $(ft^3/s)/mi$, whereas only about 25 percent of the losses were greater than 10 $(ft^3/s)/mi$ (fig. 17*A*). These general relations between gains and losses are similar to the findings of Ely and others (2008) for the Chehalis River in southwest Washington and those of Konrad and others (2003) for the Methow and Twisp Rivers in north-central Washington. Unlike net exchanges for river sections, the magnitude of the gains or losses for the reaches was not correlated to the reach length, which varied from 0.1 to 31.9 mi and averaged about 7 mi.

Magirl and others (2009) presented a spatial distribution of gaining and losing reaches for all seepage investigations. For this analysis, a distribution of exchanges is discussed based on the investigated reaches, and for the case in which a reach (or part of a reach) was investigated more than once, the most detailed or reliable seepage-run data were used. This distribution accounts for potential measurement errors and other factors that may have affected estimates of gains or losses. Where reaches overlap, gains or losses for a reach may be identified for only part of the reach on the basis of measurement locations. The distribution of significant exchanges by reach is presented in appendix A. Additionally, stream reaches with gains larger than 7.0 (ft^3/s)/mi (representing the upper 48 percentile) in the basin are identified on figure 18, regardless of the percent change, because these reaches may warrant further study. The 52nd percentile represents a break point in the percentile distributions of the gaining reaches (fig. 17*A*), with a steepening of the gain-distribution line. These larger gaining reaches also identify potentially important areas for salmonid habitat. Details of the reach exchanges are described below in a downstream direction for (1) the Yakima River, (2) the Naches River, (3) the American and Tieton Rivers, and (4) smaller streams.

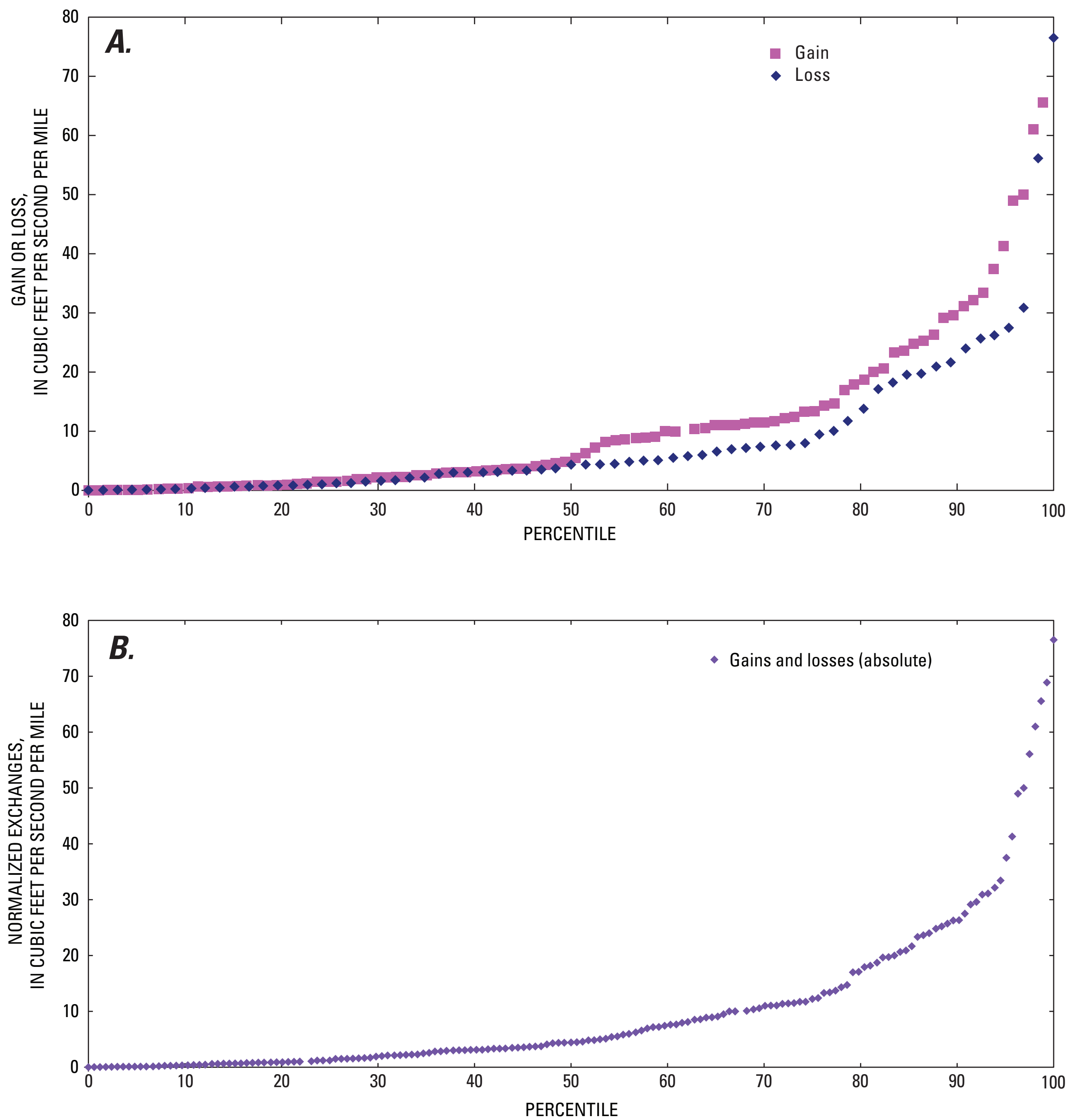


Figure 17. Percentile distribution of normalized (*A*) gain and loss and (*B*) combined gain and absolute value of loss for stream reaches, Yakima River basin, Washington.

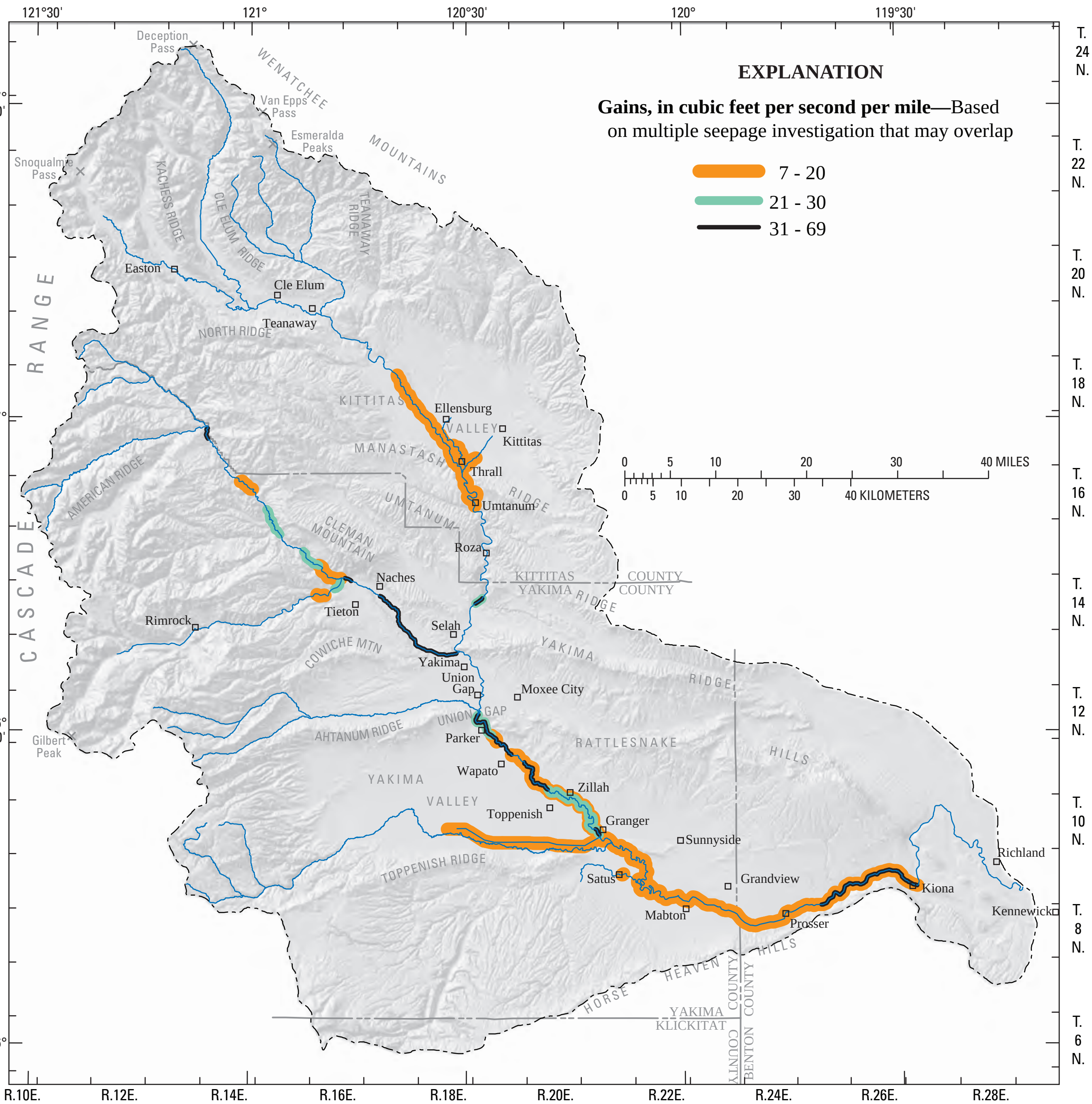


Figure 18. Location of stream reaches with gains greater than 7 cubic feet per second per mile, Yakima River basin, Washington.

Yakima River

Yakima River above Roza Dam

For the upper Yakima River basin, five seepage investigations included parts of the Yakima River above Roza dam. The most upstream, mainstem reach in which discharge was measured extended from Keechelus Reservoir (Yakima River at Martin) to the Yakima River at Cle Elum gaging station (RM 214.4–182.5). In July 1988, this 31.9-mi long reach had a net gain of 137 ft^3/s (4.3 [(ft^3/s)/mi]), which was about 4 percent of the measured flow at Cle Elum. Historical discharge data for selected winter low-flow periods, when discharge was nearly zero at the Yakima River at Martin and at the Cle Elum River near Roslyn indicate gains of 50–200 ft^3/s. A September 2001 seepage run for part of this reach (RM 202.3–195.4), called the Easton reach (fig. 8), had a net gain of 24 ft^3/s (3.5 [(ft^3/s)/mi]), which was about 14 percent of the most-downstream measured flow. For part of the complete 31.9-mi reach, discharge data from streamflow gaging sites can be used to further verify that the reach typically gains water. The sum of the discharges at the gaging stations at the Yakima River at Easton (RM 202) and the Cle Elum River near Roslyn accounts for most of the discharge at the Yakima River at Cle Elum gaging station (RM 182.5), especially during low-flow periods, when flow in the ungaged tributary streams is very small. For the period of water years 1960–2001, all but 15 of the 504 monthly mean values indicate a net gain at Cle Elum; 14 of the 15 values indicate losses that were less than one percent of the discharge measured at Cle Elum. For low-flow periods, and assuming a conservative 10 percent measurement error, gains for this 19.5-mi reach range from about 50 to 200 ft^3/s. These reaches are used by spring chinook for pre-spawning holding and spawning, and the complete 31.9-mi segment contains the most productive spring chinook spawning area in the basin.

Two seepage runs were made in the reach extending from the Yakima River at Cle Elum to RM 165.4 (Yakima River at the Thorp highway bridge). A July 1988 seepage run for this 17.1-mi reach showed a net loss of -137 ft^3/s (-7.7 [(ft^3/s)/mi]) and a February 2005 run showed a net loss of -32.8 ft^3/s (2.8 [(ft^3/s)/mi]). The July 1988 loss was about 4 percent of the 3,590 ft^3/s discharge that was measured at RM 165.4, and the February loss was about 5 percent of the 625 ft^3/s discharge measured at Thorp. A consistent loss over a wide range of discharge values suggests that this is a losing reach, which as previously described, is consistent with channel losses occurring where a river enters a structural basin (in this case the Kittitas Basin). However, gains likely occur near the terminus of the Roslyn Basin. The February seepage run, which subdivided this reach, showed that more than two-thirds of the losses occurred between RM 176.0 and the most-downstream site. An August 1999 seepage run extending from the Yakima River at Cle Elum to the Yakima River at Ellensburg (RM 155.9) that includes the above reach showed a net gain of 381 ft^3/s (14.3 [(ft^3/s)/mi]), or about 14 percent of the downstream discharge. The estimated loss in flow to Thorp indicates that most of the gain estimated from the August run occurred between Thorp and Ellensburg. Additionally, the February 2005 seepage run from RM 165.4 to the Yakima River near the head of the Yakima River Canyon (RM 148.4) showed a net gain of 101 ft^3/s (5.9 [(ft^3/s)/mi]), or 14 percent of the downstream discharge. This latter reach was subdivided into three parts for the February seepage run, and all three segments showed gains. The river therefore gains water from some point below the Thorp Bridge (RM 165.4) to the head of the canyon; this gain corresponds to the broad-scale river-aquifer exchanges previously described, with groundwater discharging to the river at upgradient locations near the terminus of a structural basin. Local and complex exchanges occur along this reach, and it was identified as a priority reach for salmonid habitat restoration (Snyder and Stanford, 2001). Thermal profile data (discussed in a later section of this document) for most of this reach confirm the existence of complex exchanges that are governed by a variety of factors.

Three seepage runs included discharge measurements in reaches that ended at the Yakima River at Umtanum (RM 140.4). The July 1988 seepage run extending from the Thorp bridge site to Umtanum showed a gain of 224 ft^3/s (8.9 [(ft^3/s)/ mi]), or about 6 percent of the flow at Umtanum; on the basis of the previous discussion, most of this gain likely occurred upstream of the mouth of the canyon (RM 148.4). The August 1999 run, extending from RM 155.9 to Umtanum showed a net loss 213 ft^3/s (-13.72 [(ft^3/s)/mi]), or about 8 percent of the flow at Umtanum, and a December 2000 run from RM 145.5 to the Umtanum gaging station showed a net loss of 1 ft^3/s (-0.2 [(ft^3/s)/mi]), or less than 0.5 percent of the 769 ft^3/s measured at Umtanum. The much larger flows (3,800 and 2,730 ft^3/s) during the first two runs, combined with potential measurement error (given the magnitude of the discharge and the numerous inflows/outflows occurring during the irrigation season during these two runs), suggest that net exchange in the reach from about the head of the canyon to Umtanum is near neutral. However, patches of groundwater discharge are known to occur based on data from temperature-sensitive radio transmitters implanted in spring chinook salmon (Berman and Quinn, 1991). The December 2000 run also showed a less than 1-percent change in discharge from Umtanum to above the Roza dam (RM 131), further suggesting near neutral net exchange throughout the canyon.

Yakima River below Roza Dam to Yakima River above Ahtanum Creek at Union Gap

Five seepage investigations included part or all of the Yakima River below Roza dam at RM 127.7 to RM 107.3 (Yakima River above Ahtanum Creek at Union Gap), and results from the seepage investigations that were assessed to be the most accurate are described below. Seepage investigations during September 2005 and March 2006 indicate that from RM 127.7 to RM 124.4 at the mouth of the canyon there is a net loss (-16 and -25 ft^3/s, respectively); the normalized losses were -4.9 to -7.4 (ft^3/s)/mi. Streamflow losses near the mouth of the canyon where the river flows out into the valley would be expected in this short 3.3-mi reach. The August 1999 seepage run for the reach from Umtanum to above Selah Creek at RM 123.9 indicates a 60 ft^3/s gain (3.7 [(ft^3/s)/mi]) or about 7 percent of the discharge at RM 123.9. Considering that the September 2005 and March 2006 seepage runs from RM 124.4 to RM 123.5 (0.4 mi below the end of the reach measured in August) showed net gains of 21 and 28 ft^3/s, respectively, the estimated August gain likely begins at about RM 124.4, and extends through RM 123.5.

The September 2005 and March 2006 seepage runs indicate neutral net exchanges from RM 123.5 to RM 116.7 (Yakima River at Harlen Landing), and the September-run data, which subdivided that reach, also indicate neutral conditions from RM 121.7 to RM 116.7. Exchanges between RM 116.7 and RM 107.3 can be estimated from seepage runs in July 1988, July 2004, September 2005, and March 2006. This reach includes inflow from the Naches River and the Roza power return (Roza Wasteway #2), and the reach contains the Union Gap reach (mouth of Naches River to RM 107.3) that was ranked the highest in the basin for benefits from flood plain restoration (Snyder and Stanford, 2001). The first three seepage runs had net gains that were between 4 and 25 ft^3/s (less than 1 percent of the discharge at RM 107.3). Whereas, the March seepage run had a net loss of -247 ft^3/s (-26.3 [(ft^3/s)/mi]) that was about 11 percent of the discharge measured at RM 107.3; the loss was 40 percent of the discharge at RM 116.7 and 26 percent of the Naches River inflow. The September 2005 seepage run subdivided this reach, and the results indicated a loss between RM 116.7 and the Roza power return at RM 113.2 and a gain from RM 113.2 to the end of the reach at RM 107.3; however, the changes in discharge were only about one percent of the observed flow. Based on the conceptual model of broad-scale river-aquifer exchanges in the structural basins with groundwater discharging upgradient from Union Gap (Kinnison and Sceva, 1963; Vaccaro and others, 2009) and groundwater levels (Vaccaro and others, 2009), it is unclear why the results differ, and that a loss was estimated from the March seepage run. About 30–100 ft^3/s of groundwater is captured by Wide Hollow Creek and Moxee Drain, and thus, it is likely that the remaining groundwater discharge is less than the potential measurement error. For example, the discharge at the gaging station at RM 107.3 ranged from 2,240 to 3,280 ft^3/s for the four seepage runs.

Yakima River above Ahtanum Creek at Union Gap to Yakima River at Euclid Bridge near Grandview

Eight seepage investigations included all or part of this river section that extended from RM 107.3 to RM 55. Of the five investigations that included the complete section, four were made during the irrigation season and one in March (prior to the irrigations season but when canals were being primed and some drains/wasteways where flowing). For the irrigation season runs, discharge at the Yakima River above Ahtanum Creek gaging station ranged from 2,240 to 3,560 ft^3/s, and measured discharge downstream at Yakima River at Parker (RM 103.7) ranged from 97 to 685 ft^3/s (discharge reduction from RM 107.3 due to Wapato and Sunnyside canal diversions); whereas, discharge was 2,054 ft^3/s at Parker for the March run. Additionally, these five runs also used RM 82.9 and RM 72.4 (Yakima River above Granger Drain and Yakima River above Satus Creek, respectively) as a downstream measurement point. Exchanges were estimated for each section: the 52.3-mi section (RM 107.3 to RM 55), the 34.9-mi section (RM 107.3 to RM 72.4), and the 24.4-mi section (RM 107.3 to RM 82.9). For the longest section ending at RM 55, exchanges varied widely, from -0.3 to 16.4 (ft^3/s)/mi, with four of the five showing gains. All five runs showed gains ranging from 0.7 to 15.7 (ft^3/s)/mi for the section ending at RM 72.4, and for the section ending at RM 82.9, exchanges ranged from -0.6 to 6.2 (ft^3/s)/mi (with only one run showing a loss). Together, these results indicate that all three sections are gaining and that during the early spring prior to the irrigation season with higher flows the entire section appears to be about neutral but with a significant gain between RM 107.3 and RM 82.9. The latter is likely caused by a combination of higher stage in the river and lower groundwater levels resulting from groundwater drainage during late October through March.

Although a gain occurs in these sections, measurements from numerous upstream reaches in these long sections indicate a complex relation between gains and losses. Based on concurrence of measurement locations and (or) more detailed investigations of parts of these sections, selected reaches are able to be identified that have gains or losses. These reaches (appendix A) are described below.

Five seepage investigations included the 3.7-mi reach from Union Gap to the Yakima River at Parker (RM 103.7). Three investigations estimated gains of 25–33 (ft^3/s)/mi and two indicated losses of about -5 (ft^3/s)/mi, but the losses were only about 1 percent of the discharge quantities at Union Gap and the discharge for the Sunnyside and Wapato canals that divert in this short reach. This reach is identified as gaining based on consistency of results for three of the runs with gains. One of these runs was made just prior to the irrigation season when the diversions for Sunnyside and Wapato canals were much smaller than during the irrigation season, and another run was done just after the irrigation season when diversions had ceased. Although this is a gaining reach, mini-piezometer data (described in the following section) indicate a losing section that begins upstream of Parker.

Two seepage runs for the 0.9-mi reach between RMs 103.7 and 102.7 yielded net exchanges of 12.2 and 69 (ft^3/s)/mi. The larger value was during higher flows in the non-irrigation season and indicates flow dependency of exchanges, that is, the exchanges vary by both season and flow. Using data from another seepage run and other discharge data, exchanges ranging from about 5 to 15 (ft^3/s)/mi were estimated for this short reach. Between RMs 102.7 and 100.3, a net exchange of -17.1 (ft^3/s)/mi was estimated from a September low-flow (390 ft^3/s) run and the higher-flow (2,100 ft^3/s) March run yielded a net exchange of

37.5 (ft^3/s)/mi. Similar to above, this reach also displays flow dependency of exchanges. However, in this case there was a reversal in the direction of the exchanges that was opposite of what was expected. The March run included a 2.3-mi reach from RM 100.3 to 98 and a 4.9-mi reach from RM 98 to 93.1, with estimated exchanges of -77 and 50 (ft^3/s)/mi (gain of 240 ft^3/s), respectively. The 4.9-mi reach was part of a longer reach (RM 98 to 86.6) measured two days earlier as part of the seepage run, and had a net exchange of 11 (ft^3/s)/mi, suggesting losses between about RM 93.1 and 86.6.

Three seepage runs, including the higher-flow March run, had common measurement sites at RMs 102.7 and 82.9 (a 19.8-mi section), and include the reaches described above. All three had normalized gains that ranged from 2.3 to 11.3 (ft^3/s)/mi, indicating that the direction and magnitude of exchanges over short reaches are moderated when extended to long sections. Additionally, two of these runs also included the reach from RM 102.7 to 93.1 that had normalized exchanges of -3.0 and 10.7 (ft^3/s)/mi. Three runs included the reach from RM 93.1 to 82.9, with normalized gains of 6.1, 10.2, and 24.8 (ft^3/s)/mi. The separation of the exchanges for the 19.8-mi section into two reaches further indicates complex spatial relations, flow dependency, and vigorous (significant) gains in the lower 10-mi part of the section. At the end of the downstream reach (RM 83.7 to 82.9), two runs had estimated, normalized gains of 2.1 and 50 (ft^3/s)/mi, and using information from another run, a normalized gain of 78 (ft^3/s)/mi was estimated; again this information also indicates the prevalence of very large gains in the lower part of this segment. Thermal-profile data for part of this section (described in a later section and shown in Vaccaro and Maloy [2006]) also indicate groundwater discharge in the form of dramatic cooling of the streamflow over part of this 19.8-mi section during August at low flows.

Four seepage runs for a 10.5-mi reach from RM 82.9 to 72.4 estimated normalized exchanges of 10.4, -4.0, -11.6, and 5.8 (ft^3/s)/mi. The two runs with normalized losses also had RM 75.6 (Yakima River below Toppenish Creek) as a common measurement site. Both runs showed a loss from RM 82.9 to 75.6 and a gain from RM 75.6 to 72.4. Based on measurements from a July 1988 seepage run, a 10 (ft^3/s)/mi normalized gain can be estimated for this latter reach. Thus, the results indicate that the lower part of the 10.5-mi reach is gaining and the upper part varies based on the magnitude of discharge and likely the type of climatic year (dry in contrast to a wet or average year).

The last part of the complete section (RM 107.3 to RM 55) had five seepage runs with measurement sites at RMs 72.4 and 55. The results from these runs varied widely, with net normalized exchanges ranging from -20 to 18 (ft^3/s)/mi. This reach was subdivided into two segments by two of the runs, and the results showed gains to about RM 59.8 (Yakima River at Mabton) and losses to RM 55. The results suggest that the exchanges in the lower part of this 17.4-mi reach are highly sensitive to flow quantities, time of year, and type of climatic year (for example, dry in contrast to wet/average).

Yakima River below Euclid Bridge

Three seepage runs, two from RM 55 to 46.1 and one to RM 46.3 end at about the Yakima River at Prosser, which is below the Chandler-Prosser power canal diversion; the diversion ranged from 546 to 1,330 ft^3/s during the runs. Another seepage run ended at RM 43.9 and a second ended at RM 43. All but one of the results from the runs indicated gains, but because of the potential measurement error associated with the power diversion and the magnitude of the discharge at RM 55, only one of the runs had a significant gain. The narrowing of the structural Toppenish Basin with a concurrent decrease in sediment thickness in this location would suggest that this would be a gaining reach. Calculated normalized gains of 3.5 and 13.6 (ft^3/s)/mi from seepage runs for the reach between RM 55 and RM 43.9, and neutral exchanges between RM 43.9 and 43, further suggest that this is a gaining reach.

Seepage runs for the reach from RM 43 to 29.9 (Yakima River at Kiona) had estimated normalized exchanges of 5.4 and 32 (ft^3/s)/mi. Another run from RM 46.3 to 29.9 had an estimated normalized exchange of 13 (ft^3/s)/mi, and a normalized exchange of 32 (ft^3/s)/mi was estimated for a run between RM 43.9 and 29.9. The 13.1-mi reach is used by fall chinook salmon for spawning, likely attributable to the presence of good spawning gravels and groundwater discharge. A gain would be expected for this more bedrock-controlled reach because of its physiographic setting and decrease in sediment thickness. This aspect is important because though it is commonly thought that bedrock-controlled reaches may not be ideal salmonid habitat, groundwater discharge would be focused in the river channel and would occur throughout most of the year. This type of habitat provided by groundwater discharge in bedrock-controlled areas also would occur in the humid uplands where ESA-listed bull trout spawn. From RM 29.9 to 8.4 (Yakima River at Van Geisan Bridge), losses were estimated from two runs. Groundwater-level data from this study (Vaccaro and others, 2009) and previous work (Brown, 1979; Drost and others, 1997) also indicate that this is a losing reach over most of its length. Drost and others (1997) indicate that this is especially true where the Saddle Mountains unit is exposed in the streambed north of Benton City.

Naches River

A July 2004 seepage investigation by WaDOE (Carey, 2006) for a section that included nearly the complete Naches River (RM 43.5–0.5) contained 17 reaches. Sixteen of the reaches ranged in length from 0.5 to 3.2 mi and the remaining reach (the most downstream one) was 12.3-mi long. Additionally, two other reaches (RM 43.5–36 and RM 17.2–16.3) were investigated by the USGS in August 2002. Normalized exchanges for the 19 reaches ranged from about -31 to 66 (ft^3/s)/mi; 10 of the reaches had gains and 9 had losses.

For the July 2004 investigation, losses totaled 179 ft^3/s and gains totaled 385 ft^3/s, yielding a net exchange of 206 ft^3/s (4.8 [(ft^3/s)/mi]) for the river; the reaches with gains had larger exchanges than those with losses. The average, absolute normalized exchange for the 17 reaches was about 20 (ft^3/s)/mi, which is about the 85th percentile for all of the reaches investigated (fig. 17*B*). More than 50 percent of the Naches River reaches had an absolute normalized exchange greater than 20 (ft^3/s)/mi, indicating that exchanges in the Naches River generally are more dynamic than those for the Yakima River. Additionally, the large normalized values for the Naches River also are larger than those for other large rivers with investigations conducted by the USGS. For example, the large exchanges are in contrast to those reported by Ely and others (2008) for the Chehalis River basin in southwestern Washington where all but 2 of 35 calculated normalized exchanges (absolute values) were less than 20 (ft^3/s)/mi (80 percent were less than 10 [(ft^3/s)/mi]) and the two largest exchanges were losses. The large variations in exchanges also highlight the problem associated with using long reaches for seepage investigations. For example, from RM 43.5 to 31.1 (about the same length as the 12.3-mi lower reach) there were eight seepage-run reaches, five of which had losses and three gains. There was a net gain over this section (a 10 percent increase) but the discharge measurements for the eight reaches indicated that exchanges oscillated between gaining and losing. For the discussion below, Naches River reaches are aggregated if two or more contiguous reaches had the same directions of exchange.

A normalized loss of -24 (ft^3/s)/mi occurred from RM 43.5 to 43 that was followed by a normalized gain of 61 (ft^3/s)/mi to RM 42. From RM 42 to 38.8, a normalized loss of -10.3 (ft^3/s)/mi was measured, which in turn was followed by a normalized gain of 6.7 (ft^3/s)/mi to RM 34. A -4.5 (ft^3/s)/mi normalized loss occurred from RM 34 to 31.1, which was followed by a normalized gain of 29 (ft^3/s)/mi to RM 28. The next downstream reach from RM 28 to 23.9 showed a -14.9 (ft^3/s)/mi normalized loss. However, a thermal infrared (TIR) survey of the Naches River (Carey, 2006) showed large streamflow cooling between RM 30.1 and 25.7 indicating gains attributed to a series of springs and seeps. Thus, loses between RMs 28 and 23.9 likely occur downstream of these groundwater inputs; the TIR data also indicated warming below about RM 25.5. From RM 23.9 to 17.6 there was a normalized gain of 17 (ft^3/s)/mi. Losses occurred from RM 17.6 to 12.8 that totaled 60 ft^3/s (-12.5 [(ft^3/s)/mi]). The final 12.3 mi of the section had a normalized gain of 41.3 (ft^3/s)/mi. However, information presented in Kinnison and Sceva (1963) and groundwater-level data collected as part of this study (Vaccaro and others, 2009) indicates that the most downstream part of this section is losing. The lower 5 mi of this section also was identified as an extensive upwelling zone containing substantial fish habitat (Snyder and Stanford, 2001).

The vigorous exchanges that alternate between gaining and losing are consistent with the physical setting of the Naches River and in general, with higher gradient streams. These streams alternate from steep gradients to lower gradients, and in some locations, the lower-gradient segments are associated with a widening of the river valley. The variation from bedrock controlled to alluvial valley streamflow strongly affects the gains-losses in such systems. The magnitude of the exchanges indicates that there should be good salmonid habitat along much of the Naches River. Segments of the Naches River between about RM 32 to 26 and RM 17.6 to the mouth have been identified as high-priority restoration reaches (Snyder and Stanford, 2001).

The two reaches investigated in August 2002 were from RM 43.5 to 36 and RM 17.2 to 16.3. The first reach had a normalized gain of 2.27 (ft^3/s)/mi, which is consistent with the exchange calculated from the July seepage run for the same two sites. A very large normalized gain of about 66 (ft^3/s)/mi was calculated over the short, 0.9-mi, second reach. The July estimate for a reach that includes this 0.9-mi segment indicated a loss, but the July streamflow was more than double the streamflow during the August seepage run. Thermal-profile data (described later) also indicates the 0.9-mi segment is gaining but quickly transitions to losing as the river enters a broad alluvial valley.

American and Tieton Rivers

One seepage investigation was conducted for the American River and two for the Tieton River. The American River investigation included two reaches for the section between RM 13.3 to 0.6, and it was conducted during a low-flow period in September. The Tieton River investigations included an August 2003 seepage run for the section from RM 14 to 2.3 (11.7 mi) that was divided into three reaches, and a July 2004 seepage run for the section from RM 14 to 0.5 (13.5 mi) with nine reaches. Discharge during both of the Tieton River investigations generally were similar, with the August discharge being about 30 ft^3/s less (10 percent).

The American River reach between RM 13.3 and 5.7 had a normalized gain of 1.5 ft^3/s-mi (about a 50 percent increase), and a normalized gain of 0.9 (ft^3/s)/mi (a 10 percent increase) was estimated for the reach between RM 5.7 and 0.6. For the complete section, the net gain was 15 ft^3/s (about 1.2 (ft^3/s)/mi, or a 44 percent increase). The large difference in the magnitude of exchanges between the Naches and American Rivers is related to several factors. First, the Naches River discharge during the investigation was an order of magnitude larger than the American River discharge (432 ft^3/s in contrast to 42 ft^3/s). The steeper stream gradient of the American River (0.012 ft/ft) compared to the Naches River (0.0062 ft/ft) and more bedrock control (limited alluvial aquifer) limits the exchanges in the American River. However, locally where an alluvial aquifer occurs (for example, see fig. 10*A*) it would support vigorous exchanges because streamflow losses would quickly become gains; for example, in areas of transitions from pools to riffles to bedrock control.

The three reaches from RM 14.0 to 2.3 for the Tieton River investigation in August 2003 were all losing, but none of the losses were greater than 5 percent of the measured discharge. However, the net loss for this 11.7-mi section was -19 ft^3/s (-1.6 [(ft^3/s)/mi]) or about 7 percent of the discharge measured at RM 14. The July seepage run had a net gain of 17 ft^3/s (1.5 [(ft^3/s)/mi]) from RM 14 to 2.2 that was about 6 percent of the discharge at RM 14. Similar to the August run, no gains or losses for four reaches from RM 14 to 6.1 were greater than 5 percent. The next two downstream reaches (RM 6.1 to 4 and RM 4 to 3) had a significant loss and gain (-16 and 17 ft^3/s, respectively), that was followed by a decrease of only 1 percent from RM 3.0 to 2.2; these estimates are consistent with no significant exchange estimated from the August seepage run for about this same reach. For the July investigation, the Tieton River had a net gain of 25 ft^3/s (6.9 [(ft^3/s)/mi]) to RM 0.5 that was about 10 percent of the discharge at RM 14; this is in contrast to the smaller (6 percent) gain to RM 2.2. Based on the more detailed July investigation, the significant exchanges occurred in four of the five reaches below RM 6.1 and normalized exchanges varied from -25.7 to 23.6 (ft^3/s)/mi, and averaged (absolute) about 18.5 (ft^3/s)/mi (compared to 9.7 (ft^3/s)/mi for the complete section). It is in the lower part of the system that there are areas with a larger flood plain, side channels, and an alluvial aquifer. For example, from RM 6.1 to 4.0 there was a net normalized loss of -7.6 (ft^3/s)/mi where the river flowed from a bedrock-controlled valley into a widening alluvial valley. This loss was followed by a net normalized gain of 17 (ft^3/s)/mi from RM 4.0 to 3 where the river became constrained by bedrock with a diminishing of the alluvial valley aquifer. Below Oak Creek at about RM 2.2 there is a nick point, after which the alluvial valley widens continually to the mouth of the Tieton River. It is in this lower part where the most vigorous exchanges occur that can be attributed to the presence of a large alluvial aquifer; such exchanges may provide good habitat for holding or rearing fish.

Excluding areas of springs, which are not mapped, good salmonid habitat in the higher gradient American River (0.012 ft/ft) and upper parts of the Tieton River (gradient 0.01 ft/ft) likely is associated with areas where the stream gradient diminishes in a widening of a river valley with distinct pool-riffle structure, deeper pools, and groundwater discharge areas near the narrowing of the valley and (or) channel upstream of a bedrock-controlled area. These types of areas would support more vigorous exchanges and some parts likely would provide areas of slow velocity and shallow water. Widening and flattening stream valleys, however, are the types of areas that are more prone to development and other human activities, such as campgrounds.

Smaller Streams

Seepage investigations for short reaches of smaller streams were made throughout the basin. Results are described on the basis of three areas in the Yakima River basin—upper, middle, and lower. In the upper basin, there were seepage investigations for the Teanaway River, and Taneum, Swauk, Naneum, Cooke, Manastash, Wilson, Cherry, and Umtanum Creeks. In the middle basin, a seepage investigation was done on Ahtanum Creek in 1897 by the USGS. In the lower basin, Yakima Nation provided seepage information for Toppenish Creek and Marion drain, and the USGS investigated seepage on Satus Creek.

Upper Basin

The investigation for the downstream 3.6 mi of the Teanaway River showed that exchange was near neutral with only a 0.11 (ft^3/s)/mi normalized gain (about a 3 percent gain). However, data from monitoring wells along this part of the river (Snyder and Stanford, 2001) indicate localized, complex exchanges.

Information for Taneum Creek indicates both flow and site dependency of exchanges. Discharge measurements during four seepage runs varied from a maximum of 32 ft^3/s in June 2005 to 3.9 ft^3/s in August 2005. The June investigation for a 6-mi section between RMs 10 and 4 had a 22 percent normalized gain (about 1 [(ft^3/s)/mi]). A seepage investigation between RMs 10 and 2 made in July included three reaches, two of which included the RM 10–4 section. The net gain for the 8-mi section was only 1.1 ft^3/s (about 0.18 [(ft^3/s)/ mi]), but it represented a 10 percent gain. The upper reach in this section had a normalized loss of -1 (ft^3/s)/mi (24 percent) to RM 7.9 and another reach had a normalized gain of 0.8 (ft^3/s)/ mi (27 percent) to RM 4. The next downstream reach (RM 4–2) had a normalized loss of -1.2 (ft^3/s)/mi (27 percent). Consistent with the July run, an August investigation found a -2.2 (ft^3/s)/mi (53 percent) normalized loss for the upper (RM 10–7.9) reach but an insignificant (2 percent) loss from the combined downstream reaches (RM 7.9–2). The fourth seepage investigation in November 2003 covered the section between RM 6.9 and 1.6 and included two reaches; discharge was most similar to the lower August flows. Taneum Creek had a normalized loss of -0.47 (ft^3/s)/mi (28 percent) from the upper reach (RM 6.9–3.3) that was followed by another loss of -1.21 (ft^3/s)/mi (51 percent) from the lower reach (RM 3.3–1.6). Together, the data indicate that during higher flows the creek gains water to at least RM 4. During lower flows there appears to be a distinct losing segment from about RM 4 to 1.6. Losses would be expected where Taneum Creek flows out onto the valley floor, especially near its terminal fan. The July seepage run results indicate that during transition flows, the RM 10–4 section has losses to RM 7.9 that is followed by gains to RM 4.

WaDOE information for Swauk Creek from RM 5.9 to 0.1 indicates that this is a losing reach, with a loss of about -0.1 (ft^3/s)/mi. The physical setting as Swauk Creek nears its mouth with an alluvial fan would be consistent with a losing reach. This control is similar to that described above for Taneum Creek.

Naneum Creek had four seepage investigations (June, July, August, and October 2005). Three to four reaches were included in the section from RM 22.6 to 15.3. Measurements at RM 17.4 and 15.3 are relative to the main channel of the creek and not to side channels that may flow during high-flow periods. The seepage runs indicate a gaining reach from RM 22.6 to 20, especially at higher flows. Three runs included the reach from RM 20 to 17.4 and the results were not conclusive. Two runs had insignificant (3 percent) gains and one had a 20 percent loss (-0.8 [(ft^3/s)/mi]). Similarly, the August and October runs included the reach from RM 17.4 to 15.3; the August run had an insignificant (1 percent) gain, whereas the October run had a significant (11 percent) normalized gain of 0.6 (ft^3/s)/mi. Thus, the data indicate that Naneum Creek (1) gains from RM 22.6 to 20; (2) likely gains during higher flows and outside of the irrigation season, and loses during lower flows from RM 20 to 17.4; and (3) generally gains from RM 17.4 to 15.3.

Cooke and Umtanum Creeks were each investigated with two seepage runs. Cooke Creek had two significant gaining reaches, from RM 17.4 to 3.4 and from RM 3.4 to 3.0. Gains for Cooke Creek were as large as 30 percent, with normalized gains ranging from 0.1 to 1.6 (ft^3/s)/mi. Similarly, Umtanum Creek has a distinct gaining reach from RM 4.6 to 0.2. Seepage runs showed gains in this reach as much as 42 percent. This area of Umtanum Creek is basalt-bedrock controlled, and is groundwater fed much of the year. Cuffney and others (1997) rated Umtanum Creek as unimpaired for fish, and benthic invertebrate and algal communities. Cool water at the mouth of the creek may provide habitat for fish.

Wilson and Cherry Creeks, mean annual discharge of 120 and 168 ft^3/s, respectively, discharge near the terminus of the Kittitas basin. Under natural conditions, these creeks would have flowed most of the year with low base flows. Owing to surface-water irrigation, the creeks now act as farm drains for much of the year and abstract excess water (groundwater and surface water) from irrigation in the Kittitas Reclamation District. In order to better understand the groundwater component, a seepage run was completed on small sections of each creek during December when they do not receive direct surface water from the irrigation systems. For the 3.1-mi section from RM 4.2 to 1.1, Wilson Creek had a normalized gain of 70 percent or about 11.5 (ft^3/s)/mi, which corresponds to the magnitude of exchanges estimated for the Yakima and Naches Rivers. Similarly, Cherry Creek gained about 18 percent from RM 1.3 to 0.3 (10.6 [(ft^3/s)/mi]). Streamflow records indicate that the groundwater baseflow component of Wilson and Cherry Creeks is about 70 and 50 percent of total flow, respectively. The above information suggests that the two creeks gain groundwater at a high rate throughout most of their extents in the basin-fill sediments.

Middle and Lower Basins

A seepage run was completed in 1897 by the USGS for the North Fork Ahtanum Creek and Ahtanum Creek between RM 24.6 and 16.2, and included three reaches that ranged in length from 1.8 to 3.5 mi. A normalized loss of -6.9 (ft^3/s)/mi (50 percent) was calculated between RM 24.6 and 22.8 for the North Fork of Ahtanum Creek. The loss is consistent with the creek flowing out onto a valley floor where it leaves the bedrock-controlled, upland valley. Between RM 22 and 20.9, a 21 percent gain (2.94 [(ft^3/s)/mi]) was observed. In this area, the alluvial valley diminishes at what is locally named the Narrows (a basalt-controlled steep-walled valley), and groundwater discharges to the stream near and in the head of the Narrows and loses water through the rest of the Narrows. Downstream to RM 16.2, the creek lost water at a normalized rate of -1.7 (ft^3/s)/mi where it emerges from the Narrows. In an analysis of the groundwater in Ahtanum Valley, Foxworthy (1962) described similar relations for Ahtanum Creek. A seepage run with one reach was made in March 2005 prior to irrigation for the section from RM 22 to near the mouth at the site Ahtanum Creek at Union Gap. The results indicated that net exchange in the section was neutral; thus, suggesting that the gains are balanced by the losses from above the Narrows to the mouth.

In the structural Toppenish Basin, a seepage investigation completed in March 2009 by the YN on Marion Drain between RM 20.8 and 0.3 indicated very large net gains over this section. The drain gained about 180 ft^3/s (from 7 ft^3/s at RM 20.8 to 187 ft^3/s at RM 0.3), and all reaches within the section were gaining. The reach with the most vigorous exchanges extends from about RM 17.3 to 12.9 and had normalized gains on the order of 12 (ft^3/s)/mi. Marion drain is used by summer steelhead and fall chinook salmon for spawning, and this utilization likely is related to the groundwater discharge and its source; the groundwater is derived from both Toppenish/Simcoe Creek and excess Yakima River water from irrigation in the Wapato Irrigation Project (WIP). Similar to Wilson and Cherry Creeks, the normalized exchanges are more typical of the magnitude of exchanges for the Yakima and Naches Rivers and not to those of smaller streams. As another example of a large drain and how they function, Sulphur Creek Wasteway typically flows at 50–70 ft^3/s from November through February owing to groundwater discharge. The magnitude of the exchanges indicates the importance of larger drains with respect to flow in the shallow groundwater system and river-aquifer exchanges. For the former case, large drains locally are a major control on the shallow flow system, and for the latter case, the discharge of groundwater to the drains ultimately results in point surface-water discharges to the Yakima River and thus, a decrease in diffuse groundwater discharge.

A series of discharge measurements by the YN on Toppenish Creek from RM 45.1 to 40.2 between June 2006 and February 2008 provided average, seasonal seepage information. The results show Toppenish Creek loses water from RM 45.1 to 41.6 as it flows onto its large alluvial fan, and then gains water from RM 41.6 to 40.2. The average seasonal normalized losses (ranging from about 3 to 4.4 [(ft^3/s)/mi]) were more vigorous than the gains (ranging from about -0.3 to -2.2 [(ft^3/s)/mi]). Losses, as a percentage, tend to be largest during the July through September period when flows are lower and smallest during the January through March period. In contrast, gains tend to be largest during the

October through December period and smallest during the July through September period. The losses across the fan provide a component of the gains observed in Marion drain.

The most southern creek investigated in the basin was Satus Creek, where a seepage run for a section from RM 37.7 to 3.0 was made in September 2003. Of the five reaches in this section, three had significant exchanges. From RM 37.7 to 24.7, the creek lost all of it flow (4.3 ft^3/s or 0.33 [(ft^3/s)/mi]). From RM 24.7 to 17.8, all flow in Satus Creek was attributable to inflow from Logy Creek and exchange in this reach is considered neutral. A loss of 7 percent (-0.11 [(ft^3/s)/mi]) was measured from RM 17.8 to 8.0, and the loss was followed by a gain of 44 percent (2.5 [(ft^3/s)/mi]) from RM 8.0 to 3.2. The gain in the latter 4.8-mi reach likely can be attributed to groundwater discharge from the surface-water irrigated areas in the Satus extension of the WIP. The final reach (RM 3.2–3.0) had no significant exchange. The Satus Creek basin has a high production of summer steelhead (D. Lind, Yakama Nation, written commun., 2009) and given the location of steelhead redds that are generally associated with groundwater discharge, gaining shorter segments from RM 24.7 to about 7.5 should occur, again indicating the importance of incorporating short reaches in seepage investigations.

Mini-Piezometer Measurements

The use of mini-piezometers to measure stream water levels and concurrent adjacent groundwater levels to indicate the direction of exchanges (groundwater discharge or streamflow losses) was described early in the literature, and was oriented to studies of salmonid habitat (Gangmark and Bakkala, 1958; Terhune, 1958; Coble, 1961; Vaux, 1962). This method was modified for the reach surveys in the Yakima River basin using in-stream manometer-style measurements (Fokkens and Weijenberg, 1968; Lee and Cherry, 1978; Winter and others, 1988). Instream mini-piezometers are miniature monitoring wells that are hand-driven into the streambed to a depth of 3.0 to 6.5 ft. They are used for measuring groundwater levels with concurrent measurement of surface-water levels, and both are referenced to the top of the piezometer. A mini-piezometer typically comprises a 7-ft pipe that is crimped and perforated with small holes at the bottom. To the extent possible, the piezometers are installed to avoid areas where there may be a large influence from hyporheic flow, such as on point bars or the terminus of a pool/riffle/island. After placement, mini-piezometers are developed (pumped) to improve the hydraulic connection between the piezometer and streambed. The USGS uses a manometer board to make direct measurements of the hydraulic heads (fig. 19), but in streambeds comprising low hydraulic conductivity material, a steel tape or electrical tape is used instead of a manometer to make measurements relative to the top of the piezometer (Simonds and others, 2004), similar to the method employed by WaDOE (Carey, 2006).

The mini-piezometer measurements—groundwater levels and concurrent river water level—provide an estimate of the vertical hydraulic gradient (VHG) between the river and the shallow groundwater. By convention, a positive VHG value indicates an upward vertical gradient (groundwater discharge to the channel) and a negative value indicates a downward vertical gradient (streamflow losses to the underlying aquifer). For discussion purposes, absolute values also are used in order to describe direct comparisons of the magnitude of the VHGs. Measured VHGs reflect local conditions only and may not be representative at the reach scale. For example, a negative gradient may be observed at a site within a reach that has an overall net gain because the net gain for a reach typically occurs over a small fraction of the total length of a reach and the negative VHG may have been measured in a losing part of this reach. Additionally, the fraction varies by geologic terrane, for example, igneous in contrast to sedimentary rocks and thus the fraction accounting for the net gain may be small (Konrad, 2006). Single measurements also do not capture seasonal variations; for example, Simonds and others (2004) and Cox and others (2005) determined that seasonal or temporal changes (or reversals) in the direction of the VHG are dependent on the relative magnitude of streamflow. Reversals of this type are displayed by some of the data collected in the basin, and the reversals are consistent with flow-dependency of some exchanges as described previously for the seepage runs. However, Cox and others (2005) also show that the VHG can be maintained over a reasonably large range of flows. Variations and changes in VHGs also are known to occur across a river transect (Stanford and others, 2002; Cox and others, 2005) and are consistent with previously documented changes in directions across transects. For example, Jackman and others (1997) found large variations in the VHG across the width of a small stream, and data presented in White and others (1987) suggest variations in groundwater discharge across a 21-ft wide river.

Mini-Piezometer Results

The USGS made mini-piezometer measurements at 33 sites (15 on the Naches River and 18 on the Yakima River) during August and September 2002, and at 7 sites on the lower Yakima River during August of 2006 and 2007. WaDOE made mini-piezometer measurements four times between June and October 2004 at eight sites on the Naches River and at one site on the Tieton River (Carey, 2006). Three of the WaDOE sites were vandalized, so that only one measurement was available for two of these sites and three measurements were available for the remaining site. FLBL made measurements at 36 transects between July 2000 and April 2001 and the number of measurement sites per transect ranged from 2 to 13 (Stanford and others, 2002). Six of these transects were in locations that were useful for understanding the VHG in such areas as side channels or spring brooks, but the data were not applicable to

Figure 19. Hydrologist making a mini-piezometer measurement using a manometer board in the Parker reach of the Yakima River, Washington. (Photograph taken by William Simonds, U.S. Geological Survey, September 5, 2002.)

locations in the mainstem that do not have a large component of hyporheic flow. The information from the remaining 30 transects, however, were incorporated in this analysis for this study. The FLBL data were available only in graphical form, and the estimates of VHG are based on the graphs. An average VHG for a river transect was calculated using estimates centered on the thalweg. Therefore, the FLBL values listed in this report indicate the magnitude and direction of the VHG, but the magnitudes of the values are relative, with the smaller VHG values being least accurate because actual values were difficult to discern from the graphs.

The 99 measured VHGs used in the analyses made as part of this study and associated information for the measuring sites are presented in table 1 and shown on figure 20 (note that for the case of more than one measurement at a site the average value is shown). The USGS measurement at RM 103.7 was estimated based on the depth of penetration of the piezometer below the streambed and the depth of the surface water because the piezometer was dry; based on this method the VHG at this site was estimated to be -5 ft/ft. The 99 measurements had an average VHG of -0.36 ft/ft (median -0.35 ft/ft), and in terms of absolute values, the average was 0.29 ft/ft (median 0.05 ft/ft). Of the 99 measurements, 70 indicated negative VHGs (propensity for streamflow losses), 29 indicated positive VHGs (propensity for streamflow gains). The range in values of VHGs was four orders of magnitude. In terms of absolute values, 17 percent of the VHGs were less than 0.01 ft/ft, 50 percent were less than 0.05 ft/ft, 65 percent were less than 0.1 ft/ft, 90 percent were less than 0.5 ft/ft, and 94 percent were less than 1 ft/ft (fig. 21). Overall, the measurements indicate that VHGs tend to be small and larger values are less common. The large spatial variability of the gradients (fig. 20) indicates the complexity of VHGs and that VHGs represent local in contrast to reach-long exchange.

Table 1. Mini-piezometer data for the Naches, Yakima, and Tieton Rivers, Yakima River basin, Washington.

[**Location identifier** for Washington Department of Energy (WaDOE) sites in Carey (2006) and Flathead Lake Biological Laboratory (FLBL) sites in Snyder and Stanford (2001). Temperature and conductivity measured in piezometer and in stream. Daily mean discharge from Bureau of Reclamation, Yakima Project Hydromet system (http://www.usbr.gov/pn/hydromet/yakima/). Temperature is in degrees Celsius. Conductivity is in microsiemens per centimeter. Discharge is in cubic feet per second. **Abbreviations**: ft/ft, foot per foot; ft^3/s, cubic foot per second; –, no data]

Date	Location identifier	River mile	Latitude	Longitude	Vertical hydraulic gradient (ft/ft)	Groundwater		Surface water			Daily mean discharge (ft^3/s)
						Temperature	Conductivity	Temperature	Conductivity	Temperature difference	
U.S. Geological Survey measurements											
Naches River											
08-12-2002	1	16.6	46.746528	-120.767889	0.003	15.5	98.1	18.8	63.1	3.3	223
08-12-2002	2	16	46.742333	-120.757222	-.004	13.3	116.8	19.2	63.4	5.9	223
08-12-2002	3	15.1	46.736000	-120.742500	.005	14.8	140.4	20.5	65.2	5.7	223
08-13-2002	4	14.5	46.729389	-120.711333	-.035	18.0	80.1	15.8	75.9	-2.2	227
08-13-2002	5	12.8	46.724167	-120.698028	.060	16.9	68.5	16.1	68.1	-.8	227
08-13-2002	6	12.0	46.717194	-120.682250	-.007	19.3	83.5	19.2	71.6	-.1	227
08-13-2002	7	10.9	46.707556	-120.663722	.011	19.5	74.7	20.8	73.3	1.3	227
08-13-2002	8	9.4	46.690806	-120.652861	.012	15.1	91.0	20.0	65.5	4.9	227
08-13-2002	9	8.8	46.682222	-120.650444	-.055	19.1	84.9	20.9	70.3	1.8	227
08-14-2002	10	7.0	46.661667	-120.632139	-.033	19.0	73.0	17.8	73.6	-1.2	228
08-14-2002	11	6.3	46.653861	-120.624778	-.016	20.3	87.1	18.8	73.1	-1.5	228
08-14-2002	12	5.0	46.640333	-120.609083	-.002	19.7	87.1	20.6	76.4	.9	228
08-14-2002	13	4.0	46.632611	-120.593972	-.008	20.4	84.0	21.3	78.6	.9	228
08-14-2002	14	3.5	46.632528	-120.581667	-.004	19.1	111.3	21.9	81.5	2.8	228
08-14-2002	15	2.5	46.626694	-120.562556	.010	16.5	239.0	22.0	90.0	5.5	228
Yakima River											
09-05-2002	Y1	103.7	46.496556	-120.440750	[1]-5.0	–	–	16.9	110	–	564
07-16-2007	12505040	103	46.490405	-120.431173	-.17						482
07-11-2006	1	102.9	46.488056	120.428528	-.80	21.5	94	19.0	83		519
09-05-2002	Y2	102.7	46.485972	-120.429944	-.044	19.0	118	17.9	109	-1.1	564
07-11-2006	2	102.6	46.485361	120.424222	3.5	22.5	97	22.3	97	-.2	519
09-05-2002	Y3	102.3	46.483694	-120.419111	-.514	17.7	112	17.5	109	-.2	564
09-05-2002	Y4	102.1	46.480806	-120.420806	-.012	19.9	93	–	108		564
09-05-2002	Y5	101.6	46.481194	-120.410722	.047	17.9	116	20.4	107	2.5	564
09-05-2002	Y6	100.9	46.472250	-120.406056	-.001	19.6	164	21.8	106	2.2	564
07-11-2006	3	100.7	46.471083	120.404167	1.5	22.4	104	22.2	97	-.2	519
07-11-2006	4	100.6	46.470917	120.403278	4.0	21.9	225	20.1	120	-1.83	519
09-06-2002	Y7	100.1	46.464722	-120.392833	-.305	17.7	113	16.4	111	-1.3	585
09-06-2002	Y8	98.4	46.454806	-120.368972	-.098	18.6	60	17.9	110	-.7	585
09-06-2002	Y9	97.2	46.444444	-120.350250	-.088	18.7	115	18.0	113	-.7	585
09-06-2002	Y10	95.9	46.429361	-120.351611	-.004	19.7	152	18.8	118	-.9	585
09-06-2002	Y11	95.0	46.419972	-120.341528	.004	17.2	129	22.5	117	5.3	585
07-16-2007	12505270	94.4	46.417628	-120.331168	-.34	–	–	–	–	–	482
07-16-2007	12505270	94.4	46.417628	-120.331168	1.91	–	–	–	–	–	482
09-06-2002	Y12	93.6	46.414889	-120.318778	-.029	19.3	122	19.1	114	-.2	585
08-19-2002	Y13	92.7	46.403750	-120.307528	.006	13.6	165.4	20.5	97.9	6.9	658
08-19-2002	Y14	92.1	46.403556	-120.296944	-.037	20.5	99.2	20.8	97.5	.3	658
08-19-2002	Y15	91.4	46.402861	-120.285694	-.052	21.2	108.6	20.9	101.1	-.3	658
08-20-2002	Y16	91.4	46.402861	-120.285694	.008	18.9	110.5	17.6	104.6	-1.3	678
08-20-2002	Y17R	90.8	46.397667	-120.277861	-.108	19.8	106.5	17.9	103.2	-1.9	678
08-20-2002	Y17L	90.8	46.398000	-120.277611	-.179	19.5	105.5	17.7	103.9	-1.8	678
07-17-2007	12505330	86.2	46.373185	-120.225053	.48	–	–	–	–	–	482

Table 1. Mini-piezometer data for the Naches, Yakima, and Tieton Rivers, Yakima River basin, Washington.—Continued.

[**Location identifier** for Washington Department of Energy (WaDOE) sites in Carey (2006) and Flathead Lake Biological Laboratory (FLBL) sites in Snyder and Stanford (2001). Temperature and conductivity measured in piezometer and in stream. Mean daily discharge from Bureau of Reclamation, Yakima Project Hydromet system (http://www.usbr.gov/pn/hydromet/yakima/). Temperature is in degrees Celsius. Conductivity is in microsiemens per centimeter. Discharge is in cubic feet per second. **Abbreviations**: ft/ft, foot per foot; ft^3/s, cubic foot per second; –, no data]

Date	Location identifier	River mile	Latitude	Longitude	Vertical hydraulic gradient (ft/ft)	Groundwater		Surface water			Daily mean discharge (ft^3/s)
						Temp-erature	Conduc-tivity	Temp-erature	Conduc-tivity	Temperature difference	
Washington State Department of Ecology measurements											
Naches River											
06-29-2004	38-NAC-0.5	0.5	46.62678	-120.52383	-0.155	–	–	–	–	–	892
08-03-2004	38-NAC-0.5	.5	46.62678	-120.52383	-.179	–	–	–	–	–	416
08-31-2004	38-NAC-0.5	.5	46.62678	-120.52383	-.208	16.4	–	–	–	–	598
10-14-2004	38-NAC-0.5	.5	46.62678	-120.52383	-.206	14.7	–	–	–	–	790
06-30-2004	38-NAC-03.7	3.7	46.63185	-120.58547	.012	–	–	–	–	–	829
08-03-2004	38-NAC-03.7	3.7	46.63185	-120.58547	.049	17.1	–	–	–	–	416
08-31-2004	38-NAC-03.7	3.7	46.63185	-120.58547	.035	16.8	–	–	–	–	598
10-15-2004	38-NAC-03.7	3.7	46.63185	-120.58547	.028	13.5	–	–	–	–	715
07-02-2004	38-NAC-08.5	8.5	46.67822	-120.64975	-.005	–	–	–	–	–	794
08-06-2004	38-NAC-08.5	8.5	46.67822	-120.64975	-.048	15.9	–	–	–	–	477
08-31-2004	38-NAC-08.5	8.5	46.67822	-120.64975	-.032	17.1	–	–	–	–	598
06-30-2004	38-NAC-10.5	10.5	46.70275	-120.65985	.015	–	–	–	–	–	829
07-01-2004	38-NAC-12.8	12.8	46.72401	-120.69912	-.328	–	–	–	–	–	821
06-30-2004	38-NAC-26.8	26.8	46.80605	-120.92075	-.098	–	–	–	–	–	829
08-05-2004	38-NAC-26.8	26.8	46.80605	-120.92075	-.184	17.7	–	–	–	–	487
08-31-2004	38-NAC-26.8	26.8	46.80605	-120.92075	-.24	16.8	–	–	–	–	598
10-13-2004	38-NAC-26.8	26.8	46.80605	-120.92075	-.283	11.2	–	–	–	–	828
07-01-2004	38-NAC-31.1	31.1	46.85656	-120.95592	-.101		–	–	–	–	821
08-06-2004	38-NAC-31.1	31.1	46.85656	-120.95592	.078	14.5	–	–	–	–	477
09-02-2004	38-NAC-31.1	31.1	46.85656	-120.95592	-.055	13.6	–	–	–	–	648
07-01-2004	38-NAC-41.1	41.1	46.94935	-121.07055	-.021	–	–	–	–	–	821
08-09-2004	38-NAC-41.1	41.1	46.94935	-121.07055	.004	15.6	–	–	–	–	468
09-03-2004	38-NAC-41.1	41.1	46.94935	-121.07055	-.009	13.6	–	–	–	–	697
10-11-2004	38-NAC-41.1	41.1	46.94935	-121.07055	.007	9.8	–	–	–	–	1,140
Tieton River											
07-02-2004	38-TIE-02.3	2.3	46.72338	-120.81297	0.000	–	–	–	–	–	317
08-08-2004	38-TIE-02.3	2.3	46.72338	-120.81297	.014	12.7	–	–	–	–	329
08-30-2004	38-TIE-02.3	2.3	46.72338	-120.81297	-.046	13.8	–	–	–	–	439
10-19-2004	38-TIE-02.3	2.3	46.72338	-120.81297	.075	12.3	–	–	–	–	96
Flathead Lake Biological Laboratory measurements											
Yakima River											
09-13-2000	Cle Elum reach-1	181	47.18339	-120.91494	0.25	–	–	–	–	–	580
09-13-2000	Cle Elum Reach -2	180.3	47.18008	-120.90187	-.05	–	–	–	–	–	580
09-13-2000	Cle Elum reach-3	179.3	47.18037	-120.88668	-.20	–	–	–	–	–	580
09-13-2000	Cle Elum reach-4	177.6	47.17275	-120.86027	-.60	–	–	–	–	–	580
10-02-2000	Cle Elum reach-5	176.2	47.16856	-120.83777	-.02	–	–	–	–	–	826
10-02-2000	Cle Elum reach-6	175.5	47.16510	-120.82184	.37	–	–	–	–	–	826
10-02-2000	Kittitas reach-1	162.4	47.07785	-120.67035	-.02	–	–	–	–	–	1,154

Table 1. Mini-piezometer data for the Naches, Yakima, and Tieton Rivers, Yakima River basin, Washington.—Continued.

[**Location identifier** for Washington Department of Energy (WaDOE) sites in Carey (2006) and Flathead Lake Biological Laboratory (FLBL) sites in Snyder and Stanford (2001). Temperature and conductivity measured in piezometer and in stream. Mean daily discharge from Bureau of Reclamation, Yakima Project Hydromet system (http://www.usbr.gov/pn/hydromet/yakima/). Temperature is in degrees Celsius. Conductivity is in microsiemens per centimeter. Discharge is in cubic feet per second. **Abbreviations**: ft/ft, foot per foot; ft^3/s, cubic foot per second; –, no data]

Date	Location identifier	River mile	Latitude	Longitude	Vertical hydraulic gradient (ft/ft)	Groundwater		Surface water			Daily mean discharge (ft^3/s)
						Temp-erature	Conduc-tivity	Temp-erature	Conduc-tivity	Temperature difference	
Flathead Lake Biological Laboratory measurements—Continued											
Yakima River—Continued											
09-14-2000	Kittitas reach-2	152.7	46.97700	-120.55988	-0.50	–	–	–	–	–	927
09-14-2000	Kittitas reach-3	150.5	46.95364	-120.53733	-.07	–	–	–	–	–	927
09-14-2000	Kittitas reach-4	148.7	46.93237	-120.52115	-.10	–	–	–	–	–	927
09-14-2000	Kittitas reach-5	148.2	46.92625	-120.51768	-.60	–	–	–	–	–	927
09-18-2000	Kittitas reach-6	147.7	46.92231	-120.51219	.01	–	–	–	–	–	927
09-18-2000	Kittitas reach-7	147.4	46.91571	-120.51032	-.25	–	–	–	–	–	927
11-14-2000	Union Gap reach-1	114.4	46.61556	-120.48886	-.05	–	–	–	–	–	1,380
04-04-2001	Union Gap reach-3	111.5	46.59548	-120.47049	-.05	–	–	–	–	–	1,520
04-04-2001	Union Gap reach-4	112	46.58931	-120.46806	-1.45	–	–	–	–	–	1,520
04-04-2001	Union Gap reach-6	111.2	46.58115	-120.46276	-.06	–	–	–	–	–	1,520
04-04-2001	Union Gap reach-7	109.9	46.56526	-120.46391	-.10	–	–	–	–	–	1,520
04-04-2001	Union Gap reach-8	108.1	46.54415	-120.46908	-.04	–	–	–	–	–	1,520
10-24-2000	Wapato reach-1	102.7	46.48797	-120.42981	-.40	–	–	–	–	–	1,788
10-24-2000	Wapato reach-2	102.5	46.48466	-120.42583	-.05	–	–	–	–	–	1,788
10-24-2000	Wapato reach-3	101.2	46.47649	-120.40880	-.20	–	–	–	–	–	1,788
10-24-2000	Wapato reach-4	100	46.46404	-120.39290	-.25	–	–	–	–	–	1,788
11-07-2000	Wapato reach-5	90.6	46.39713	-120.27467	-.02	–	–	–	–	–	1,472
11-07-2000	Wapato reach-6	89.5	46.39616	-120.25752	-.23	–	–	–	–	–	1,472
11-07-2000	Wapato reach-7	88	46.38431	-120.24390	-.05	–	–	–	–	–	1,472
11-07-2000	Wapato reach-8	83.8	46.34485	-120.21050	-.03	–	–	–	–	–	1,472
Naches River											
07-28-2000	Naches reach-1	8.9	46.68344	-120.65391	-0.10	–	–	–	–	–	254
07-28-2000	Naches reach-2	7.9	46.67152	-120.64264	-.45	–	–	–	–	–	254
07-28-2000	Naches reach-3	5.2	46.64199	-120.61432	-.02	–	–	–	–	–	254

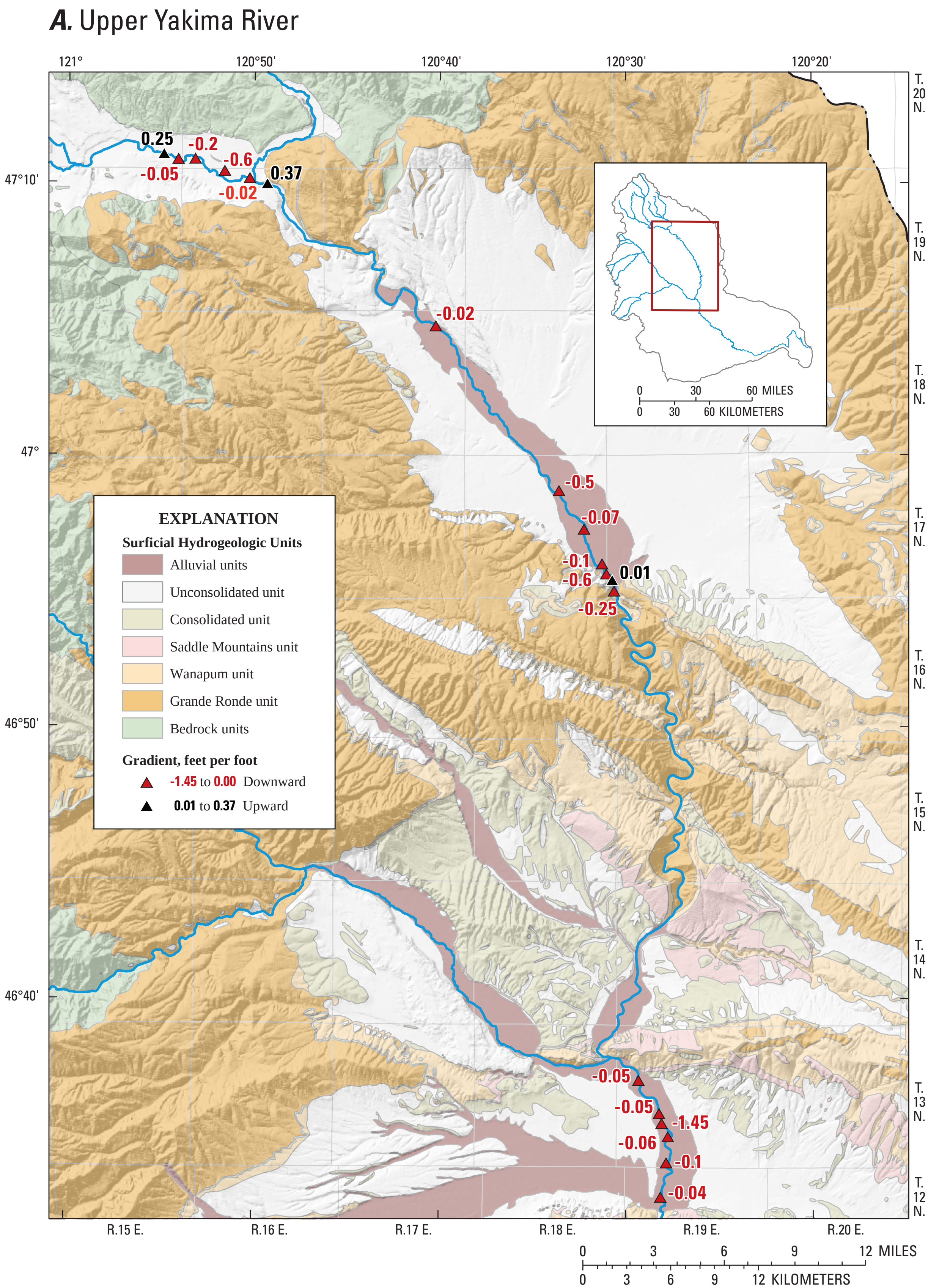


Figure 20. Direction and magnitude of vertical hydraulic gradients measured in mini-piezometers, (*A*) upper Yakima River, (*B*) Naches River, and (*C*) lower Yakima River, Yakima River basin, Washington.

B. Naches River

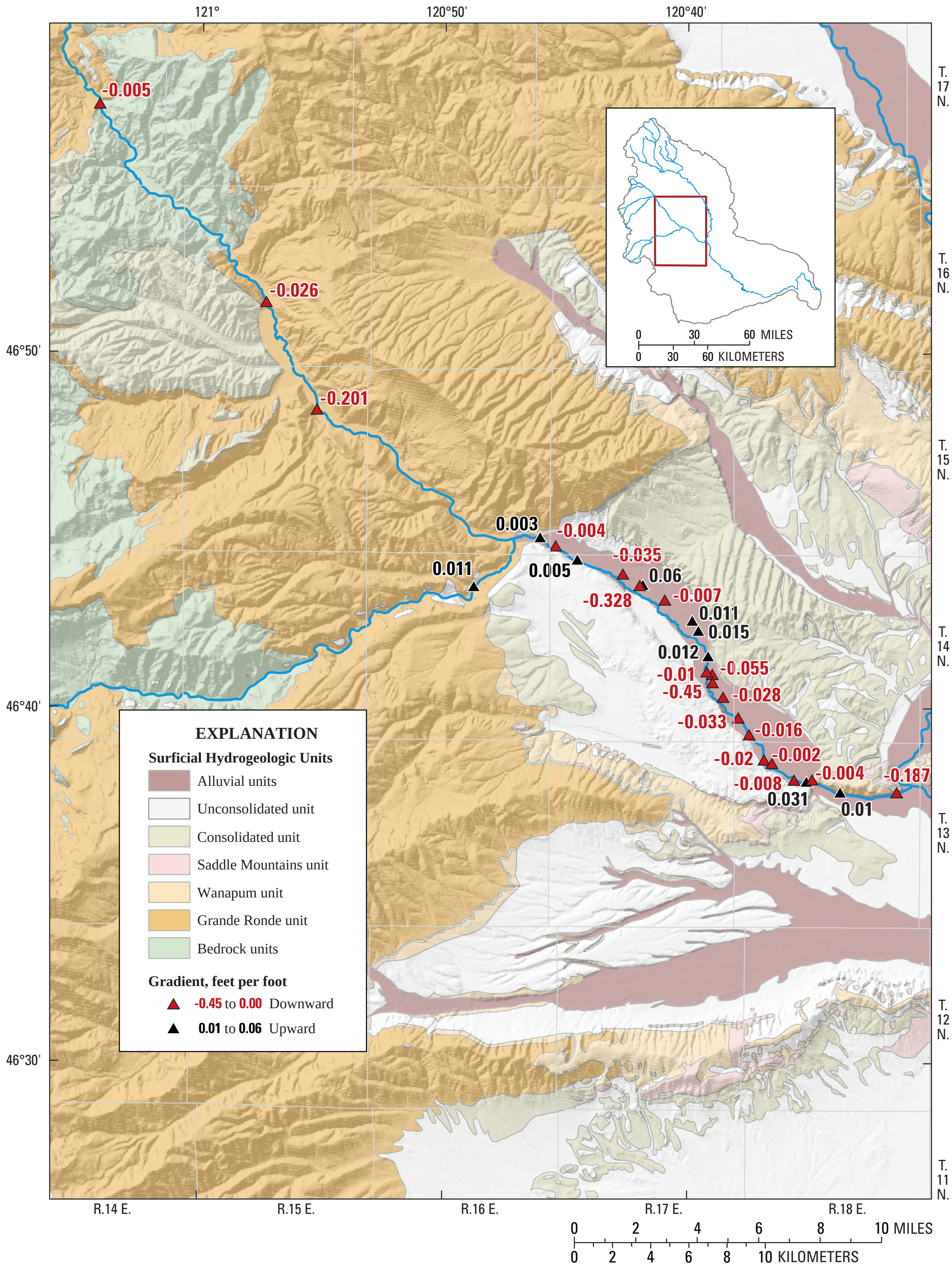


Figure 20.—Continued.

C. Lower Yakima River

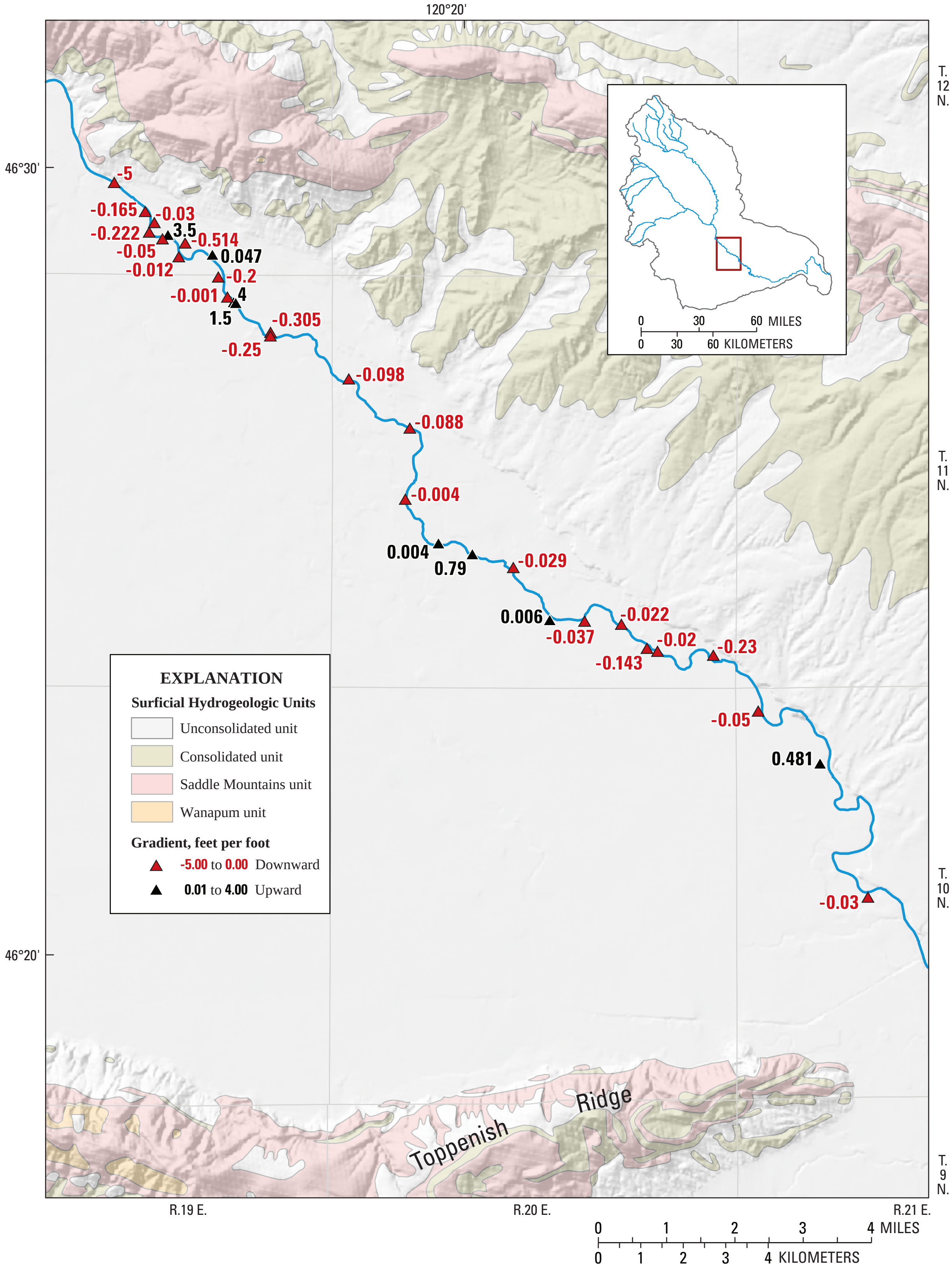


Figure 20.—Continued.

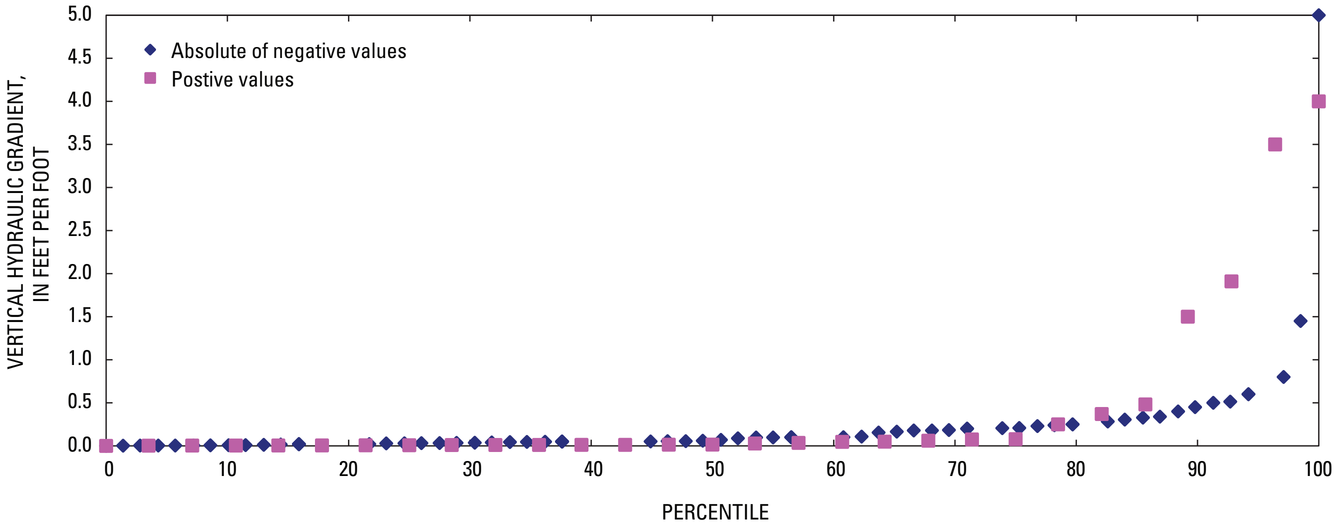


Figure 21. Percentile distribution of vertical hydraulic gradients measured in mini-piezometers, Yakima River basin, Washington.

The averages and medians of the negative and positive VHGs were -0.23, -0.065 and 0.43, 0.015 ft/ft, respectively; excluding the large negative VHG estimated at RM 103.7, the average and median of the negative VHGs were -0.16 and -0.06 ft/ft. Almost 50 percent of the negative VHGs were greater (in absolute terms) than 0.05 ft/ft, and 44 percent were greater than 0.1 ft/ft. In contrast, only 33 percent of the positive VHGs were greater than 0.05 ft/ft, and 22 percent were greater than 0.1 ft/ft (fig. 21). Thus, the negative VHGs were not only more prevalent but tended to have larger magnitudes; some negative VHGs also were measured in reaches that were identified as gaining in the seepage investigations. Although it may be expected that large, negative VHGs would be related to high flows (Simonds and others, 2004; Cox and others, 2005), there was no apparent correlation between discharge and magnitude of the VHG. The average of the daily mean discharges coincident with the 70 negative VHGs, however, was almost double the average discharge associated with the 29 positive VHGs.

The percentile distribution of the measured VHGs indicates that the negative and positive values are similar through about the 60th percentile, beyond which the negative values tend to be larger in absolute terms, up to an order of magnitude by the 75th percentile (fig. 21). Beyond the 80th percentile, however, the positive values become much larger, indicating that the largest VHGs have a different controlling mechanism. The shapes of the percentile distributions are similar to those for the seepage runs (fig. 16) but the seepage gains became larger than the losses at about the 55th percentile, in contrast to the 80th percentile for the VHG data.

The similarity between the shape of the distributions for the seepage data and the VHG data suggests that there may be a general relation between the two data sets. Additionally, if numerous VHG measurements were made within a reach, it may be possible to calculate an effective average value, which when cast in terms of a flux, would approximate the flux for the entire reach. Thus, it is of interest to examine whether a single VHG value could be representative of typical normalized exchanges (a flux) if it was applicable over a unit length (1 mi). To determine the latter, the VHGs were formulated as fluxes by estimating the hydraulic conductivity of the streambed materials, which generally are coarse-grained at the measurement sites. Pitz (2006) estimated hydraulic conductivity in the upper Yakima River at six mini-piezometers sites on the basis of 16 constant-head injection tests; the values ranged from 17 to 156 ft/d, with a geometric mean of 58 ft/d. The estimated values were consistent with those in the published literature based on grain size (Pitz, 2006). Although it is recognized that the readings from each piezometer reflect a local, site-specific hydraulic conductivity, a flux or rate can be estimated in two ways using the estimate of mean hydraulic conductivity. First, assuming the gradient (absolute value) is applied to a unit area (1 ft^2), the gradient is multiplied by the conductivity to yield a flux per unit area that can be expressed in units of inches per day. The flux value calculated by using this method would allow an improved assessment of the “reasonableness” of the gradients because the rate is cast in terms of the more understandable units of inches per day. Alternatively, the flux can be calculated for a stream length of 1 mi and an effective stream width. The width is estimated on the basis of a reasonable visual match between the percentile distribution of the VHG data and the seepage data. Although hydraulic conductivity along a stream reach is expected to be highly variable due to heterogeneities on and immediately beneath the bed of the channel, using one value for all VHGs suggests an effective value that could be applicable along either losing or gaining reaches. The basic assumption in applying this concept is that gains and losses occur vertically and are driven by the VHG. Although this may be true for losses, it likely is not true everywhere for gains in that a lateral or nearly lateral flow component exists in many gaining areas, especially within the structural basins where the water table is shallow as a consequence of the infiltration of surface water applied to agricultural fields. Results from both of these methods (categorized by positive and negative VHGs) are described below.

The fluxes per unit area calculated for the negative VHGs (suggesting streamflow losses) ranged from 0.005 to 24 in/d (the latter is derived from the estimated VHG at RM 103.7 described above). Fifty-six percent of the 70 values were less than 0.5 in/d and 75 percent were less than 1 in/d. Indeed, all but three values (96 percent) were less than 3 in/d; the three largest values were 3.9, 7, and 24 in/d. Except for the largest value, the fluxes appear reasonable, and river losses could likely support such values. Based on numerous seepage tests for unlined canals excavated in the Pasco gravels (a coarse-grained geologic unit) in eastern Benton County, an average seepage rate of about 8.4 in/d was reported by Drost and others (1997), further indicating that the coarse-grained streambed materials could support the estimated losses. Drost and others (1997) also report that for 379 canal seepage tests, only three indicated losses greater than 24 in/d and 6 were between 12 and 20 in/d. Those data suggest that the estimated 24 in/d value may be too large, and that the water table at that location (RM 103.7) may be completely disconnected from the river; that is, there may have been an unsaturated zone below the stream at the time of the measurement. Therefore, a unit VHG (1 ft/ft) may have been a better estimate at that location. A good match between the percentile distributions of the negative VHGs and the reach streamflow losses estimated from the seepage investigations (fig. 22*A*) was obtained using an effective width of 15 ft; all but the largest fluxes described above are shown on figure 22*A*. Differences between the two distributions are minor, further indicating that the negative VHGs could support the estimated reach seepage losses.

The calculated fluxes per unit area for the 29 positive VHGs ranged from 0.01 to 19.3 in/d. Seventy-five percent of the values were less than 0.4 in/d, and the next three largest values (76th –86th percentiles) were between 1.2 and 2.3 in/d. The remaining four largest values ranged from 7.3 to 19.3 in/d. Similar to the losses, except for the latter four values, the estimated fluxes appear reasonable. A reasonable match between the percentile distributions (fig. 22*B*) was obtained using an effective width of 52 ft; all but the five largest fluxes are shown on figure 22*B*. Below the 75th percentile, differences between the two distributions are minor, indicating that the calculated VHGs (groundwater discharge) could support the estimated reach gains. Although the two largest values shown on figure 22*B* do not fit the distribution (VHG values become larger at a lower percentile than the seepage values), they are consistent with the magnitude of the estimated normalized reach seepage gains. The distribution essentially shows that the upper 25 percent of the VHG values formulated as normalized values are much larger than the seepage values. The largest five values (89–734 [(ft^3/s)/mi]), especially the largest four, are much greater than any of the 118 seepage run values, and reasonable reductions in hydraulic conductivity and estimated width could not account for these larger values. The variation of these values from the seepage data distribution suggests that the VHG is not the controlling factor at those locations for exchanges and that other mechanisms, such as lateral inflow (groundwater discharge is not vertical), dominate the hydrologic exchange process. Large positive VHGs, therefore, are probably associated with fine-grained streambed material, and this may also be true for the two largest VHG values sown on figure 22*B*.

The effective widths used to match the two distributions differed. The smaller width (15 ft) employed for the losses would suggest that losses occur over small areas, but the losses likely occur across larger widths. An approximate doubling of the width to 30 ft would result in a hydraulic conductivity value of 29 ft/d, which is greater than several values measured by Pitz (2006). Perhaps in areas of losses there are more fine-grained sediments in the streambed matrix. Similarly, the larger width of 52 ft estimated for positive VHGs would be appropriate along some reaches but may be either too large or too small for other reaches. Increasing or decreasing the effective width within reasonable ranges, however, would result in reach-effective conductivity values within the range of those measured by Pitz (2006) for all but the largest of the positive VHGs. The differences in the effective width between the positive and negative gradients and the percentile distribution of VHGs also suggests that losses are influenced by small-scale geomorphic controls and that gains are more influenced by larger scale variations in the extent of the aquifer and streambed.

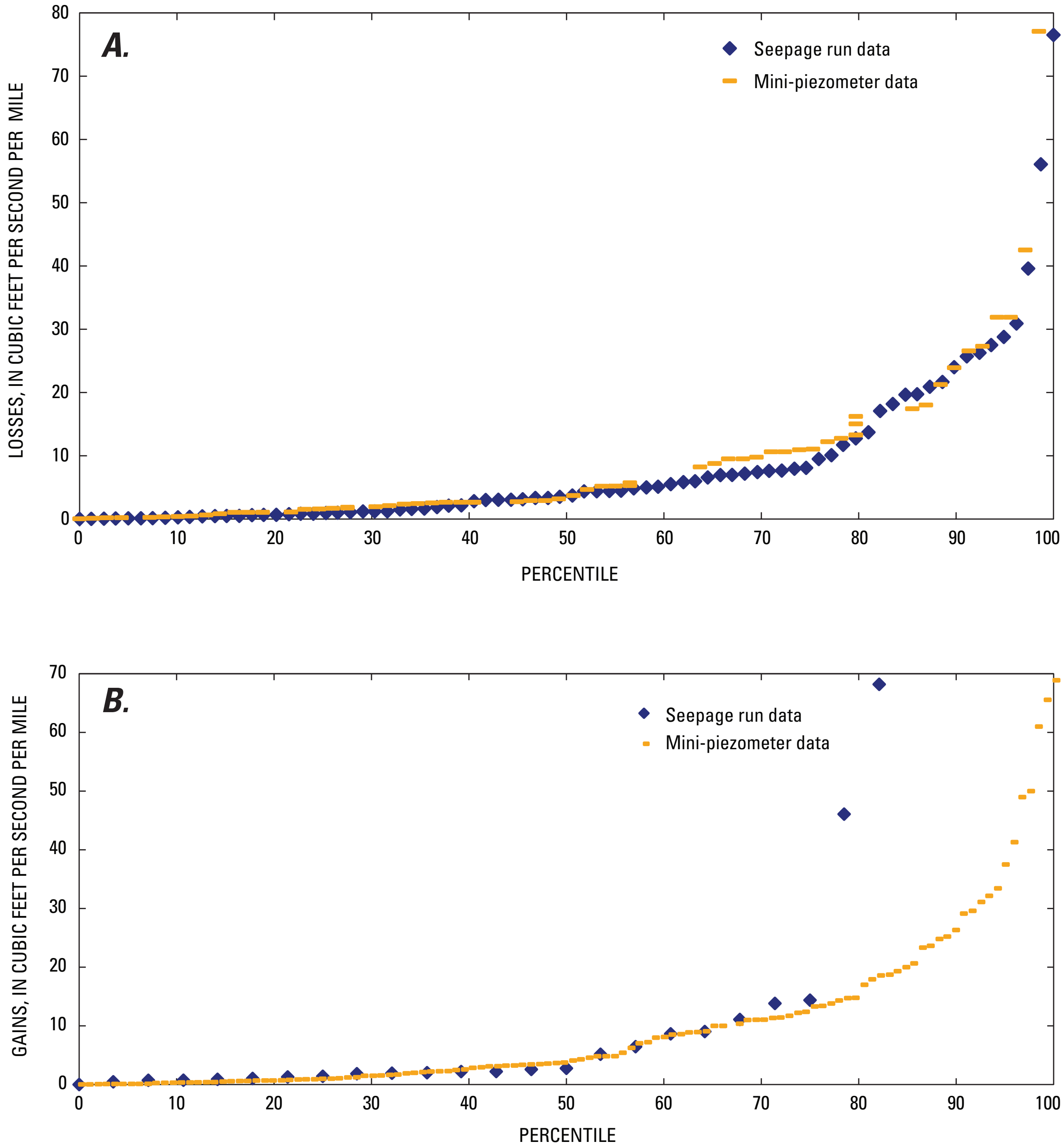


Figure 22. Percentile distributions of normalized exchanges from seepage runs and normalized exchanges calculated from vertical hydraulic gradients measured in mini-piezometers, (*A*) losses (as absolute values), and (*B*) gains, Yakima River basin, Washington.

Spatial Variations

The spatial variability in vertical hydraulic gradient in streams of the Yakima River basin can be illustrated by an examination of data for three stream sections, (1) the Naches and Tieton Rivers, herein referred to as the Naches River section, (2) the upper (above Union Gap) Yakima River, and (3) the lower Yakima River. The distribution and magnitude of the VHG within each section also was highly variable (fig. 20). Sixty-eight percent of the VHG values determined for the Naches River were negative, whereas 78 and 72 percent of the values for the upper and lower Yakima River, respectively, were negative. The median VHG values for the sections were:

	Vertical hydraulic gradient (ft/ft)	Negative vertical hydraulic gradient (ft/ft)	Positive vertical hydraulic gradient (ft/ft)
Naches, Tieton	-0.01	-0.05	0.01
Upper Yakima	-.06	-.09	.25
Lower Yakima	-.04	-.09	.48

Naches River

The measured VHGs for the Naches River varied over several orders of magnitude, and showed no clear spatial pattern. The measurements at RM 0.5 were negative over a broad range of flows (416–892 ft^3/s). RM 0.5, the end point of a seepage-run reach (RM 12.8–0.5) that showed a net gain, is near where groundwater level data show the river to be losing water. Of the 27 VHG measurements in this 12.3-mi reach, 9 were positive and 18 were negative, indicating local variations and possibly alternating gaining and losing areas. Several of the positive VHG values were in an area where the river channel changes direction and likely receives discharge from the alluvial aquifer. The largest negative VHG was measured at RM 7.9. At this location, the gravel-bedded channel widens, which would “favor” streamflow losses. Measurements at RM 15.1 and 14.5 that were in a losing reach (RM 16–12.8) based on seepage run data had a positive and negative VHG, respectively. Location of the river (abutting the southern extent of the alluvial valley aquifer) and channel orientation would also contribute to the differences in VHG. The reach from RM 17.1 to 16 had a positive VHG at its upper end and a negative VHG at its lower end. On the basis of seepage run results and other data (described previously) this reach is known to be a transitional area from gaining to losing and the VHG measurements appear to reflect this transition.

The three most upstream VHG measurement sites on the Naches River also were streamflow measuring sites for a seepage run. Four VHG measurements at RM 26.8, which is in a reach that was identified as losing, were all negative (average -0.2 ft/ft); however, on the basis of seepage run data, the 1.2-mi reach ending at RM 26.8 had only a 1-percent loss. Three VHG measurements at RM 31.1 ranged from -0.1 to 0.08 ft/ft (average -0.026 ft/ft), and the values were not related to discharge except that the largest negative VHG was measured concurrently with the largest measured discharge (July 1, 2004). The 2.9-mi seepage-run reach ending at RM 31.1 had an indicated net loss of 3 percent on July 20, 2004; discharge was about 35 percent less than that on July 1, when the large negative VHG was measured. Although this may be a transitional location (from negative to positive VHG) with the sign of the VHG dependent on discharge quantities, a negative VHG was measured in August at an even lower discharge. Similar to measurements at RM 31.1, four VHG measurements at RM 41.1 alternated between negative and positive values and averaged -0.005 ft/ft, with the largest magnitude of -0.021 ft/ft occurring during the highest measured discharge of the four measurements. This reach also was identified as a losing reach, but again, by only 1 percent of the discharge at the downstream-most measurement. The upstream limit of the losing reach may vary seasonally, similar to the conditions described by Konrad (2006) for the Methow River in north central Washington.

The directions of four VHG measurements (average 0.011 ft/ft) on the Tieton River at RM 2.3 also vary, with one near neutral, two positive, and one negative. These values appear to be somewhat flow related because the negative value when the discharge was largest (439 ft^3/s) and the largest positive value was measured when the discharge was the lowest (96 ft^3/s).

Upper Yakima River

There were 19 averaged values based on VHG measurements by FLBL that extended from near Cle Elum (RM 181) to Union Gap (RM 108.1) (fig. 20*A*). All but two of these averaged measurements were negative. As described previously, these averages were estimated from measurements along transects at each location, and more than 80 percent of the VHGs for 32 transects measurements were negative.

Four of the six sites in the Cle Elum reach had negative VHGs (fig. 20*A*). The average of the negative values (-0.22 ft/ft) in this reach was about the 75th percentile for the negative values for the Yakima River basin (fig. 21), and suggests the potential for vigorous exchange. The negative VHGs appear to be related to geomorphic controls. A positive VHG was measured at the most upstream site where the flood plain becomes more constrained by roads and farmlands, which tends to focus groundwater discharge. The other positive VHG occurs where the Roslyn basin narrows below the mouth of the Teanaway River, which is consistent with groundwater discharging near structural-basin outlets. Similar to the negative values, the two positive values were at about the 80th percentile for all of the measured positive values in the basin.

The next site downstream of the Cle Elum reach was located near the end of an identified seepage-run losing reach near Thorp that is at the head of the Kittitas basin where, hydrologically, losses should occur. In this area, the valley widens and a side channel begins which could enhance the probability of the river losing water and would be consistent with the measured negative VHG. The next four averaged measurements were in the lower part of the Kittitas basin (RM 152.7–148.2), and the sites lie in what was identified as a priority reach (the Kittitas reach) for restoration (Snyder and Stanford, 2001) because of the larger flood plain and complex braided channel network. The four averaged VHGs were negative, of which the magnitudes of two were very large (-0.5 and -0.6 ft/ft; about the 90th and 95th percentile values, respectively). Side channels emanating from near these two sites may provide a geomorphic framework for losing conditions. The next downstream VHG was positive, and it occurred where the flood plain becomes more constrained by Manastash Ridge just upstream of the Yakima Canyon. The last measurement, at the head of the Yakima Canyon, had a large negative value (-0.25 ft/ft), and likely represents a combination of local conditions in this complex braided channel area and a widening of the canyon just below the measurement site.

In the Union Gap reach (RM 116.3–107.3), all six of the averaged measurements were negative, and averaged -0.29 ft/ ft, mainly because the largest average value was -1.45 ft/ft. Of the 30 transects measurements, only five had a positive VHG, and the two largest values occurred in a transect (not used in this analysis) that was in a spring brook where upwelling was observed (Stanford and others, 2002). The propensity of negative values may reflect localized geomorphic controls in this complex braided channel of the Union Gap reach. As discussed previously, groundwater discharge is expected upgradient near the terminus of the Yakima structural basin, but this was not confirmed by seepage investigations in this reach.

Lower Yakima River

There were 33 VHG measurements in the Yakima River between RM 103.7 and 86.2. The measurements averaged 0.1 ft/ft (median -0.04 ft/ft) and ranged from -5 to 4 ft/ft. The positive VHGs averaged 1.0 and the negatives -0.4 ft/ft, and similar to the basin-wide distribution (fig. 21), fully 72 percent were negative. For all the VHG measurements in the basin, the five largest positive VHGs and the largest-magnitude negative VHG occurred in the lower Yakima River. The percentile distribution for the negative VHGs was similar to that for all data. Whereas, the distribution for the positive values was more bimodal with 49 percent of the values being greater than 0.45 ft/ft and 49 percent being less than 0.009 ft/ft. This information suggests that exchanges in the lower Yakima River have the potential to be vigorous and that locally, streamflow losses may be less vigorous than gains.

The largest negative VHG occurred at RM 103.7, which was the end point of a seepage-run reach. This reach was estimated to be a gaining reach with a strong transition to losing upgradient from RM 103.7. Indeed, the large negative VHG was estimated and not measured because the water table was below the bottom of the mini-piezometer. The next largest negative value (-0.51 ft/ft—no other negative measurements had a magnitude greater than 0.5 ft/ft) occurred at RM 102.3 in a reach (RM 102.7–100.3) that was identified as losing in two seepage runs and gaining in another, suggesting that at least locally, a strong losing section likely exists in this reach; this reach, however, also contained the largest positive VHG. The upstream reach (RM 103.7–102.7) was a gaining reach and the second largest positive VHG occurred at RM 102.6, suggesting that gains may continue below RM 102.7. At RM 100.7 the fourth largest positive VHG (1.5 ft/ft) was measured. The combination of large positive and negative VHGs indicates that the reach below RM 102.7 is an ‘active’ reach for exchanges. The third largest magnitude of all the VHGs (1.9 ft/ft) was measured at RM 94.4 in a gaining reach contained in the Parker reach (fig. 8) that is known to be very active for exchanges as described for the seepage investigations; Stanford and others (2002) also identified the Parker reach as having active exchanges.

Shallow Groundwater Information

Localized information on river-aquifer exchanges and the shallow groundwater system that supports the exchanges can be obtained from measurements of temperature and water levels in shallow wells. For this study, such information collected at shallow monitoring wells (table 2) comprises two data sets. The wells are completed in the upper part of the local water-table (unconfined) aquifer.

The first data set includes data from four sites, designated BLM (Bureau of Land Management), Wapato, Toppenish, and Satus (fig. 9). The Wapato and Toppenish sites are on YN’s Wapato Wildlife Area and the Satus site at the Satus Wildlife Area. At each site, three wells were placed near either the mainstem of the Yakima River or nearby side channels, and the wells were drilled in a line approximately perpendicular to the channel, at distances ranging from several feet to 140 ft from the bank (see for example fig. 23*A*). At the Wapato site, a fourth well was placed farther away from the river in a relic slough, and at the Satus site a fourth well was located about 150 ft from the river. To monitor water temperatures just below the ground surface, shallow (5–8 ft) wells (piezometers) were hand driven at the BLM, Toppenish, and Satus sites, but at the Wapato site a back hoe was used to install a piezometer in very coarse-grained material. The deeper wells, which ranged in depth from about 16 to 43 ft (table 2), were hydraulically driven. Water temperatures and water levels also were periodically measured in FLBL monitoring wells (designated with an “F” on figures here; Snyder and Stanford, 2000) at the BLM, Wapato, and Toppenish sites also were

Table 2. Well information and relation between well identification number and U.S. Geological Survey well numbers for monitoring sites, Yakima River basin, Washington.

[**Abbreviations**: USGS, U.S. Geological Survey; BLM, Bureau of Land Management]

Site	Well identification No.	USGS No.	Well depth (feet)
BLM	1	17N/18E-25J01	20
	2	17N/18E-25J02	18
	3	17N/18E-25J03	20.5
	3A	17N/18E-25J05	5.1
	F1	17N/18E-25J04	17.7
Wapato	1	12N/19E-34F01	20.6
	2	12N/19E-34F02	20.8
	3	12N/19E-34F03	21
	4	12N/19E-34F04	16.5
	1A	12N/19E-34F06	7.6
	F1	12N/19E-34F05	14.5
	F2	12N/19E-34E01	10.25
	F6	11N/19E-03J02	10.3
Toppenish	1	11N/20E-34C01	29
	2	11N/20E-34C02	30
	3	11N/20E-34C03	20
	1A	11N/20E-34C04	8
	F1	11N/20E-27N01	15
	F2	11N/20E-27N02	14.4
Satus	1	10N/21E-36M02	43
	2	10N/21E-36M03	31
	3	10N/21E-36M04	31
	4	10N/21E-36M05	21
	1A	10N/21E-36M06	7.8
Satus Wildlife Area	18H01	9N/22E-18H01	10
	18J01	9N/22E-18J01	15
	18K01	9N/22E-18K01	20
	18K02	9N/22E-18K02	10
	18F01	9N/22E-18F01	10
	7N02	9N/22E-7N02	10
	7N03	9N/22E-7N03	20
	2R03	9N/22E-2R03	10
	2R04	9N/22E-2R04	20

periodically monitored for groundwater temperature and water level. The primary reason for monitoring at these sites was to determine the relation between river-aquifer exchanges and fluctuations in river stage and (or) flood plain recharge. The variations in physical settings (both stream and bank) provide information on these near-bank relations over a range in physical settings. Of particular importance is that the monitoring period included a drought year (2001) and near-average runoff years, and the data described below clearly shows variations between such years.

The second data set comprises groundwater temperatures and water levels from 9 shallow (10- and 20-ft deep; table 2), hydraulically-driven monitor wells at six different sites in the Satus Wildlife Area (SWA) (fig. 9). At 3 of the sites, paired wells (one 10- and one 20-ft deep) were monitored. The physical setting of the sites ranges from agricultural (paired wells located near an agricultural drain-North drain) to relic oxbow lakes, Satus Creek, and the Yakima River (fig. 9 and fig. 24). The data provided information on the relations of shallow groundwater over a large range in settings, including near surface-water bodies.

Near Bank River-Aquifer Exchanges

The first data set provides information on near-bank river-aquifer exchanges in different physical settings. The BLM site (figs. 9 and 23*A*) is near the downstream end of what is termed the Kittitas reach (Snyder and Stanford, 2000) in the Kittitas Basin (Jones and others, 2006). This site is downstream of a river bend (fig. 23*A*) and about 2.4 mi upstream of the head of the Yakima Canyon. The site abuts agricultural land to the east and the bank (about 6 ft high) is overlain with silty-sand overbank deposits that are intermixed with gravel and some cobbles. The wells (19.6–21.5-ft deep) along the left bank penetrate mainly sandy material with some gravels; an FLBL monitor well (F1) was located near these wells. The streambed material at this location is mainly cobbles and gravels. The Wapato site (fig. 9) is in the Parker reach (fig. 8) in an area with dense riparian vegetation (fig. 23*B*). The site is downstream of a bend in the river where a side channel re-enters, and upstream of a shallow run-riffle near the end of a deeper pool-run. The cobble bank (very little overbank deposits) is about 5.5-ft high. The three wells on the right bank close to the river penetrate gravels and cobbles and are about 20-ft deep (table 2); the fourth well (16.5-ft deep) also penetrates gravels and cobbles and is about 115 ft from the river. The shallow (7.6-ft deep) monitor well is about 20 ft from the bank. Three FLBL wells at the Wapato site, which ranged in depth from 10.25 to 14.5-ft deep, also were monitored. The Toppenish site (fig. 9) is located at the downstream end of the Parker reach (fig. 8). The three wells here (45–80 ft from the right bank) range in depth from 20 to 30-ft and penetrate caliche cemented gravel and cobbles (fig. 23*C*). The wells are located on a steep 6-ft high bank just downstream of a gravel-bedded side channel where the surface-water monitoring site and a shallow, hand-driven piezometer are located. Two FLBL wells (14.4 and 15-ft deep) are located upstream (900 and 1,300 ft) of the site, and they also were monitored for groundwater temperature. The fourth site, Satus (fig. 9), is in the Granger reach (fig. 8) on a secondary side channel with a long, shallow run containing gravels (fig. 23*D*). The 6-ft bank is steep and the riparian vegetation at the site consists of mixed grasses and other low-lying plants. The wells on the right bank range in depth from about 21 to 43-ft and penetrate mainly silty sands with some gravel. A 7.8-ft deep piezometer is hand-driven about 15 ft from the bank near a 31-ft deep monitor well in order to measure shallow groundwater temperatures.

Figure 23. Location of groundwater monitoring wells and surface-water stations at (*A*) BLM, (*B*) Wapato, (*C*) Toppenish, and (*D*) Satus sites on the Yakima River, Yakima River basin, Washington.

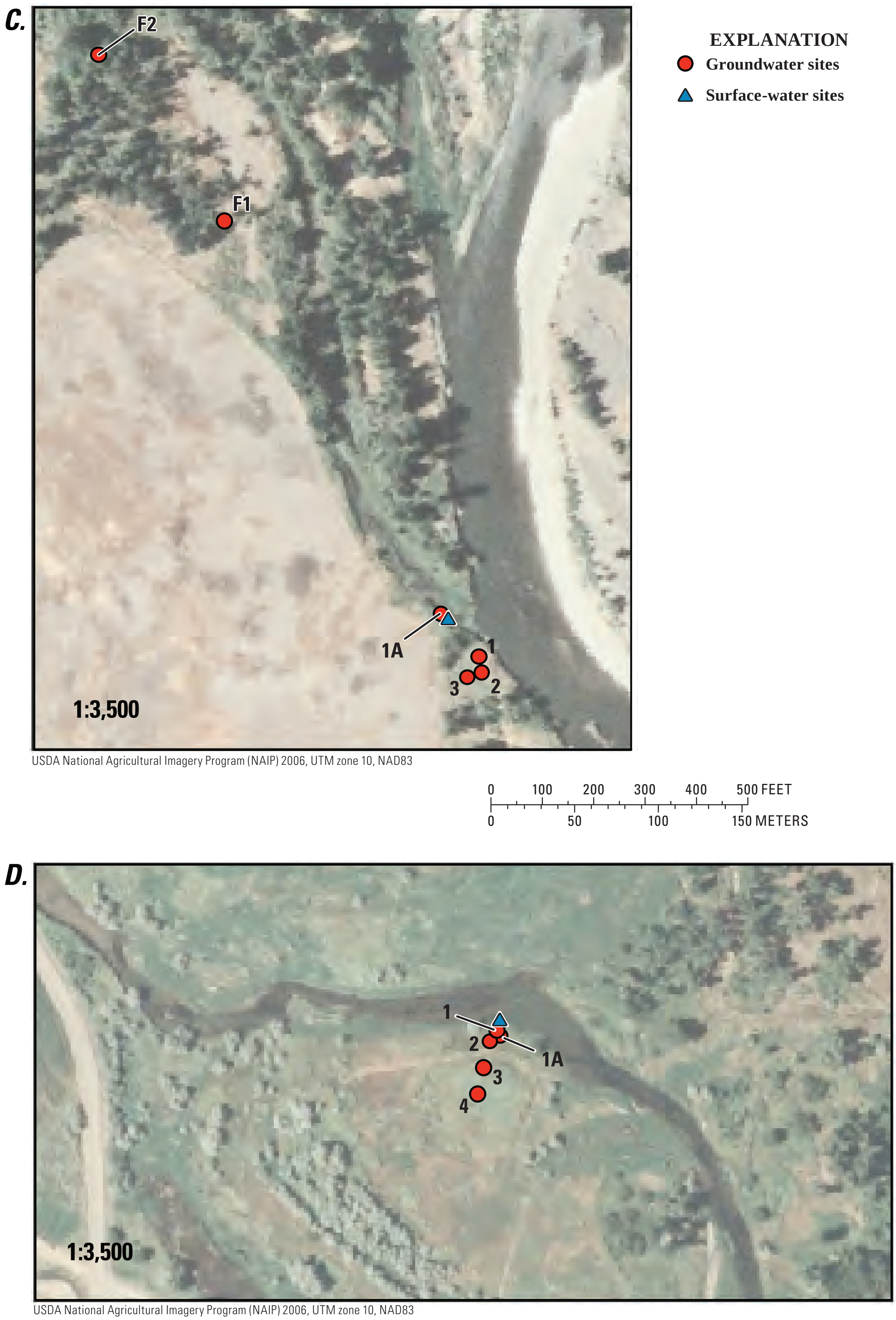


Figure 23.—Continued.

Measured depth-to-water (DTW) during field visits to the BLM site ranged from 2 to 4.5 ft below land surface. At the Wapato site, DTW had a larger range and except at well F6, ranged from about 1 to 7.5 ft. DTW at F6 ranged from 2.6 to 10.8 ft. DTW at the Toppenish site ranged from 1.5 to 6.5 ft, with most measurements between 3.5 and 5 ft. DTW ranged from 2.7 to 6.2 ft at the Satus site, and most DTWs were 4.5–5.5 ft. The DTW data tend to mimic concurrent water levels in the adjacent stream, and thus, show that the system at each site represents shallow groundwater and is representative of the local exchanges and relations to surface water.

For all monitor wells, the altitude of the water-level measuring point was surveyed and referenced to the nearest established benchmarks; the altitude of the top of the stand-pipe for streamflow stage monitoring also was determined. At the four near-bank sites, data were lost from various monitor wells and surface-water sites owing to equipment malfunction, accidents, vandalism, and theft. For example, during a high-water event at the Toppenish site, a floating log destroyed most of the surface-water monitoring equipment. At another site, the top of one of the wells was broken off by a vehicle. In cases of destroyed or damaged data loggers, if the well was considered a high priority monitoring site, available equipment was re-deployed from a lower priority site. Thus, there are discontinuities in the length of records between and within sites. For the SWA monitoring, only one data logger was lost (well 18J01, fig. 24).

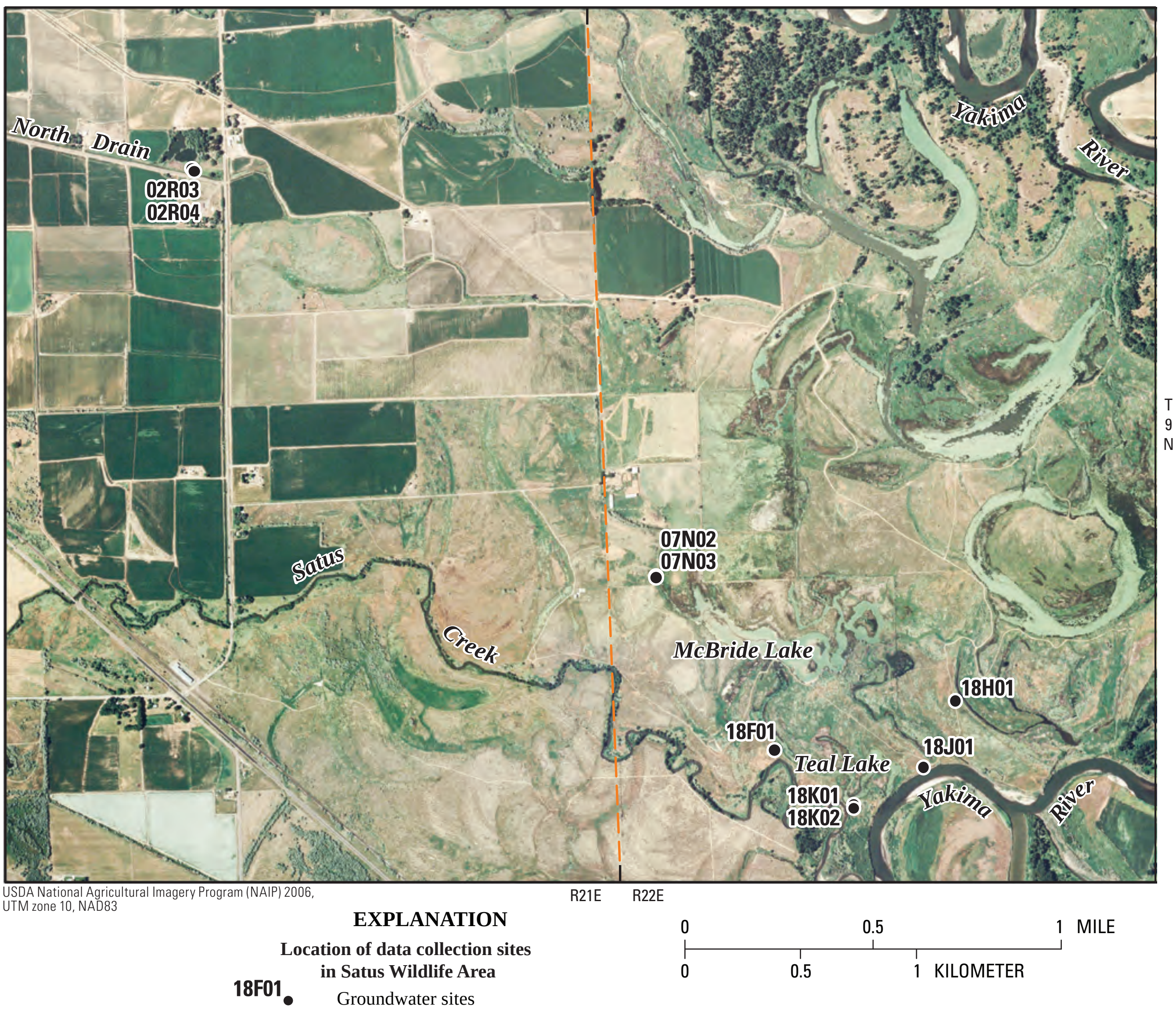


Figure 24. Location of groundwater monitoring wells, Satus Wildlife Area, Yakima River, Yakima River basin, Washington.

Relations Between Shallow Groundwater in a Floodplain and Nearby Surface-Water Bodies

BLM Site

The altitude of the river's surface and the adjacent groundwater levels at the BLM site closely track each other, with the river levels generally slightly higher (fig. 25*A*), indicating the potential for infiltration of surface water to the aquifer and thus a decrease in streamflow. During two larger streamflow events (April 2002 and January 29–February 7, 2003), however, water levels in the wells were higher than the river level. For the former event, levels in wells 1 and 3 were higher and likely also were higher in well 2, but these data are missing for both periods. For the latter event, data are available only for well 3, and its water levels were higher. However, water temperature in well 2 decreased by about 1.7°C, equivalent to streamflow temperature, within a day after the event peak, indicating that water levels in well 2 also were higher (fig. 25*B*). The water temperature in well 1 did not increase because it was already tracking the colder streamflow temperature. Occurrences of overbank flows during these periods raised groundwater levels, which declined more slowly than the subsequent drop in river level. The responses of water levels in the wells are nearly concurrent with river level changes, and are displayed fully in well 3, 140-ft from the river (fig. 25*A*). As described previously for broad-scale river-aquifer exchanges, this site is in an area (near the terminus of a structural basin) where groundwater discharge to the river is expected (Kinnison and Sceva, 1963; Vaccaro and others, 2009). The water-level data suggests that groundwater moves parallel to the river at this site and likely discharges further downstream, where the river bends to the east and intercepts groundwater flow paths.

Streamflow and groundwater temperature data also indicate that the BLM site is in a losing reach of the Yakima River. The streamflow temperature logger at the site was lost in a bank collapse about a year after it was installed, so that beginning on November 20, 2002, daily-mean measured temperature at Yakima River at Cle Elum (data from Reclamation's Hydromet: http://www.usbr.gov/pn/hydromet/yakima/yakwebarcread.html) is used as a surrogate for stream temperature at the BLM site (fig. 25*B*). Comparison of temperature data from the Cle Elum and the BLM sites indicate that the temporal variability between the two sites (separated by 38 river miles) is similar. During the rising limb of the temperature thermograph (from about March through August), the water at the BLM site can be as much as 2°C warmer than that at Cle Elum; during the falling limb, the temperatures are about the same; and during the winter season, water temperatures at the BLM site generally are only slightly lower than those at Cle Elum. Thus, the temperature at Cle Elum adequately represents the timing and range of temperature at the BLM site.

Starting in about October 2001, the trend in water temperature in well 1 (well nearest to the river) closely follows the stream temperature (fig. 25*B*), indicating the influence of streamflow on groundwater temperature. Excluding July 2001, prior to October, water temperatures in well 1 were a more subdued replica of streamflow temperature and displayed a typical lag behind the annual streamflow heating cycle, indicating that during this period the quantity of streamflow losses, which may have been affected by the 2001 drought, were not large enough to influence the groundwater temperature. During July 2001, the temperature data logger was re-deployed higher in the well bore, and the measured temperature closely followed the streamflow. Thus, from June to October of 2001 of the drought year, below normal streamflow losses likely resulted in a larger vertical temperature gradient in the alluvial aquifer. After October 2001, streamflow losses and accompanying heat advection were large enough to allow mixing throughout the depth range of the well. Vertical temperature gradients may be an important component of exchanges because the temperature of groundwater discharge can thus vary as a function of the strength of the gradient.

Water temperatures in well 2 are less variable than those in well 1, and they lag and are lower than the maximum streamflow temperatures (fig. 25*B*). When discharge decreases in the river after 'flip-flop' starts in September 2001 (the time when flows increase on the Naches River due to increased reservoir releases from Rimrock, and flows are decreased on the upper Yakima River), the temperature thermograph in well 2 becomes more typical of a groundwater-type thermograph (minimal daily and multi-day variations) but still displays a large annual variation (10-12°C), indicating it is influenced by streamflow losses. During part of January–February 2002, there is an apparent larger influence of streamflow losses on temperatures in well 2 that is displayed by a drop in temperature, and starting with increasing streamflow in April, the water temperature in well 2 closely follows (without the daily variability displayed in well 1) the stream temperature thermograph. Similar to 2001, this co-varying relation ends with the decrease in streamflow discharge as 'flip-flop' occurs. A large February 1, 2003, rain-on-snow event, with attendant overbank flows, is clearly indicated by a 2°C drop in groundwater temperature, but the lower temperatures dissipated in less than 10 hours as the surface-water inflow mixed with the ambient groundwater. Thus, at a distance of only 50 ft from the stream, the effects of changes in streamflow losses, which are predicated on discharge (in 2002 the monthly mean discharges for August, September, and October were 2,700, 700, and 450 ft^3/s, respectively), vary widely. As described previously, not only are the direction of exchanges controlled by discharge quantities and stages, but also the quantity of gains/losses and how the resulting effects propagate as changes in groundwater temperature.

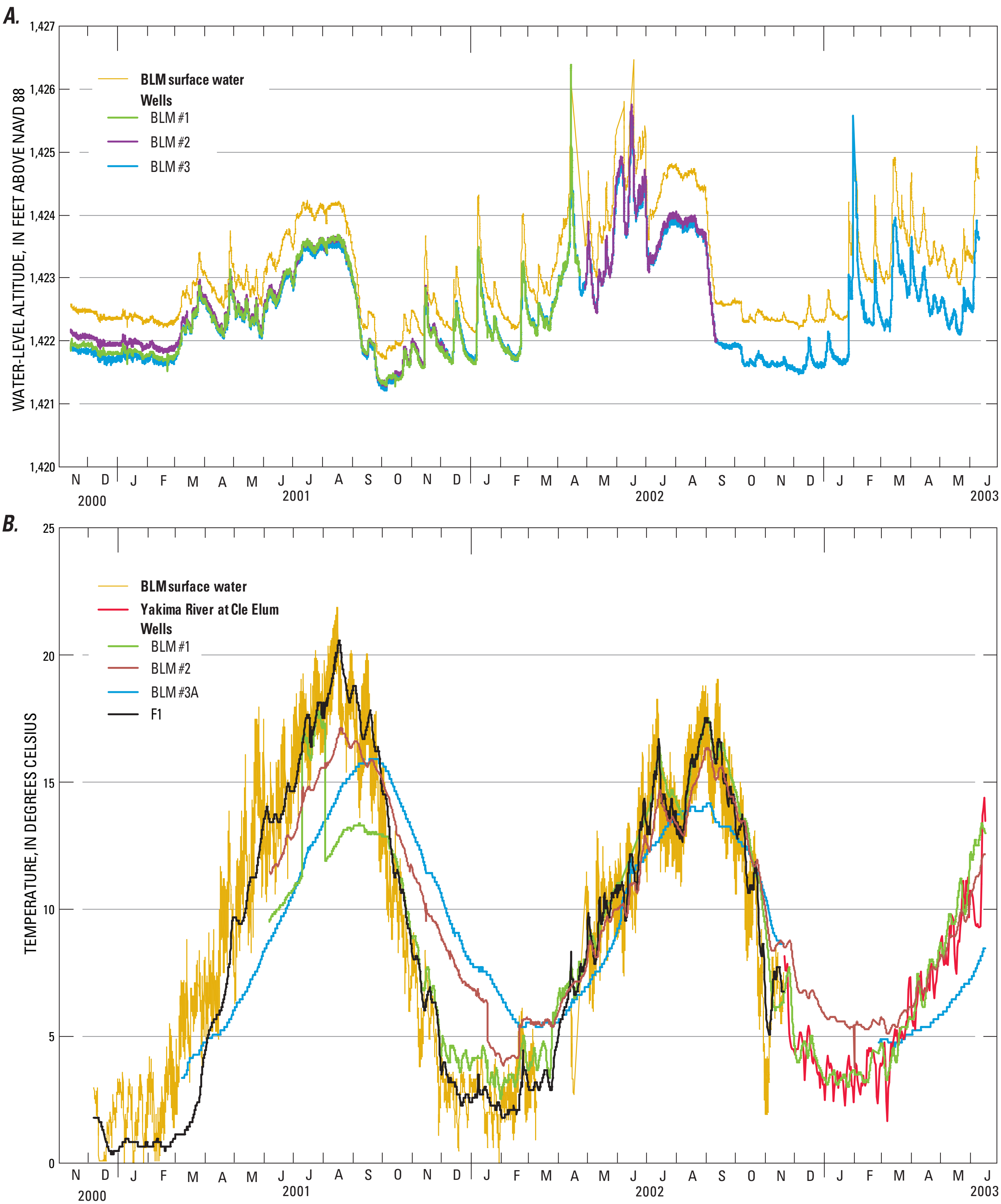


Figure 25. (*A*) water-level altitudes and (*B*) water temperatures in monitoring wells and at surface-water stations, BLM site, Yakima River, Yakima River basin, Washington.

Water temperature in shallow well 3A (fig. 25*B*) further shows how (1) streamflow losses affect groundwater temperatures, and (2) the near-bank very shallow groundwater system functions. The temperature thermograph is typical of groundwater thermographs in that it is smooth, but the range in temperature is much larger than normally expected for groundwater, indicating the influence of streamflow losses. The influence of the magnitude of losses is clearly exhibited in the thermograph. During the 2001 drought year, maximum temperatures in well 3A were more than 5°C lower than those of surface water and lagged by about 1.5 months. In contrast, during the wetter and non-proratable year 2002 (with more surface water being diverted to and used in the adjacent the Kittitas Reclamation District), the temperature differential between the stream and groundwater during the maximum was less than that in 2001 and there was no lag in the annual peaks. However, the two maximum temperature peaks observed at the other BLM monitoring wells did not occur in well 3A because the influence of the losses was attenuated over distance. Thus, daily variability in groundwater elevations from surface-water pressure effects are displayed at least as far away as well 3, which is close to well 3A, but these pressure effects do not materialize as temperature changes.

The thermograph for water in well F1 generally is coherent with the surface-water thermograph (fig. 25*B*), and indicates that groundwater in this 20-ft well is strongly influenced by infiltrating surface water. Surface water must flow through the coarse-gained sediments and later discharge to the river where it makes a large bend to the east (a left bend from the left bank where the wells are located) about 0.25 miles downstream. In addition to the coarse-grained sediments, another factor contributing to the close relation between the river and the water in well F1 likely is the lowering of the bank in this area, from about 5 ft at the upstream wells to less than 1 ft near F1. From the beginning of the record to about March 28, 2001, temperature in F1 does not closely track the surface-water temperature. With increasing discharge after the low-flow winter period, there appears to be about a 15 to 20-day lag for surface water to become the dominant component in F1. This relation is also displayed from the end of March to mid-April in 2002.

Together, the water-level and temperature data at this site show how groundwater temperatures and water levels are affected by streamflow losses. Effects of the losses are reflected by the water levels and temperature of water in the wells, from near the stream bank to more than 100 ft distant. These effects are represented by the large range in temperature and the variation in the time lag of annual maximum and minimum temperature. What is not known is the possible influence of surface-water irrigation effects on the near-bank exchanges. For example, 2001 was a proratable year, and the Kittitas Reclamation District was allocated less water than its full entitlement, which it received in 2002. As a result of less water in 2001, there may have been lower groundwater levels in the adjacent irrigated lands and thus, a diminished effect on the groundwater flow system in this area. The return flows for the irrigation season were also much less in 2001 than in 2002. For example, the annual mean discharge for Cherry Creek, which receives irrigation return flows (both surface water and groundwater), was nearly 100 ft^3/s less in 2001 than in 2002, which is equivalent to about a 40 percent reduction in mean annual discharge.

Although the BLM site is in a losing reach, the losses may be an important component for later discharge to the river. For example, the distance from the site to the bend in the river where groundwater likely would discharge is about 1,500 ft. Using calculated hydraulic gradients and a reasonable range in lateral hydraulic conductivity and saturated thickness, a discharge per unit area can be calculated. In turn, that value can be used with an estimate of effective porosity to calculate a range in groundwater velocity from about 2 to 20 ft/d. These values yield travel times to the bend that range from 75 to 750 days. Thus, it is possible that the colder water from the river that is recharging the groundwater system during January through March may return to the river farther downstream during July through mid-September, when streamflow temperatures are highest. Thus in this location, streamflow losses may be important for providing cool groundwater for later discharge.

Wapato Site

The water-level and temperature data for the Wapato site display interesting attributes, and also indicate the large difference between a drought year and nearly average (but not wet) years. From the beginning of the record to about April 11, 2002, surface-water levels are higher than the groundwater levels (fig. 26*A*), indicating streamflow losses. During this period, groundwater temperatures in wells 1A and 2 closely match the stream temperatures (fig. 26*B*). After April 11, the differences (hydraulic gradient) between surface-water and groundwater levels greatly diminish. Between April 11 and April 14, the discharge at Yakima River at Parker increased from 3,360 to 15,800 ft^3/s, and as a result, water levels in the groundwater rose. During the spring-runoff period from late May to the end of June, discharge exceeded 9,000 ft^3/s and groundwater levels closely matched river levels through early July; there was a loss of surface-water record from July 7 through November 19, 2002. Unlike 2001, throughout the winter, groundwater and river levels were relatively similar and higher. This likely is due to both the larger runoff-season discharge and the overall wetter year; note that groundwater levels in non-prorating years in WIP just to the west of the site may be as much as 6-ft higher (Vaccaro and others, 2009). The large rain-on-snow event from January 1 through February 2 produced over-bank flows exceeding 22,000 ft^3/s at the site. Thereafter, groundwater levels exceeded surface-water levels (fig. 26*A*). Thus, the difference in discharge to produce over-bank flows (16,000 ft^3/s in April 2002 compared to 22,000 ft^3/s in February 2003) largely controls how exchanges function in this area. This aspect is clearly displayed by the elevation data for well 4 that had the highest water level, which extended for almost a week, during this event. The slough that well 4 is in flowed during this period and shows the larger effects of sloughs/side channels on groundwater than overbank flows.

The temperature data are consistent with the water-level data because temperature in wells 1A and 2 closely match the stream temperature. Groundwater in well 3, which has almost identical water levels as well 2, however, displays a more muted temperature thermograph that does not have large daily variability, but has a large (16°C) annual variation. The temperatures in well 3 thus indicate that the daily effects of heat transport are attenuated at the 57-ft depth of this well. However unlike 2001, the dry year, after the April 2002 event and continuing though early September 2002, temperatures in well 3 generally are similar to those in both the other wells and the surface water, and the annual maximum (which lags by about one month) is about the same as the surface water maximum (fig. 26*B*). The difference in temperature from 2001 to 2002 further shows the importance of large runoff events and runoff periods on near bank exchanges. During the period when groundwater levels were higher than the streamflow levels, it is not known if groundwater temperatures were cooler than streamflow due to missing data.

The temperatures in the three FLBL wells (fig. 26*C*) provide information on flood plain interactions that are some distance from the main channel. For the temperature thermographs, daily values from the Yakima River at Parker site (data from Reclamation's Hydromet— http://www.usbr.gov/pn/hydromet/yakima/yakwebarcread.html), which closely follows the Wapato surface-water temperatures, are used for comparison purposes because the well thermographs are easier to visualize using daily data for the surface water in contrast to more 'noisy' Wapato-site 30-minute data.

The three wells are located in relic sloughs that flow at times during high flow events, and their thermographs are different from the other Wapato well thermographs. Well F1 is about 435 ft from the main channel, and has as much as a 10°C annual cycle, much more than a typical groundwater thermograph that is unaffected by surface water, showing the influence of exchanges this far from the river. Water temperatures in well F1 are coherent with streamflow temperatures from the rising limb of the thermograph to the annual peak and afterwards they lag, especially during the cold winter season (fig. 26*C*). With the onset of spring runoff (especially in June 2002), F1 temperatures closely follow streamflow temperatures, and unlike in 2001 when annual maximums differed by as much as 4°C, the annual maximums generally were within 1-2°C of the streamflow maximums. The F1thermographs indicate that lateral groundwater flow composed of surface-water losses is influencing the temperatures in this shallow well. The close correspondence of 1–2 day groundwater peaks to events or runoff periods, for example, January 2002 and February 2002 and 2003, also suggests that water may flow in this slough during these periods. However, unlike F2 and F3, the temperature in F1 increased during these events, otherwise its thermograph is coherent with many of the variations in the stream thermograph. Although there may be several reasons for the short-lived warming during these events that occurred in F1, there are no data to analyze their cause. These variations indicate a complex relation between the events and groundwater temperatures in F1. This aspect is further indicated by the fact that these peaks displayed in F1 are not displayed in the thermograph for well 3 (fig. 26*B*), which is only 55 ft from the main channel.

Water temperatures in F2 have a smaller annual range (about 4°C) in comparison to F1, and more mimic a typical groundwater-temperature thermograph (fig. 26*C*). However, there are distinct 2–10 day changes in temperature that follow changes in discharge, indicating the influence of streamflow losses at this well that is about 1,000 ft from the river. Again, the temperature thermograph and the vegetation type in the slough where F2 is located suggest that groundwater, derived from the river, is flowing downgradient below the slough. The sloughs likely represent relic buried channels containing coarse-grained material and provide a preferred pathway for groundwater flow.

Groundwater temperature in F6 (located about 3,400 ft southeast of well 1) display a more typical groundwater-temperature thermograph than either F1 or F2 because it has an annual amplitude on the order of about 2°C, which is less than the 10°C and 4°C amplitudes measured in F1 and F2, respectively. The temperatures in F6, however, show influences of larger streamflow events, for example, January through May 2002 and the February event of 2003. For the former period, temperatures in F6 became relatively constant over the complete period, indicating a large input of water. For the latter event in February, the effects of surface-water are seen for about 1 month, that is, the colder surface water recharging the groundwater system dissipated in that time. Field observations indicated that the slough supported streamflow during several of the high-flow periods. Larger events during 2002 resulted in lower groundwater temperatures during at May and June. The data show the importance of these sloughs for providing a pathway for recharging the shallow groundwater system with colder water. During the snowmelt runoff period, however, groundwater temperatures rose due to the input of warmer surface water. Overall, the data indicates the importance of an active flood plain; the Wapato site is in a reach identified as having the largest active flood plain in the basin (Snyder and Stanford, 2000; 2001). The data indicate that rain-on-snow events, in contrast to the spring runoff period, are important for supplying cold water to the groundwater system.

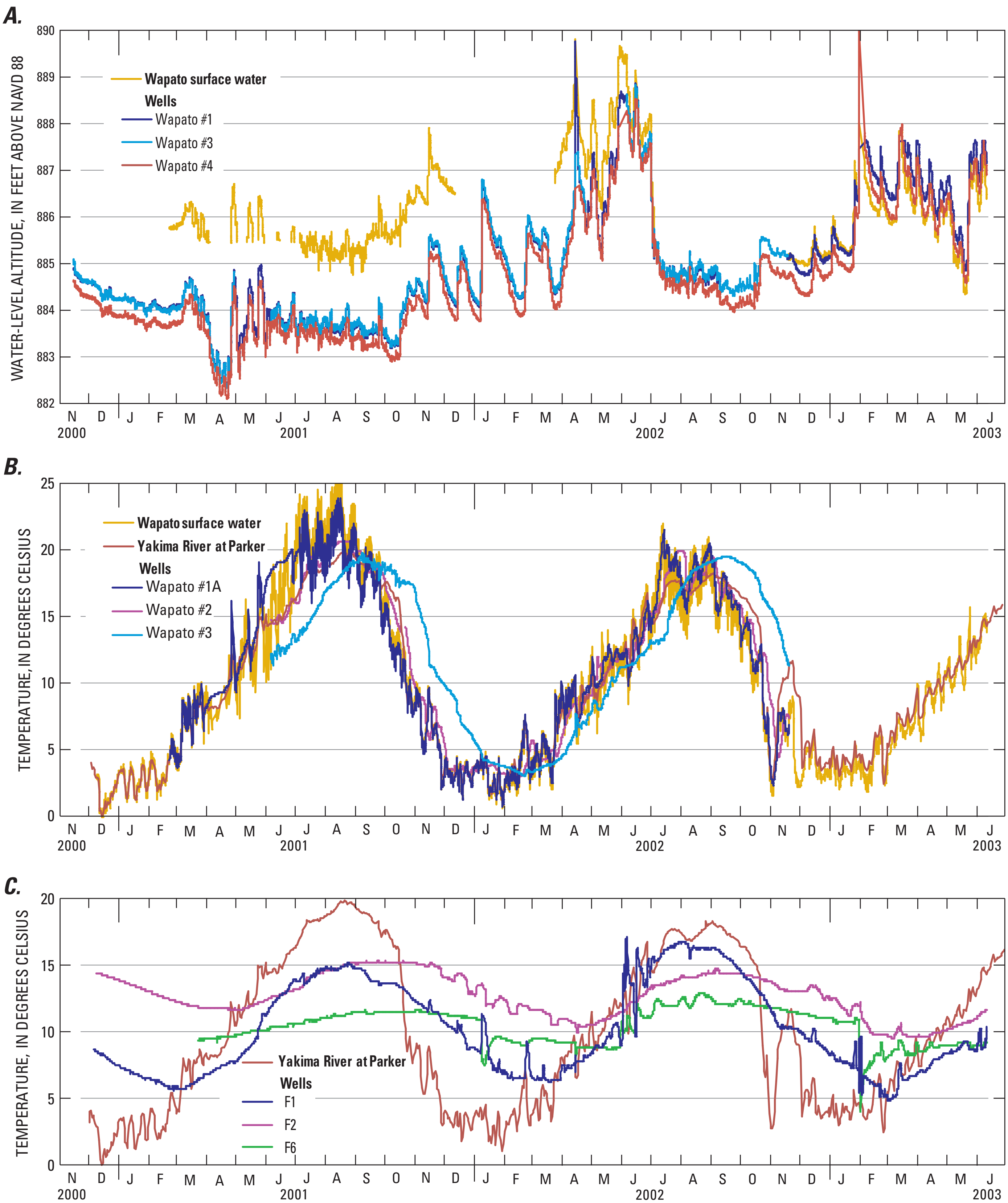


Figure 26. (*A*) water-level altitudes and (*B*) water temperatures in monitoring wells and at surface-water stations, Wapato site, Yakima River, Yakima River basin, Washington.

Toppenish Site

Elevation data clearly show that the Toppenish site is in an area of groundwater discharge with groundwater levels being higher than the stream levels (fig. 27*A*). Except during events or high spring runoff, the hydraulic gradients between sites are relatively constant over time. Differences between the 2001 drought year and the other years are mainly reflected in a larger gradient between the surface water and the groundwater from November 2000 through March 2001, and the overall rise in groundwater levels starting in November of 2001. Of interest is the close correspondence between the hydrographs because the elevation of the water table mimics the surface-water levels in a gaining area, similar to the final part (after the February 2002 event) of the record for the Wapato site (fig. 26*A*); the ability to maintain a lateral hydraulic gradient under varying streamflow levels was also noted previously for the VHGs. The correspondence shows the influence of the pressure wave of the surface water on the groundwater system, as far away as 80 ft (well 3) (fig. 27*A*). Indeed, a site that is 1,400-ft northwest from the Toppenish site was periodically monitored (14 measurements), and the groundwater levels suggest a subdued replica of the hydrograph with a pronounced higher water level (nearly 2 ft) during the extended 2002 spring-runoff period. The data from this site, which are significantly correlated to measured levels at well 3, also show the overall trend to higher levels from 2001 to 2003. Thus, it appears that the sediments composing the upper part of the aquifer allow the pressure wave to propagate over large distances in this water table aquifer. Therefore, it may be possible that pressure-wave effects can raise water levels in an area of shallow groundwater such that the water levels would intercept the land surface in low-lying sloughs or depressions. This concept may be related to near-bank, seasonal wetlands observed along the Yakima River in the Parker and Toppenish reaches (fig. 8).

Water temperature thermographs for the wells (fig. 27*B*) are distinctly groundwater types because of their small annual variations, especially when compared to those at a losing site (Wapato site, fig. 26*B*). Annual variations (excluding peaks and well 1A) are on the order of 1–2°C compared to as much as 16°C in well 2 at the Wapato site. In the 2001 drought year, annual maximum/minimum temperatures lag by about 2 months and in the wetter 2002, they lag by about 1 month. Temperatures in well 1, which is 30-ft deep and about 45 ft from the river, show effects of surface water pushing into the aquifer for rain-on-snow events, but not during periods of increased streamflow in the spring-snowmelt runoff season. Effects of events are especially displayed during the February 2003 event when temperature in well 1 decreased by 5.4°C, and this colder water dissipated over a period of 2–3 days when temperatures increased by more than 3°C. Within 21 days, the temperatures in well 1had returned to typical values; during this period and after the quick initial rise in temperature, the temperature thermograph inversely mimicked the groundwater level hydrograph. Unlike temperatures in well F1 (described below) whose thermograph inversely mimicked the groundwater hydrograph of well 1 for this complete period, the initial rapid rise in temperatures in well 1 indicate that this water was transported laterally to the river—suggesting groundwater velocities are on the order of 15-22 ft/d. Using the lateral gradient from well 3 to well 1, an effective porosity of 0.1, and letting lateral hydraulic conductivity range from 25 to 100 ft/d yields velocities ranging from 10 to 35 ft/d, which is consistent with the transport of the cold water over those few days. A rough estimate of the amount of surface water that entered the aquifer can be made by using the well depth, distance from river, and a specific yield of 0.15. These values, when considered in conjunction with the temperature data, suggests that per unit area, about 202 ft^3 of surface water moved 45 ft into the aquifer. At well 3 (80 ft from river), only the large February 2003 event is displayed by the temperature data with a 4.5°C drop in temperature. This temperature drop occurred over a 3.5-hour period, and within 7 hours the temperature had returned to normal, suggesting that the quantity of surface water input into the shallow part of the water-table aquifer was not large because the effect of the event was greatly diminished at a distance of 80 ft from the river. Temperatures from the shallow (8 ft) well 1A, which is 10 ft from the side channel (near the surface-water site), display a larger annual variation (5.4°C) in comparison to wells 1 and 3 and only one event, a smaller January 2002 event, is seen in the data. The larger annual amplitude suggests increased influence from surface water, but it is not known why the temperatures in the well do not respond to events. Additionally, its annual minimum and maximum temperatures lead those in wells 1 and 3 by about 2 months and 1 month, respectively, but closely follow F1 and F2 annual peaks.

Water temperature in the FLBL wells (F1 and F2) have a larger annual cycle than temperatures in both wells 1 and 3, but their annual maximum and minimum lags are similar to those in well 1A (fig. 27*B*). Water temperature in F1, which is about 880 ft from the river, clearly shows the effects of the most events. For example the large February 2003 event produced a temperature decrease in F1, and its temperature of 6.2°C was similar to that of well 1. This colder water from the February event dissipated over about a month—as displayed in the temperature thermograph that inversely mimics water levels in well 1. The location of well F1 (in a low lying area near the side channel) and well depth (15 ft) likely contributes to its temperature responding more to streamflow fluctuations (note the more short-temporal fluctuations in its temperature thermograph) in comparison to temperature in wells 1 and 3. This aspect is partly related to the fact that the side channel is not deep, which results in a large area being inundated that would need to drain back into the channel. The thermograph for well F2 displays both similarities and differences from the thermograph for F1. There are temperature peaks in summer of 2001 that are not displayed in any of the other well thermographs. These peaks suggest that there are influences from upgradient irrigation drainage. Additionally, the February 2003 event lowered the temperature fully 7.3°C, from 11 to 3.7°C, but the temperature rebounded within 2 days to 9.1°C.

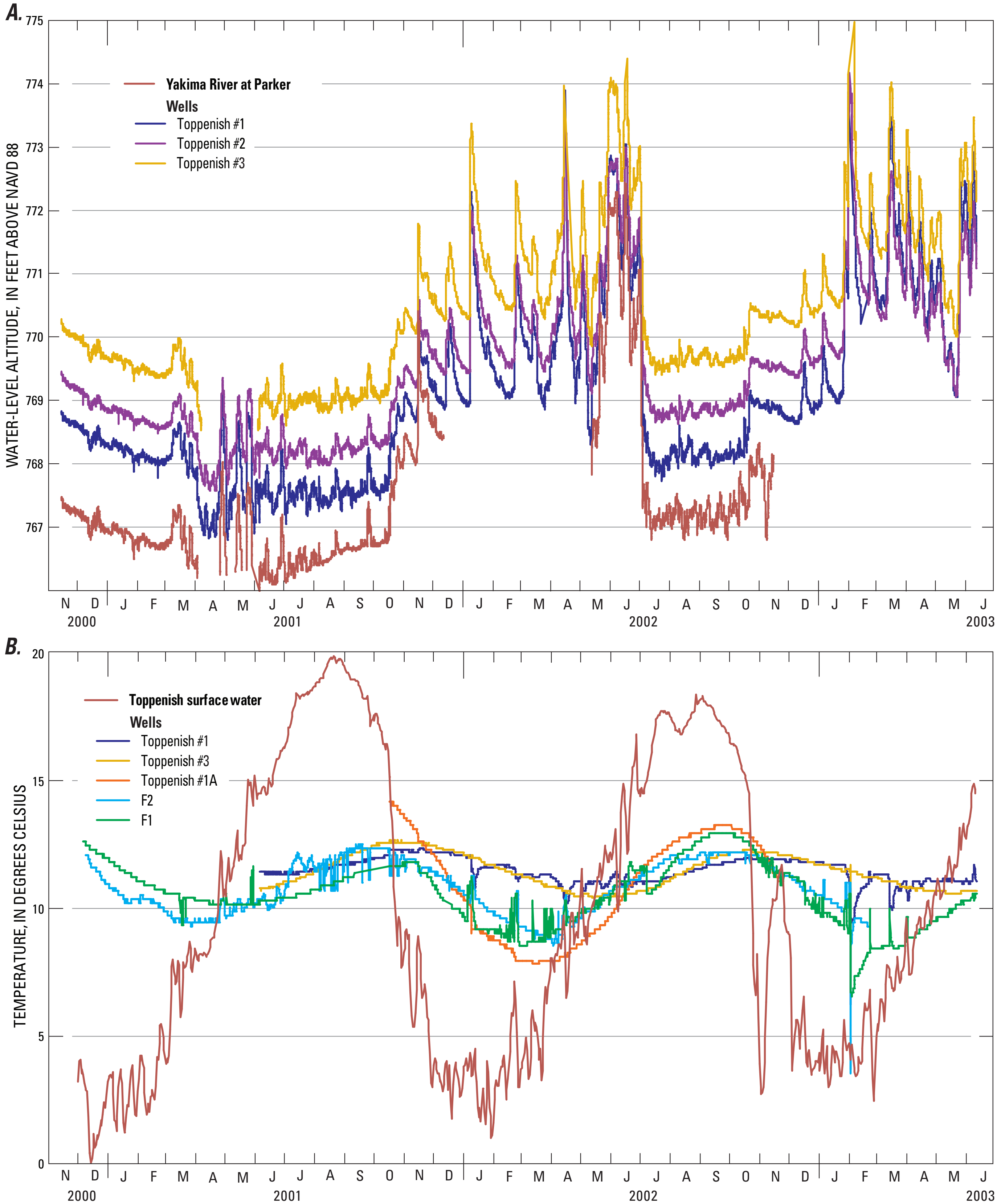


Figure 27. (*A*) water-level altitudes and (*B*) water temperatures in monitoring wells and at surface-water stations, Toppenish site, Yakima River, Yakima River basin, Washington.

Variations between these thermographs further indicate the complexity of exchanges over relatively small distances and the importance of landscape characteristics such as sloughs and side channels.

Satus Site

The water level and temperature data for the Satus site (fig. 28*A*, *B*) display interesting attributes. Except for several daily occurrences, the water-level data indicate that the river level was lower than well 1 (nearest the river), and starting with a smaller event in November 2001, the river level became higher than the groundwater levels. The higher river levels persisted throughout the winter and extended to beyond the large April 2002 event. Thereafter, the levels in the river were lower than the groundwater levels, including during a large February 2003 event, when over-bank flows likely increased groundwater levels that drained much slower than the recession in river levels.

Differences between a dry year and average years are clearly indicated by the data. During the 2001 drought year, groundwater levels generally were lower than during 2002 and 2003 (fig. 28*A*). Well 1 had higher levels than wells 2 and 4, which had levels lower than the river levels, suggesting complex relations over very small distances and the importance of small river-level changes. Lower groundwater levels in 2001 throughout the WIP, which the site abuts, likely affected groundwater flow directions. About 400 ft downgradient from the site is a relic channel that is about 5–6-ft lower than the surrounding land surface. This channel (also readily identified by the vegetation—trees in contrast to grasses/shrubs at the site) may contain coarse-grained sediments and function as a drain to the local groundwater system. With the tripling of streamflow quantities from October 11 through October 24, 2001, levels in the river and groundwater all rose concurrently, with events and recessions displayed in all the data. Again, this concurrency of elevation changes shows the influence of the pressure wave of the surface water on the groundwater system, as far away as 135 ft at well 4. With the river level recession after the large April 2002 event (daily mean flow of 14,600 ft^3/s at the Yakima River near Parker) and through the remainder of the record, the river level is lower than levels in wells 1 and 2. Higher groundwater levels, compared to 2001 are sustained from July 2002 through January of 2003 because the higher levels throughout the abutting WIP during 2002 contributed to raising the levels in this area.

Groundwater temperatures (fig. 28*B*) indicate that there is minimal influence from surface water because the temperature thermographs for wells 1 and 3 display small, on the order of 3°C, annual variations without the day-to-day variability in the streamflow temperature thermograph. Note that daily mean streamflow temperatures for the Yakima River at Prosser gaging station (data from Reclamation's Hydromet—http://www.usbr.gov/pn/hydromet/yakima/yakwebarcread.html) that is 33 mi downstream is shown to (1) provide information for March through October 2001 when data are missing for the surface-water site and (2) indicate the differences between diurnal and daily variations. Starting on a January 2002 event and extending through March, the temperature in well 1 shows some influence of surface water, otherwise, throughout the complete record except for the large February 2003 event, the temperature thermograph represents a groundwater dominated thermograph. Of interest, is that during the remaining part of the time when the river levels were higher than the groundwater levels, temperatures in well 1 showed no influence of surface water. This may be due to the fact that the well 1 was the deepest of the monitoring wells, indicating that any streamflow losses did not mix with the deeper groundwater in this location. A further contributing factor likely is the lower hydraulic conductivity of the aquifer materials (silty sands) at the Satus site compared to the other three sites, which shallower wells penetrating coarse-grained materials such as gravels. Another confounding factor is that the January 2002 event (maximum discharge of 9,200 ft^3/s at the Yakima River at Parker) had a larger response in well 1 than did the much larger 22,000 ft^3/s February 2003 event, and there was no response from the April 2002 event that was the second largest during the monitoring period.

The temperature thermograph for the 31-ft deep well 3 follows the same annual variation as that of well 1 but displays almost no influence from surface-water losses. The shallow well 2A has a temperature thermograph that has a larger annual amplitude than the deeper wells (fig. 28*B*), indicating that there is some vertical temperature stratification and possible shallow mixing with surface water. The thermograph of well 2A also leads those from wells 1 and 3 by about a month, further indicating some influence of surface water on 2A's temperature. The thermograph for well 2A also is similar to that of well 1A at the Toppenish site, but the amplitude of temperature in well 2A is larger by about 1°C. The thermograph for the Toppenish site well 1A is more similar to the thermograph of well 3 (which is a typical groundwater thermograph). The above further indicates that there is some influence of surface water on temperatures in the shallow well 2A.

Starting August 14, 2002, streamflow temperature rapidly decreases, becoming lower than the temperature in well 3 by August 17, and on August 22 is the same (12.3°C) as in well 1 (fig. 28*C*). On September 9, streamflow temperature increased by 6.2°C, and thereafter followed an annual cycle typical of streamflow; except for this period, streamflow temperatures at this site and Yakima River at Prosser were similar during the monitoring (fig. 28*B*). During this 14-day period, temperatures indicate that the stream temperature was representative of groundwater. With the onset of 'flip-flop', discharge for the Naches River near north Yakima increased from 390 ft^3/s on September 1 to 1,900 ft^3/s on September 9, and by the 14^{th} the discharge was 2,200 ft^3/s. The change back to a surface-water signature at this site is consistent with the increase in discharge from the Naches arm; however, a consistent increase in discharge at Parker did not occur. It may be that after

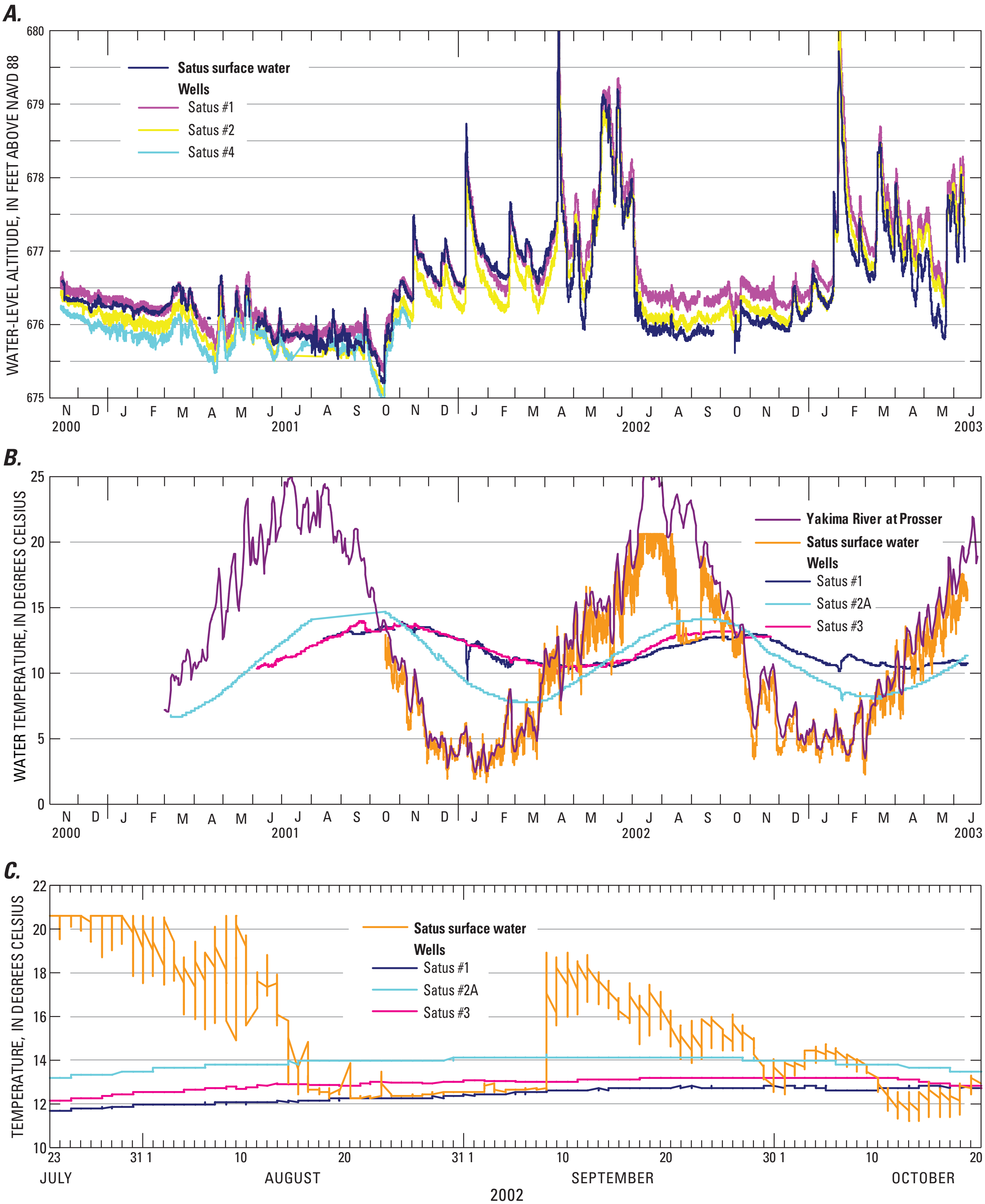


Figure 28. (*A*) water-level altitudes, (*B*) water temperatures, and (*C*) short-period temperatures in monitoring wells and at surface-water stations, Satus site, Yakima River, Yakima River basin, Washington.

streamflow diminishes to some minimum discharge on the mainstem near the head of the side channel, it takes a longer period of time to re-wet the streambed/bar sediments for flow to increase in the channel because at lower flows the entry is narrow and much of the water entering the channel is through the coarse-grained bed sediments. Rearing salmonids have been observed in this side channel, and the decrease in water temperature (on the order of 7°C) due to lower flows likely produces improved thermal habitat, indicating the importance of groundwater discharge for maintaining areas of thermal refugia.

Satus Wildlife Area

The data from the monitoring wells at the SWA, which is in a gaining reach (appendix A), show distinct spatially varying characteristics (fig. 29*A*, *B*) that indicate the effects of different hydrologic controls. The data are representative of different large-scale influences, from irrigation practices to the northeast to changes in hydrologic controls in the large flood plain that is bounded by an irrigation district (WIP), streams (Satus Creek and Yakima River), and oxbow lakes (many of which are managed for wildlife) with many interconnected channels. Groundwater is within 4–6 ft of land surface throughout most of the SWA—only 18J01 (fig. 24) had water levels greater than 10 ft below land surface. Groundwater flow in the SWA generally is from the northwest to the southeast. Lateral hydraulic gradients from the most upgradient monitoring sites (2R03/R04) to the most downgradient sites (18K01, 18J01) range from 0.0011 to 0.0014 ft/ft; differences in hydraulic heads across SWA are as much as 20 ft. Lateral hydraulic gradients between all sites (a total of 15) ranged from 0.0009 to 0.0044 ft/ft, with all but four gradients ranging from 0.0011 to 0.0021 ft/ft. These latter gradients are consistent with the low lateral gradients present in the Toppenish basin , and previously mapped groundwater levels for the water table in this area (Vaccaro and others, 2009), which show gradients ranging from 0.0015 to 0.0019 ft/ft. Of interest, the hydraulic gradient between 18H01 and 18K01 (fig. 24) shows that in this area near the Yakima River the groundwater flow is to the south, and similar to that described previously, groundwater flow near the river generally parallels the river. Water-levels generally are sustained at a higher level in 18H01 due to its proximity to an older channel in a sediment-filled relic oxbow lake that remains wet most of the year. The largest lateral gradients occurred from 18F01 to 18H01 and 18K01/K02, and these gradients reflect the local control of the Yakima River, Satus Creek, and surface-water bodies.

Data from these wells are described below in a downgradient order. The data also are analyzed with respect to potential hydrologic control of surface-water features, and therefore, daily mean streamflow are presented for the Wapato diversion (effects of surface-water irrigation), Yakima River at Parker (river effects), and the American River (surrogate for streamflow in Satus Creek and its potential effects).

Groundwater levels in wells 2R03 and 2R04 (located in close proximity to a major agricultural drain-North Drain) display a typical hydrograph responding to surface-water irrigation. Although the annual water-level changes are less than those for the central part of WIP (which can be more than 10 ft), they follow the same temporal pattern as indicated by the quantity and timing of the diversion for WIP (fig. 29*A*). Levels start to rise in early April with the onset of the irrigation season, peak in August, and decline to November. The levels stay relatively constant throughout the winter to early spring (April), with variations being derived from streamflow losses from North Drain during runoff periods that generate streamflow in the drain. The levels clearly show upward flow from 2R04 to 2R03and the influence of North Drain. The sudden rise in early August of 2003 was due to a breach in an upstream lateral that resulted in North Drain carrying much more streamflow than average; North Drain usually flows on the order of 40 ft^3/s during the irrigation season and about 4 ft^3/s during other times of year. During 2004, the water levels in the wells stayed higher for about 1 month compared to 2003 due to a longer period that the main canal for WIP operated (fig. 29*A*). Daily changes in water levels are due to variations in surface-water usage and thus, flows in North Drain, and to a minor extent, runoff events.

Temperatures in 2R03/R04 also show the influence of surface-water irrigation. Well 2R03 has a very smooth temperature thermograph typical of groundwater, but the annual range is fully 9°C (fig. 29*B*), and is an attenuated and smoothed replica of surface-water temperatures. Annual maximum temperature lag streamflow temperature and water-level altitudes by about 2 months in 2003 and 1 month in 2004; the lags are similar to those for well 3 at the Wapato site, which is in a losing section. However, the annual minimum temperature at 2R03 do not reach the low temperatures in well 3 because they are attenuated by groundwater—suggesting some stratification in the upper part of this shallow system. Temperatures in the deeper well 2R04 follow the same pattern as those in 2R03 but with smaller amplitude (fig. 29*B*). Additionally, from late August 2004 through the end of the record, the temperature thermograph for 2R04 displays a less sinusoidal shape than that for 2R03, and suggests that irrigation effects occurring upgradient have propagated downgradient and are influencing the temperature in 2R04; the annual minimum temperature in 2R04 in 2004 also was the highest (as much as 1–3°C warmer) of all the wells in the SWA. Thus, groundwater in the upper part of the shallow system in and near irrigated lands is supported by excess surface water that moves downgradient with minimal daily effects displayed by the temperature. The water-level hydrographs, in contrast, show highly variable daily fluctuations due to variations in hydraulic head in North Drain. These pressure effects propagate into the groundwater system but the VHG (upward flow to the drain) is maintained, similar to that described previously for the mini-piezometer data. Water-quality data collected on September 24, 2002,

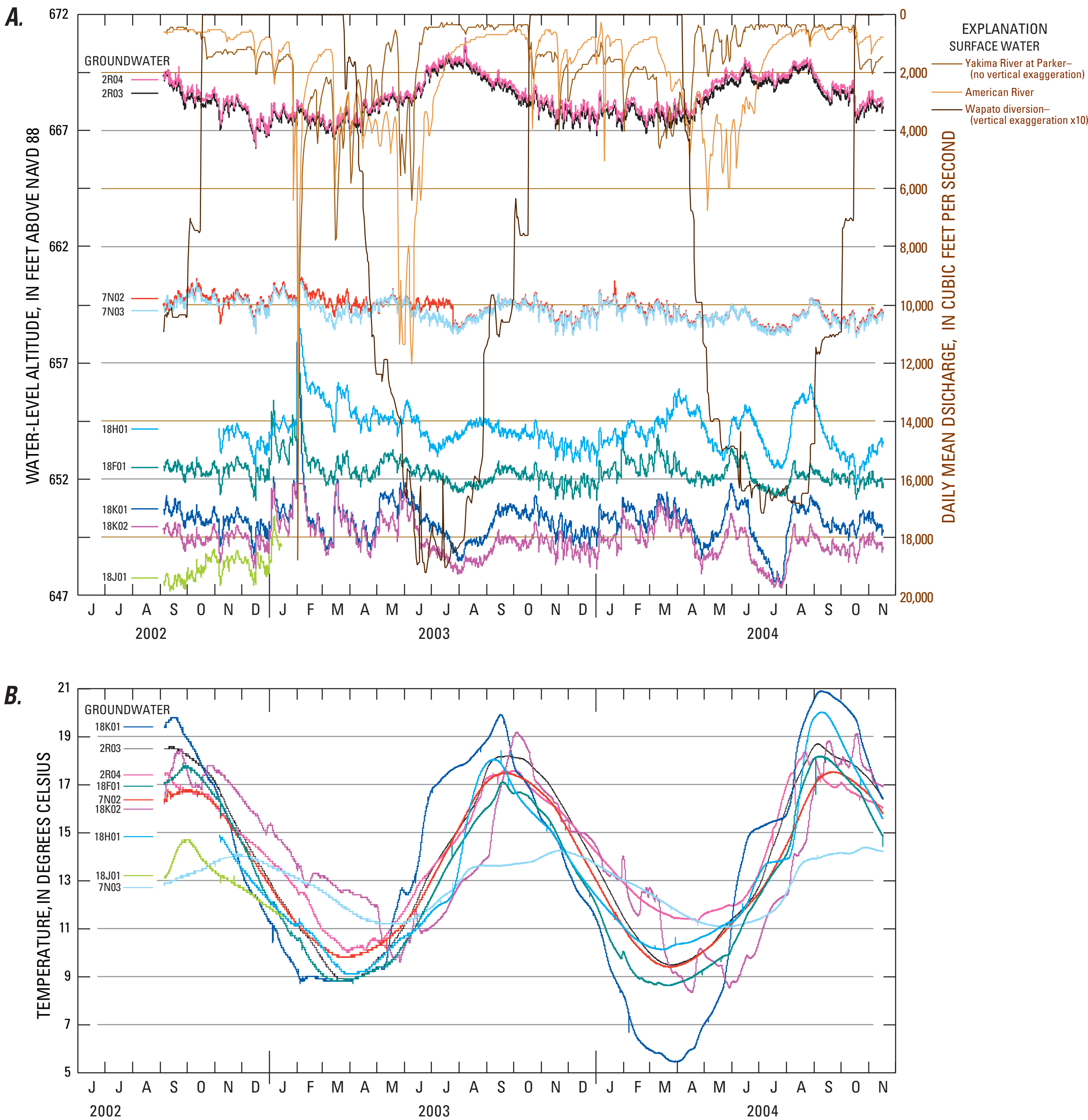


Figure 29. Groundwater (*A*) altitudes and (*B*) temperatures at monitoring wells, Satus Wildlife Area, Yakima River basin, Washington.

in these wells also show effects from irrigation. Nitrate plus nitrite in the shallow well (2R03) was 11.4 mg/L, whereas the concentration was 1.89 mg/L in 2R04. Specific conductance was nearly double in 2R03 compared to 2R04, and ph in 2R03 was 8.8 compared to 6.7 in 2R04; of the seven wells sampled, ph ranged from 6.5 to 8.8 with all but 2R03 being less than 7.0. The largest phosphorus and orthophosphate concentrations also were found in 2R03. Similarly, of the six pesticides detected in the groundwater samples in these two wells (16 total detections for all wells sampled), the largest concentrations were in 2R03, especially for atrazine and simazine. Pesticide samples in North Drain also had detections for other compounds such as trifluralin, terbacil, and metolachlor, further indicating influence of irrigation on the shallow system. The water-quality data show that the groundwater in 2R03 is the most similar to the eight surface-water sites sampled. Stable isotope concentrations of deuterium and oxygen in wells 2R03 and 2R04 were similar to concentrations measured in North Drain.

Wells 7N02 and 7N03 (10- and 20-ft deep, respectively) are downgradient from 2R03/R04 and also are next to an agricultural drain, which is the inflow to McBride Lake, a relic oxbow. The drain is supported by both groundwater and surface-water return flows. Water levels in these wells display the smallest annual amplitude of all the wells in SWA (fig. 29*A*), which is indicative of little influence from local recharge from irrigation or drain losses. This area thus represents a transitional zone between the areas controlled by surface-water irrigation practices and areas controlled by surface-water features, which are represented in the data for the other downgradient wells. Together, the well data (fig. 29*A*, *B*) indicate that in the flood plain away from active side channels, streams, and surface-water bodies, the groundwater flow system is likely not as dynamic, with small seasonal changes representing a relatively constant downgradient flux of groundwater. However, the water-levels in these wells display large and complex daily, seasonal, and annual variations relative to their hydrographs. These variations are controlled by the variations in discharge (stage) in the drain. From about October through the beginning of the irrigation season, many of the water-level variations in 7N02 and 7N03 are concurrent but smaller than those in 2R03/R04. Otherwise, most of the variations in the levels are different than those exhibited in the two upgradient wells. A distinct downward vertical gradient from 7N02 to 7N03 occurs from the beginning of the record to late July 2003. Afterwards, the vertical gradient is greatly diminished and essentially non-existent. It is not known whether this is related to the quantity of discharge in the drain or to the stage in McBride Lake. Unlike water levels in the other wells downgradient of the North Drain wells, levels in 7N02 and 7N03 display only a small effect, on the order of 1 ft, from the February 2003 event.

The temperature thermographs for 7N02/N03 (fig. 29*B*) also indicate changes from an upgradient, irrigation-controlled shallow groundwater system to a local flood plain-controlled system. Temperature in the deeper (7N03) of the two wells is quite similar to that in 2R04 and its thermograph also is similar to that of 2R03. Thus, as groundwater moves downgradient with less influence from irrigation, the temperature becomes more attenuated. Indeed, the thermograph for the 20-ft deep 7N03 has only a 3°C amplitude, lags 7N02 (amplitude of 8.1°C) by about 2 months, and is representative of a more typical groundwater thermograph without the localized influence of irrigation or surface water. In contrast to 2R03/R04, the thermographs for this paired well set shows no relation to the water-level hydrographs. No nitrate plus nitrite was detected in the water sample from 7N03, and phosphorus and ortho-phosphate concentrations were an order of magnitude less than those in 2R03. Additionally, the only the simazine pesticide was detected in the sample from 7N03 and the concentration was less than 0.005 µg/l. No water quality data were available for the shallower 7N02. Deuterium and oxygen isotope concentrations in 7N03 were essentially the same as for the inflow to McBride Lake (directly adjacent to the wells), and the source of water in the deeper (7N03) of the two wells and the drain likely are the same irrigation waters (see figs. 12–14), but water in 7N03 is derived from a more upgradient source.

Water levels in the remaining five wells display both similarities and differences (fig. 29*A*), and are obviously controlled by varying stages in nearby surface-water features, especially when compared to the relatively small amplitudes displayed in the smoother water-level hydrographs for the four paired, upgradient wells. Well 18H01 has the highest water levels in this group of five wells, and as noted previously, appears to be controlled by a nearby side channel. There is some coherency in water levels for 18H01 to discharge in the Yakima River through about June 2003, and thereafter, the hydrologic control on water levels likely is related to local variations in the stage of nearby channels and lakes. During the early part of the record, the effects of the February 2003 event are clearly displayed by levels in the well, as is the increasing streamflow during March 2003. The February event inundated most of the eastern part of the SWA and standing water was observed during field visits for many days; this water drained to the lakes, side channels, depressions, and the river. Rises and declines in water levels in 18H01 generally have similar temporal characteristics to the other wells in the eastern part of SWA from May through the beginning of August 2004, suggesting not only the same hydrologic control but also similar stage variations in the managed lakes in the area. However, there are distinct differences between water levels in this well and the other monitoring wells—showing that there are hydrologic controls affecting 18H01 that are not displayed by nearby wells (18K01/K02 and 18F01). For example, rising water-levels in 18H01 during July and August of 2003 are the opposite of declining water levels in these other three wells. The lakes and interconnected channels thus exert varying hydrologic control throughout the eastern part of SWA, and their effects may have been relatively similar under natural conditions. The data also indicate that the surface-water features control the shallow system, with groundwater discharging to the river in this area.

The temperature thermograph for 18H01 has about a 9°C amplitude (similar to 2R03), and also lags the streamflow temperature by about a month (fig. 29*B*). There is a lack of a relationship between the temperature thermograph and water-level hydrograph, but the large annual temperature amplitude indicates that the groundwater is principally derived from surface water. The maximum temperature observed in 18H01 (19.8°C) was the second highest of all the measured temperatures and was similar to temperatures measured in the upstream, well 3 at the Wapato site (fig. 26*B*). The groundwater in 18H01 likely represents water derived from surface-water irrigation occurring west and northwest of the site that is mixing with water moving downgradient, parallel to the river. The deuterium concentration in 18H01 was the most depleted (concentration of -99.8 ‰) compared to the other groundwater and surface-water sites. Its stable isotope concentration of oxygen also was the depleted (-13.16 ‰*)*; the five other groundwater samples ranged from -13.69 to -13.41 ‰ and the two surface-water samples ranged from -13.81 to -13.73 ‰. Isotope concentrations from this well (and the other wells) are consistent with shallow groundwater and surface-water values (figs. 12–14). The isotope values further indicate that groundwater in 18H01 is being partially derived from upgradient sources in the near river alluvial aquifer (perhaps representing Naches River water during 'flip-flop') and oxbow lakes north of the site.

Well 18F01 (about 0.5 mi south of 18H01) is located between an oxbow lake (Teal Lake) and Satus Creek (fig. 24). Water-level variations in 18F01 closely follow those in 18K01/K02 but the levels have smaller amplitude. The general consistency between water levels for 18H01, 18K01, and 18K02 further indicate that stage in the lakes and nearby streams exert hydrologic control on the local groundwater-flow system. Three of the four largest lateral hydraulic gradients were between 18F01 and nearby wells in the area, suggesting some control by Satus Creek to the south in contrast to the Yakima River; Satus Creek is deeply incised in this location and the bottom of the well bore is close to the streambed altitude. A continuous discharge record for Satus Creek is not available to determine relations between the discharge (stage) in Satus Creek and the groundwater levels, but the discharge for the USGS gaging station for American River can be used as a surrogate for events and timing of runoff because both streams are unregulated; note that the snowmelt runoff season occurs earlier in the drier Satus Creek basin that has much lower altitudes than the American River basin. Events on American River (some of which also occurred on the Yakima River) such as in January, March, and April 2003, October and November 2003, January and February 2004, and the main snowmelt-runoff season from mid to late May to mid-June 2003 and 2004 are consistent with rises in groundwater levels. Major recessions in the groundwater hydrograph also are likely related to the decline in discharge in Satus Creek during its recession period. Other parts of the hydrograph do not appear to be controlled by Satus Creek based on the American River hydrographs, but it is unknown if the discharge of North Drain to Satus Creek may account for these differences. For example, during the water-quality sampling during September, discharge in North Drain was about 40 ft^3/s and discharge in a small drain on the opposite side of a road was more than 8 ft^3/s, resulting in an increase in discharge in Satus Creek—from 33 ft^3/s above North Drain to 81 ft^3/s below North Drain. Thus, over small distances, large lateral gradients are sustained due to different hydrologic controls, and these controls occur under the larger-scale controls that yield similar water-level hydrographs throughout the eastern part of the SWA.

The temperature thermograph for 18F01 was similar to the other thermographs described above, and had an amplitude that ranged from about 8.2 to 9.5°C (fig. 29*B*); this type of thermograph is typical of surface-water effected thermographs in WIP. Excluding wells 18K01/K02, the annual minimum temperature in 18F01 is lower than the other wells, further suggesting there is some influence from Satus Creek. Stable isotope concentrations from a sample from 18F01 are similar to those from a surface-water sample of the outflow from McBride Lake, which flows to Teal Lake, and indicate common sources of water.

Data for wells 18K01 and 18K02 display attributes that show multiple influences on the shallow groundwater-flow system in this area, especially in comparison to the other wells in SWA. The paired wells are located about 100-ft southeast of Teal Lake, 300-ft northwest of the Yakima River, and 100-ft north of Satus Creek; the outflow channel for Teal Lake (a board-control gate) is about 50-ft south of the wells. The daily to annual temporal variations in the water-levels for the two wells are nearly identical, and most of these variations are similar to those displayed in 18F01 and 18H01 (fig. 29*A*). The similarity of hydrographs for wells in this eastern part of the SWA again indicates a common set of hydrologic controls, from water levels in the channels and lakes to levels in the Yakima River and Satus Creek. These controls are likely pressure affects because there are distinct differences in the temperature thermographs for the wells. Similar to 18F01, the hydrographs for18K01 and 18K02 show the influence of Satus Creek, but hydrologic control from the Yakima River also occurs, especially for the deeper 18K02.

The water-levels identify a downward vertical gradient from 18K01 to 18K02 that is sustained throughout most of the record, and gradients are as much as 0.15 ft/ft, which is consistent for values reported by Vaccaro and others (2009) for the complete aquifer system. The larger gradients compared to 2R03/R04 and 7N02/N03 indicates the presence of more fine-grained materials in this area and hydrologic control of the Yakima River and Satus Creek (the bottom of the deeper 18K02 is near the streambed altitude). The lack of nitrate and nitrite in water samples and low ammonia concentrations (note that several of the wells in this eastern part of the SWA had no dissolved oxygen) further indicate impedance to downward flow and thereby the presence of fine-grained sediments with organic materials. The vertical gradients are diminished after the large February 2003 event, and these diminished gradients continue through about the beginning of May. Gradients also are diminished from early March 2004 through about mid April, which corresponds to a period of higher streamflow in the Yakima River, which may be due to 'backing up' of groundwater due to increased river stage as evidenced by the water levels. Groundwater levels in 18K01/K02 thus appear to be more influenced by the streams than those in the previously described wells.

Temperature thermographs for 18K01 and 18K02 display different characteristics than the other temperature thermographs (fig. 29*B*). Wells 18K01 and 18K02 annual temperature amplitudes are as large as 15.5°C and 10.2°C, respectively (the largest observed in the SWA). Similar to the other sites, the largest amplitude occurred in 2004 (25 percent less runoff compared to 2003 as measured at the Yakima River at Parker). Peak-season diversions to WIP also were about 200 ft^3/s less in 2004 than in 2003. The amplitudes of the temperature thermographs thus appear to be related to the amount of water used in the irrigation district (surface-water recharge to the shallow system), and to some extent, the temperature and flows in the Yakima River and Satus Creek. Variations in flows and levels in the channels and lakes in SWA are unknown for this period. Maximum temperatures for 18K01 lagged river temperatures, as measured at the Yakima River at Prosser, by about one and one-half months and these maximums occurred about one month prior to those in 18K02. During 2004, peak temperatures in the two wells occurred at nearly the same time and lagged the Prosser temperatures by only about one month. The amplitudes and lags suggest that the more water entering the system from upgradient irrigation areas results in a more vigorous shallow groundwater system. Water levels in 18K01 display some response to events with cooling occurring during the February 2003 event and cooling during the late May to early June runoff season. However, effects from other events and increased streamflows during the runoff-season are not discernable. The larger amplitude and general lack of variations during increasing flows, indicates that 18K01 is being influenced by Teal Lake, which likely supplies water to the shallow system.

The temperature thermograph for the 20-ft deep 18K02 not only is very different from the 10-ft deep 18K01, but it is also different from the other temperature thermographs (fig. 29*B*); the annual amplitude in 18K02 also was more than 4°C less than 18K01's amplitude during 2003–04. The thermograph displays large variations from the typical sinusoidal shaped thermographs. Many of these variations are consistent with the variations in its groundwater-level hydrograph, which in turn, as described above for this site, are more related to variations in stream stage than the other hydrographs. The 1.3°C cooling from mid-September to mid-October 2002 is consistent with more of the discharge in the lower basin being provided by cooler Naches River water during 'flip-flop' and the beginning of the decrease in WIP diversions for the 2002 irrigation season (no diversion by October 17, 2002). The rise in temperature after mid-October indicates the influence of recent-irrigation water on temperature in this well, and this increase occurred while the river temperature (as measured at the Yakima River at Prosser) was decreasing from mid-October to early November. An increase in temperature in December 2002 follows the increasing groundwater levels, and shows the coherency between water levels and temperature variations. The relation between temperatures and levels is complex because the temperature variations may lag the water levels by a few days, as in the case of the large February 2003 event, to more than one month for many of the other larger water-level changes. Together, the longer maximum temperature lag in 2003 compared to the temperature lag in 18K01, relations between groundwater temperatures and levels, and co-variations with changes in streamflow discharge, indicate that groundwater in this 20-ft deep well is influenced at different times from multiple sources. Data from this well further shows that groundwater relations in the eastern part of the SWA are complex and highly variable due to multiple controls that include upgradient groundwater flow influenced by surface-water irrigation, alluvial aquifer flow, streamflow in the Yakima River and Satus Creek, and the intricate network of interconnected channels and lakes. Thus, in a flood plain with multiple influences, an active shallow-groundwater system exists and it displays variations over vertical-depth differences of less than 10 ft and lateral distances of 500 ft, and further confirms the complexity of groundwater flow in the flood plain as shown by the data for the wells in the Toppenish and Wapato sites. Further, the management of the lakes for wildfowl can have varying effects on both temperature and water levels in the shallow groundwater system because of the hydrologic control of the lakes and channels in the SWA.

Well 18J01, a shallow 15-ft deep well, had the lowest groundwater levels of the wells in the SWA; the well is on a narrow high bank between a lake and the Yakima River. The data logger for this well became lodged in the lower well-bore, and the water-level and temperature data are available for the period from early-September 2002 through mid-January 2003. Additional data would have been beneficial because the available data suggest that different factors than described above control the local flow system in this area. Through October 2002, water levels were rising in this well, and of the other eight wells, only water levels in well 7N02/N03 displayed rising groundwater levels during this period (fig. 29*A*), suggesting the influence of stage in the nearby lake that is receiving irrigation-water returns in contrast to the river. Thereafter, water level changes are similar to the other wells in the eastern part of SWA, and the lateral gradients from the other wells to this well are retained, further indicating that the levels are locally controlled by the lower levels in the surrounding surface-water bodies. Except for 7N03, the temperature maximum occurred during the same period as the other wells, but the maximum was 2–3°C smaller and was more similar to the maximum displayed in 7N03 (fig. 29*B*), which is representative of a more groundwater driven system with smaller influence from surface-water features. The shallow slope of the temperature thermograph during its recession also is most similar to 7N03. The limited data suggests that the groundwater at this site represents groundwater that is flowing from upgradient areas to the west with some influence by the nearby lake, and the data displays differences from the data for the nearby well 18H01 to the north and wells 18K01/K02 to the south.

Thermal Profiles and Potential Relation to Salmonid Habitat

Longitudinal profiles of water temperatures (thermal profiles) in long reaches of streams were obtained by a method developed during studies of river-aquifer exchanges in the Yakima River basin (Vaccaro and Maloy, 2006). The water temperatures are measured and recorded at 1- and 3-second intervals as a conductivity-temperature depth (CTD) probe is towed downstream, while concurrently recording location coordinates from a Global Positioning System (GPS) device linked to a laptop computer. Profiling is conducted during the diurnal warming part of the sinusoidal daily streamflow-temperature cycle. The method proved to be robust, reliable, and reproducible. Eleven reaches were profiled (fig. 8; see also Vaccaro and others, 2008); seven of the reaches were profiled during July through September 2001, a major drought year. The drought led to much lower flows than average and greatly reduced agricultural return flows, nonetheless the observed low-flows were relatively large (table 3) in comparison to many river systems. The remaining reaches were profiled during August and September of 2002, and although 2002 was not a drought year, flows generally were consistent with flows in 2001, but the irrigation-return flows were larger. For example, during August 2002, return flows (surface water, groundwater, and wasteway water) to the Yakima River between Parker and Kiona were about 475 ft^3/s larger in 2002 than 2001; the monthly mean discharge at Kiona in August 2001 was 824 ft^3/s. During these low-flow periods, the water is generally flowing only within the main channel and the profiling is done, to the extent possible, along the thalweg. During these low-flow periods, the presence of thermal refugia is important for holding or rearing salmonids.

The thermal profiling method was developed and tested/evaluated during the collection of data in two reaches—the Wapatox and the Naches reaches (fig. 8). For these initial "runs," however, the CTD was not fully equilibrated to ambient streamflow temperature before starting a profile or when resuming an interrupted/temporarily suspended profile. Therefore, some parts of the thermal profiles for the Wapatox and Naches reaches are not fully representative of streamflow temperatures. The shorter Wapatox reach was "re-profiled" in September of 2002, and information is presented for this profile along with ancillary information for the July 2001 profile. The Naches reach was not re-profiled and thus, there are discontinuities in the temperature data due to stops during the profile when the CTD first warmed due to exposure to direct sunlight and warm air, and then equilibrated to ambient streamflow temperature during the initial part of the resumed profile.

Replicate thermal profiles (one in August and one in September 2001) were recorded in the Parker and Toppenish reaches (fig. 8; table 3) to (1) verify that the results from the method were reproducible, (2) determine the type of differences that could occur under two different thermal loadings, and (3) re-examine segments of potential groundwater discharge (river-aquifer exchanges) identified during the August profiling. Details of the August profile for the Parker reach and those of the September profile for the Toppenish reach are presented here. No GPS data are available for the profile of the Toppenish reach obtained in August, so that only the temporal, and not the spatial, variations in temperature can be analyzed. Although the occurrences of river-aquifer exchanges, but not their locations in the channel, can be identified, the consistency between the diversity and structure (the shape of the overall profile) of the two Toppenish profiles allows for estimating the relative location of exchanges for the August profile. GPS data also were lost for the Roslyn reach due to a malfunction of the computer, so that the analyses here, too, are restricted to the temporal aspects of water temperature fluctuations and water exchanges; however, hydrologic inferences about the exchanges can be made based on reach location and large-scale physiographic features of the reach. For several reaches, the setting for the depth range for the CTD reverted from 300 cm to the factory setting of a 30 cm. As a result, for these reaches, only relative depth data is available. That is, the relative depths would match the shape of the actual depth structure, and thus, preserve the depth structure for pools and riffles.

Personnel of the Benton Conservation District (BCD) profiled five reaches (about 48 river miles) of the lower Yakima River (M. Appel, Benton Conservation District, written commun., 2008) from Prosser to the confluence with the Columbia River (fig. 8), using the methods of Vaccaro and Maloy (2006). The purpose of this profiling was to locate areas of cooler water that are potential thermal refugia for salmonids. For these profiles, BCD used two or three water craft. For all five reaches, the left and right banks also were profiled, and for four reaches, the center channel also was profiled. The most upstream reach profiled by the BCD personnel corresponds to the USGS Prosser reach. For this report, only selected BCD profiles are described.

The data comprising about 107,000 temperature measurements in 16 reaches document the thermal profile of some 160-mi of the Yakima River system (table 3; figs. 30–45). The data exhibit inter- and intra-profile variations that reflect the integration of the factors controlling the temperature of a parcel of water as it moves downstream (in a Lagrangian framework). The effects of river-aquifer exchanges

Table 3. Characteristics of water-temperature profiles along selected reaches of the Yakima and Naches Rivers, Washington, 2001, 2002, and 2008.

[**Abbreviations**: mi, mile; Max., maximum; Min., minimum; Ave., average; ft, foot; ft/s, foot per second; ft^3/s, cubic foot per second; ft/ft, foot per foot; °C, degree Celsius]

Reach	Reach length (mi)	River mile start	Temperature (degrees Celsius)			Number of measurements	Average distance between measurements (ft)	Average velocity of float (ft/s)	Daily mean discharge (ft^3/s)	Stream gradient (ft/ft)	Average altitude (ft)	Date	Time of profile	Thermal gradient		
			Max.	Min.	Ave.									°C/mile	°C/minute	°C/mile/minute
U.S. Geological Survey																
Easton	7.1	202.2	17.0	15.7	16.3	3,908	9.6	2.1	203	0.0037	2,110	09-18-2001	9:18–14:18	0.09	0.0021	0.00030
Cle Elum	6.4	7.9	15.1	14.2	14.6	2,863	11.8	2.4	179	.0055	2,082	09-19-2001	9:34–12:25	.14	.0039	.00061
Teanaway	9.4	11.75	21.2	13.4	17.6	6,930	7.1	3.5	106	.0036	2,010	07-17-2002	9:36–13:31	.80	.0319	.00340
Roslyn	10.6	176	17.0	15.4	16.3	5,712	9.8	4.9	519	.0025	1,741	09-22-2003	12:55–16:07	.12	.0065	.00063
Thorp	13.0	164.5	16.9	15.0	15.8	9,329	7.3	6.2	877	.0025	1,580	09-25-2002	13:31–16:35	.09	.0064	.00049
Canyon	13.6	148.3	18.1	16.6	17.3	4,543	15.8	7.9	3,850	.0018	1,365	08-29-2002	10:11–12:43	.11	.0098	.00072
Wapatox	5.2	16.5	19.8	13.7	16.5	3,709	7.4	1.6	290	.0042	1,515	07-31-2001	9:48–14:40	.97	.0180	.00332
Wapatox2	4.3	16.5	14.8	13.4	14.1	2,217	10.3	4.8	245	.0042	1,515	08-30-2002	8:13–09:32	.30	.0164	.00380
Naches	11.3	12.8	20.7	14.2	17.2	5,801	10.2	2.3	282	.0044	1,318	08-01-2001	9:27–16:41	.49	.0129	.00114
Parker2	13.9	103.7	22.3	17.7	20.6	6,862	10.7	3.5	334	.0029	876	09-13-2001	11:39–17:32	.26	.0102	.00074
Parker	14.2	103.7	23.3	19.4	21.8	6,137	12.2	3.5	317	.0029	876	08-28-2001	10:21–16:18	.20	.0080	.00056
Toppenish2	12.3	92.6	20.3	17.6	18.7	4,468	14.5	4.5	353	.0013	728	09-14-2001	8:43–12:40	.17	.0088	.00072
Toppenish	12.3	92.6	23.1	19.8	21.7	6,051	10.7	3.0	346	.0013	728	08-29-2001	10:03–15:05	.23	.0078	.00064
Granger	8.1	82.8	23.9	19.7	21.8	3,873	11.1	3.0	389	.0007	672	08-30-2001	10:34–14:36	.37	.0124	.00153
Prosser	12.3	46.3	21.8	20.5	20.9	8,408	7.7	3.6	604	.0015	610	08-20-2002	8:41–13:43	.01	.0003	.00002
Benton Conservation District																
Prosser-banks, left bank	11.4	46.6	20.1	17.7	19.1	6,861	8.8	3.1	485	0.0018	558	09-03-2008	10:38–16:22	0.18	0.0064	0.00056
Prosser-banks, right bank	11.5	46.6	19.8	17.8	19.1	6,655	9.1	3.2	485	.0018	558	09-03-2008	10:38–16:11	.17	.0062	.00054
Chandler,center	7.0	35.8	23.7	21.9	23.1	2,083	17.7	3.6	1,370	.0012	484	08-09-2008	10:12–13:05	.25	.0101	.00145
Benton,center channel	10.2	28.4	24.0	22.2	23.1	2,918	18.4	3.7	1,220	.0006	442	08-12-2008	10:41–14:45	.17	.0069	.00068
Benton, left bank	10.3	28.4	24.3	21.7	23.2	2,969	18.3	3.7	1,220	.0006	442	08-12-2008	10:39–14:47	.18	.0076	.00074
Snivley	11.4	16.2	25.7	23.4	24.4	3,361	17.9	3.6	1,140	.0007	373	08-13-2008	10:38–15:18	.20	.0083	.00072
Confluence, center channel	4.9	5.5	25.9	23.5	24.7	2,517	10.3	2.1	891	.0002	347	08-14-2008	10:05–13:34	.08	.0018	.00038
Confluence, right bank	6.0	5.5	27.3	19.0	23.8	2,463	12.8	2.6	891	.0003	347	08-14-2008	10:04–13.30	.16	.0045	.00078

and surface-water inflows are clearly reflected in the profiles. Smooth vertical-line segments in the plotted data generally indicate interruptions in data collection either to portage around log-jams, other obstructions, or stream conditions that made boating operation unsafe. For example, the smooth vertical-line segments at about mile 3.2 and mile 4.5 of the Easton reach (fig. 30) occurred when data collection was stopped to portage around log jams. The smooth segment at about mile 3.6, however, represents an actual cooling "event" attributed to groundwater discharge to the stream. Profiles are generally described in relation to thermal gradients in terms of degrees Celsius per mile and degrees Celsius per mile per minute. The first expression represents the temperature change over a reach. The latter expression of a gradient is used to account for the total time it took to profile a reach, which is related to reach length, streamflow velocity, any temporary suspensions in data collection or to make portages, and length of time during the diurnal heating cycle, and thus, the temperature change over the reach is divided by the total time. These two normalized gradients provide valuable information for comparing temperatures among the various reaches.

Areas of groundwater discharge (generally related to positive river-aquifer exchanges relative to the VHG) or cool surface-water inflows can be identified on the basis of deviations from the diurnal warming of the stream. That is, areas of temperature stabilization and cooling, and cooling "structures" (short spatial/temporal variations) are indicative of the discharge of relatively cooler water to the stream, and represent the deviations (negative anomalies) from the overall expected (nearly linear) thermal response of streamflow. The stabilization/cooling segments within a reach typify broad areas of groundwater discharge, whereas structures are indicative of local discharge (springs, surface-water inflows, and or alluvial aquifer discharge from re-connecting side channels or mouths of creeks). Both of the above phenomena represent what are termed 'patches' by the biological community, and the longitudinal distance between patches (connectivity) is important for most life-history stages of salmonids (Power and others, 1999; Rieman and Dunham, 2000). Patch size and connectivity are directly related to habitat and species diversity and fish populations (Wu and Loucks, 1995; Dunham and Rieman, 1999; Rieman and Dunham, 2000). Viable salmonid populations, therefore, are predicated on the distribution and abundance of these thermal patches. In intensively modified basins such as the Yakima, return flows of cool irrigation waters function as patches because in the summer they may be as much as 5°C cooler than the temperature of the Yakima River in the lower basin.

The diversity in the basins' thermal regime, as represented by the profiles, represents the riverine systems' temperature templet or longitudinal gradient, which is consistent with an environmental gradient. Temperature essentially defines a physical habitat templet (Southwood, 1977; Poff and Ward, 1990) that explicitly includes temporal variability, and provides for the overall biological community templet—including the different life stages and life history patterns of salmonids. The templet leads to a logical progression of the longitudinal gradient of fish assemblages. The structures contained in the profiles represent patches of cooling (possible refugia) or warming (areas of avoidance) that are overlaid on the basin-wide templet, and reflect the local lateral and vertical connections observed in both natural and modified river systems (Hynes, 1983; Stanford and Ward, 1993) that salmonids use or avoid (Power and others, 1999; Rieman and Dunham, 2000). These refugia are the preferred salmonid habitat during summer when river temperatures are warm and during winter in colder regions when rivers may freeze; salmonids seek out and take advantage of this habitat. The longitudinal gradient, overlaid with the distribution of patches, comprises a continuum from the headwaters to the mouth, along which habitat progressively changes and thus, species are arranged (Vannote and others, 1980).

The 'warming' structures are associated with warm water inflows, typically irrigation-return flows, but also inflows originating at wastewater-treatment plants, ponds, and gravel pits. These structures further show how natural river-aquifer exchanges have been modified as a consequence of human activities. Indeed, as previously described above, various cooling structures also are associated with irrigation-return flows.

The overall basin templet is examined in a downstream direction. The templet includes stream gradient (slope) and thermal gradient. The stream gradient is described in units of feet per foot and the thermal gradient in units of degrees Celsius per mile and degrees Celsius per mile per minute. River-aquifer exchanges are discussed in relation to what is termed thermal diversity (the overall longitudinal complexity/shape of the profile over the reach) and structure (segments within a reach).

Parts of the reaches are used by or otherwise suitable for the holding, spawning, or rearing of anadromous salmonids. For example, spring chinook stock in the Cle Elum, Easton, Teanaway, Roslyn, Thorp, Canyon, Wapatox, and Naches reaches; fall chinook stock and coho in the Parker, Toppenish, Granger, and Prosser reaches; and fall chinook stock in the Prosser, Chandler, Benton, Horn, and Snivley reaches. Summer chinook stock, historically present in the lower basin reaches, have been extirpated from the basin. Additionally, fluvial bull trout use the Easton, Cle Elum, Thorp, Wapatox, and Naches reaches. All reaches are used by anadromous salmonids for some parts of their life-history stages—migration, pre-spawning holding, rearing, and emigration. As noted above, several of the reaches, for example, the Wapatox reach, are used by resident bull trout that are listed as threatened under the ESA. The upper basin and Naches arm reaches all are used by rainbow trout, and ESA-listed summer steelhead use these reaches for some part of their life history. When appropriate, the analysis of a thermal profile of a specific river reach and its variations are related to known or potential salmonid habitat within the reach.

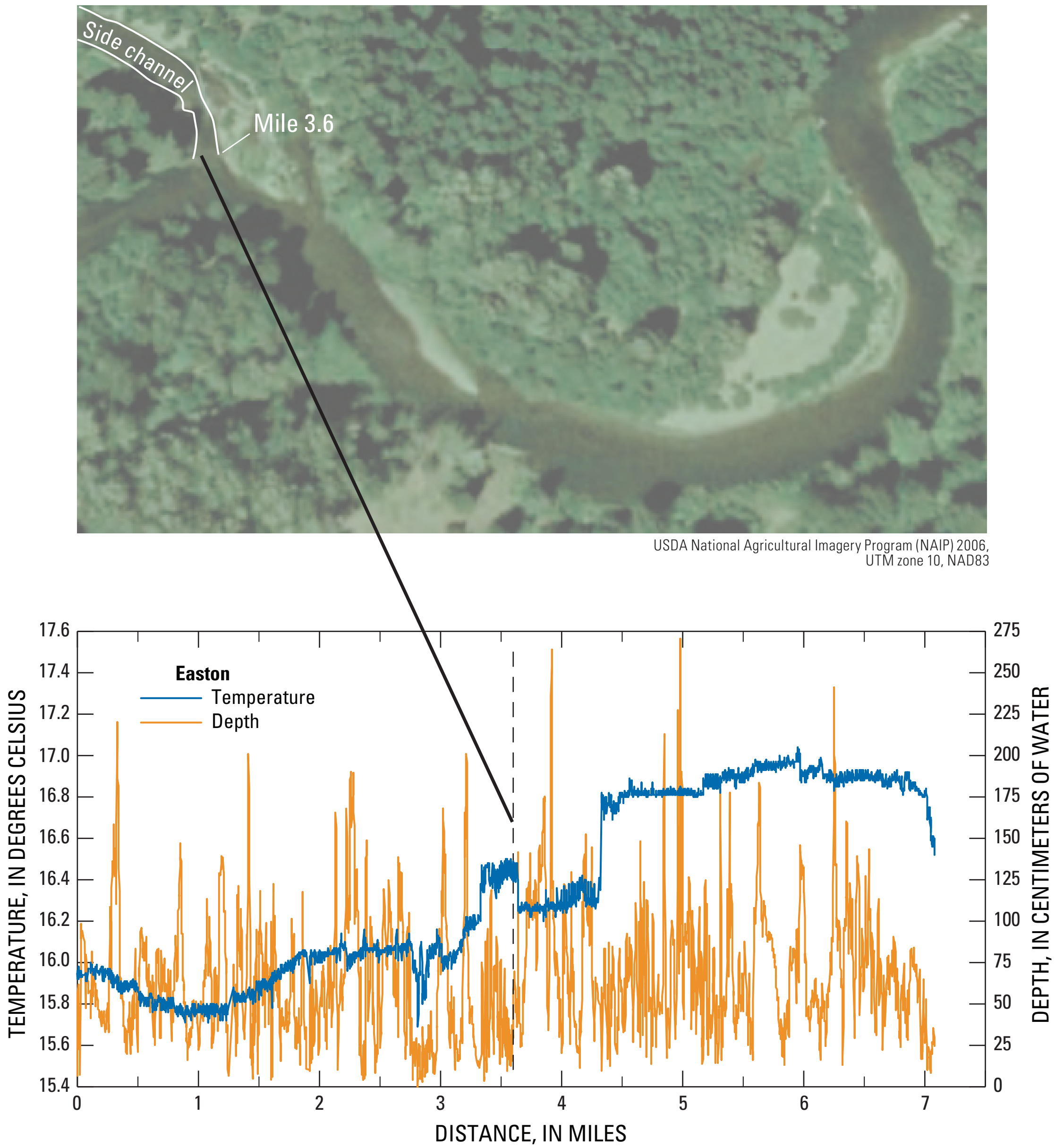


Figure 30. Longitudinal-distance gradient of temperature and depth from a thermal profile, Easton reach, Yakima River, Washington.

Easton Reach

The 7.1-mi Easton reach (fig. 8) starts just downstream of a major diversion dam at the terminus of Lake Easton (RM 202.5) with a large diversion structure and fish ladder. The reach contains high-quality salmonid habitat, has a high production of spring chinook, and exhibits evidence of exchanges, via the thermal profile, typical of headwater, mainstem high-gradient reaches (gradient of 0.0037 ft/ft, table 3). The Easton reach was identified as part of one of the eight priority reaches for restoration based on its intactness and biological richness (Snyder and Stanford, 2001). Of the 1,145 chinook redds located in the upper basin in 2004, 55 percent (88 redds/mi) were in the Easton reach (A. Dittman, National Oceanic and Atmospheric Administration, written commun., 2009). The 0.0003°C/mi/min (0.09 °C/mi) thermal gradient for this reach is typical of high-gradient, headwater type of reaches during the warm season. The Easton profile (fig. 30) displays both long and short segments of stabilization and cooling, with structure exhibited throughout. Broad areas of stabilization and cooling (miles 0–1.25, 2.0–2.7, 4.3–5.1, and 6.2–7.1) typify reasonable contributions from cooler groundwater, which is independently verifiable on the basis of both discharge measurements (table A1, RMs 202.3–195.4) and temperature data from fixed stations at the upstream and downstream ends of the Easton reach. Discharge measurements made at the upper and lower ends of the reach on September 27, 2001 (for a seepage investigation described previously) showed a net gain of about 24 ft^3/s (a 14 percent increase), indicating a considerable input of cooler groundwater. The daily mean flow in this reach on the day of the profile was about 203 ft^3/s, based on Reclamation's data for the Yakima River at Easton gaging station. The fixed station data were from Onset StowAway® TidbiTs™ (reported accuracy of 0.2°C) that were deployed on September 17, 2001, to sample at 5 minute intervals. The upstream input water temperature, reflecting the influence of the lake, was constant during the initial 1.2-mi of the profile, whereas the profile data show cooling over this segment, reflecting groundwater discharge (fig. 30). It was not until about 3 hours after the start of the profile (a distance of 4.3 mi) that the temperature of the stream became consistently warmer than the initial upstream temperature, an increase that was due in part to warming of the water during two portages around log jams (identified by the smooth line segments on figure 30, for example at miles 3.4 and 4.3). The downstream fixed-station data display a more typical linear increase in streamflow temperature due to thermal loading because the stream has a lower thermal mass than the lake. That is, the longitudinal temperature profile varies by distance—starting with the lake inflow temperature controlling stream temperature and transitioning to a combination of upstream temperature and weather controlling, and is consistent with relations and templet described by Mohseni and Stefan (1999). Overlaid on this templet is the large influence of groundwater discharge, especially considering that the upstream water temperature gradient was 0.0089 °C/min compared to the overall profile gradient of 0.0021 °C/min. The data also indicate that the downstream end of the reach is an area of groundwater discharge, which is consistent with a narrowing of the cross-sectional area of the alluvial aquifer.

A major cooling between miles 3.6–4.3 begins where a side channel reconnects to the mainstem (inset on fig. 30, side channel entering from upper left at beginning of arrow). The mouth of the side channel was dry in 2001, suggesting a large component of groundwater was being discharged from the dry gravel channel. Through the remainder of this segment, the river laterally traverses the alluvial aquifer and is likely receiving groundwater from the aquifer throughout this cooling segment. Where the segment ends, side channels (dry during the profile) extend out from the mainstem and the river loses water. Near this area, the channel was not navigable and a portage was needed because the river lost so much water, which was later regained in downstream segments.

Cle Elum Reach

The Cle Elum reach starts just below the dam at Cle Elum Lake and extends 6.4 mi to near the mouth of the Cle Elum River (fig. 8). The reach has a gradient of 0.0055 ft/ft, displays much thermal complexity (fig. 31), and has a high production of spring chinook salmon (37 redds/mi in 2004). The thermal gradient of 0.0006 °C/mi/min (0.14 °C/mi) was higher than the Easton-reach gradient (table 3), and the discharge was lower; daily mean flow on the day of the profile was about 179 ft^3/s based on Reclamation's data for the outflow from Cle Elum Lake as measured at the station Cle Elum River near Roslyn.

The profile displays stabilization of temperature from about mile 0.29 to 0.77 that is followed by a major cooling at mile 1.1 due to alluvial aquifer discharge from the alluvial fan of a small creek entering the mainstem. From the beginning of the profile through mile 1.1, favorable temperature and discharge regimes combined with favorable physical habitat may account for the presence of many redds in this segment. Cooling also occurs from mile 2.4 to 2.9 (fig. 31) due the river becoming more channelized (terminus of a series of bars where the groundwater in the alluvial aquifer would discharge) with a concomitant narrowing of the alluvial aquifer. A cooling structure from mile 3.9 to 4.1 occurs just before a constrained bend where the river changes orientation and flows more laterally across (traverses) the alluvial aquifer. These two geomorphologic controls (orientation and narrowing) allow the river to: (1) intercept some of the alluvial groundwater for the former control, and (2) receive more focused groundwater flow for the latter control. When the river becomes more constrained by bedrock in a deep (about 6.5 ft) pool at mile 5.3 there is a nearly 0.5°C cooling, showing the importance of pools for providing thermal refugia. The importance of such cool pools has been previously described by Keller and others (1996) and Bilby (1984) identified pools as one of the characteristics of cool water areas in streams in Washington. Although there is warming downstream of the pool (likely due to streamflow losses into the coarse-grained bed sediments), the following 0.4 mi segment displays stabilization of temperature as the river again becomes more constrained with a thinning of the aquifer, and subsequent aquifer discharge to the river.

The combination of channel complexity and variation in bedrock largely influences exchanges, and shows the complex relations that exist in this relatively, intact stream reach. Compared to the other reaches with minimal or no bedrock control, the profile for this reach highlights how bedrock control can influence groundwater discharge and thus, streamflow temperature. This type of control was described previously, with the analogs being the American, Tieton, Bumping, and upper Naches Rivers.

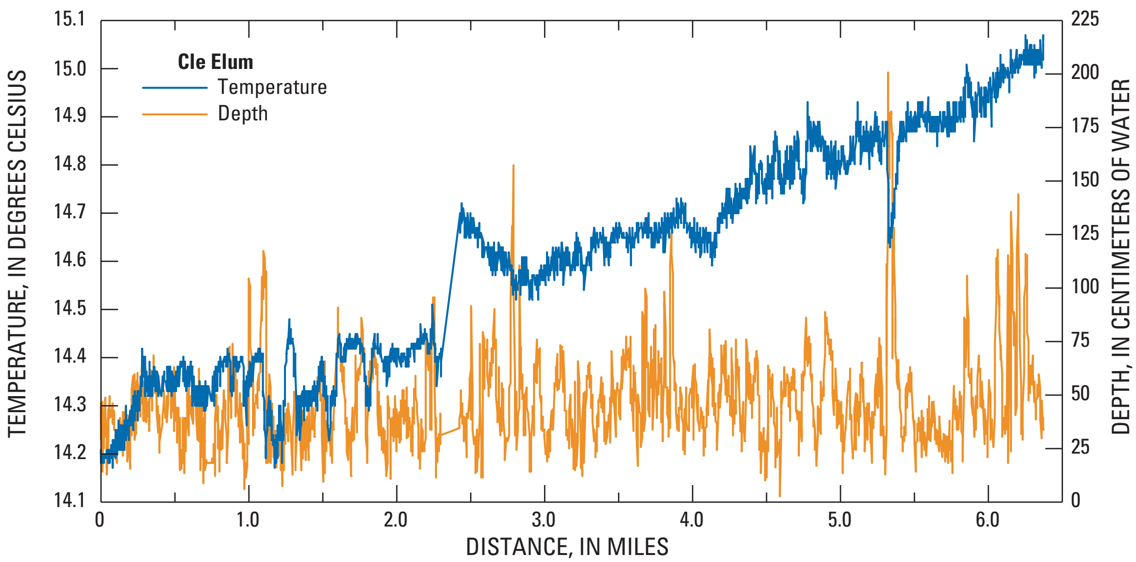


Figure 31. Longitudinal-distance gradient of temperature and depth from a thermal profile, Cle Elum reach, Cle Elum River, Yakima River, Washington.

Teanaway Reach

The Teanaway reach (fig. 8) has a stream gradient of 0.0036 ft/ft (about the same as the Easton reach, table 3), but its physical setting predicates the magnitude and type of exchanges. In contrast to the Easton and Cle Elum reaches, its complete 9.4-mi profile (fig. 32) displays a nearly linear increase in temperature with minimal diversity or structure. In this reach, the alluvial aquifer is very thin (in some locations bed sediment is absent), pools are small and rare, and it is underlain by low-permeability bedrock. There also is a conspicuous absence of side channels and except for a few locations, a flood plain. It appears that the Teanaway River loses water over most of this reach and the river losses are compounded by diversions. Additionally, in low-permeability bedrock terranes such as the setting for most of the reach, low baseflow generally results in decreased exchanges and complexity during the important low-flow period. The thermal gradient [0.0034 °C/mi/min (0.8 °C/mi)] was an order of magnitude larger than the Easton and Cle Elum reaches gradients of 0.0003 and 0.0006 °C/mi/min, respectively, and was one of the largest measured gradients, even in comparison to the lower-basin thermal gradients. Teanaway River also had the lowest discharge of the profiled reaches (table 3), with a daily mean discharge of 106 ft^3/s as measured at the Teanaway River at Forks near Cle Elum gaging station and 82 ft^3/s near its mouth (Teanaway River at Lambert Road). These differences show the importance of the hydrogeologic setting, channel complexity, and discharge on river-aquifer exchanges. Indeed, major warming (1°C) at mile 0.24 is where the combined West and Middle Forks of the Teanaway River enter the North Fork and it would have been expected that the inflow would have caused a cooling.

The increase in temperature from about mile 1.5 and ending at a decrease in temperature at mile 1.6 was due to river losses—in this short segment the channel was not navigable and a portage was needed because the river lost so much. One segment with some stabilization is between miles 3.7–4.1. This segment is where the orientation of the river becomes more perpendicular to the alluvial aquifer and the river likely intercepts groundwater; one of the few large pools also is in this segment. Two other stabilization segments (miles 5.7–6.0 and 7.3–7.5) occur where the alluvial aquifer becomes narrower and more constrained. Additionally, in the first segment, a small tributary stream joins the river but it is not known whether this stream (which may receive irrigation drainage) was dry or flowing during the profiling. From mile 8.6 to 8.9 there also was some stabilization, and the degree of stabilization decreased to the end of the profile. In the first part of the segment, the alluvial aquifer narrows between bedrock and a major highway and thus, some of the groundwater in the local, small alluvial aquifer would be expected to discharge at a decreasing rate to the end of the segment.

Overall, the lower baseflow (discharges of less than 7 ft^3/s at the mouth have been measured), large thermal gradient (0.0034 °C/mi/min-largest of the profiles), water temperatures more typical of the lower basin, and minimal exchanges suggests that this reach provides poor salmonid habitat. It also has been observed that migrating salmon move through this reach to the upper forks much earlier than many other parts of the stream system (W. Larrick, Bureau of Reclamation, oral commun., 2001). However, in 2004 there were 57 spring chinook redds (6 redds/mi) in this reach, and an additional 12 redds between the end of the reach and the mouth of the Teanaway River (A. Dittman, National Oceanic and Atmospheric Administration, written commun., 2009). This

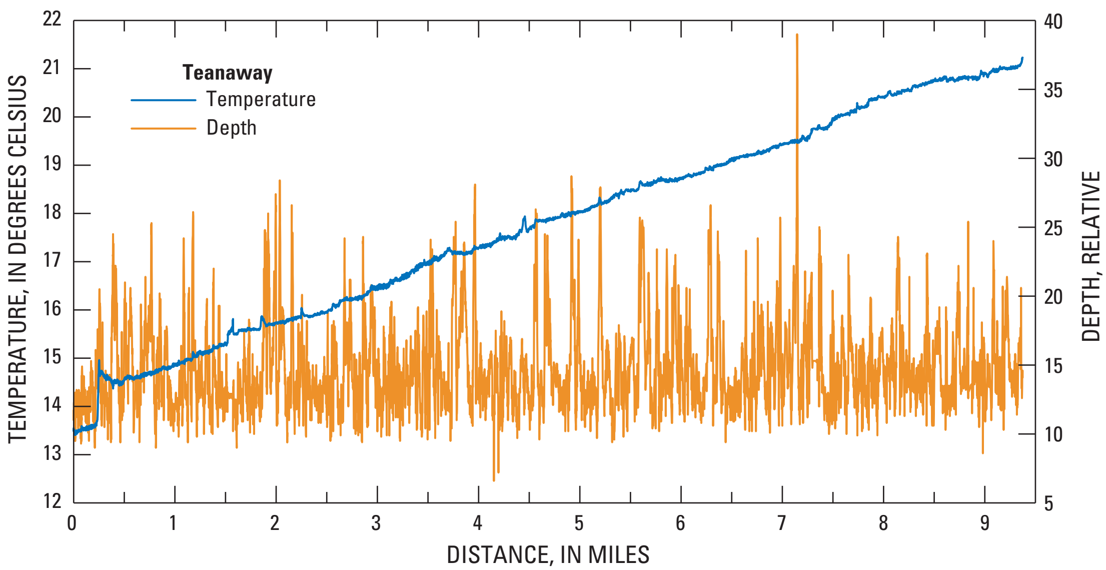


Figure 32. Longitudinal-distance gradient of temperature and depth from a thermal profile, Teanaway reach, Teanaway River, Yakima River, Washington.

data thus indicates that not only are there available spawning gravels but also locations of upwelling hyporheic water into the gravels. Water temperatures near the mouth of the river between about mid-July through mid-August generally are 20–24°C, and during the spawning period the temperatures typically range from 14 to 17°C. Thus, the chinook that spawn in this reach may complete their pre-spawning holding life-history stage in the Yakima River where summer water temperatures are more than 3°C cooler than in the lower Teanaway, and streamflow is much higher.

Roslyn Reach

The 10.6-mi Roslyn reach starts just below the mouth of the Teanaway River (RM 176) and extends to the Yakima River at Thorp Highway Bridge (RM 164.5) (fig. 8). The reach has a medium stream gradient (0.0025 ft/ft) relative to the other reaches, and a thermal gradient of 0.00063 °C/mi/min (table 3). GPS data were lost for this profile due to computer malfunction, and thus, the analysis is principally based on broad-scale landscape features. The analysis allows for relating temperature variations to groundwater discharge and habitat. General locations along the reach can be estimated based on a portage and total travel time through the reach (yielding an average velocity).

During the period from about 13:10 to 13:16 (note the large change in temperature and the decrease in relative depth to near 10 cm; fig. 33), a stop was made to portage around the Kittitas Reclamation District 1146 Drop. About 1.9-mi downstream of the portage is where the Roslyn Basin ends and the river enters the bedrock-controlled part of the reach. Excluding the variability and streamflow warming during the portage, the temperature is relatively constant through about 13:30 and the stabilization of temperature is attributable to groundwater discharging from the basin-fill aquifer as it thins towards the end of the structural basin. Excluding cooling from groundwater discharge at about 13:35 and cooling near the pool identified near 13:50, temperature increases linearly from the beginning of the canyon to about 14:15. Some groundwater discharge may originate from the abutting uplands in this area, but the quantity likely is not large because minimal thermal structure is displayed in the profile. Starting at a pool encountered at about 14:20 and extending to the beginning of a series of larger pools at 14:30, there is more variability in the profile suggesting both gains and losses along this part of the reach. From 14:30 to about 14:52, the thermal gradient is much less than the upstream gradient, which indicates a contribution of groundwater discharge from these pools. The profile becomes relatively stable from 14:52 through about 15:30 with only about a 0.1°C warming; this period occurs during the diurnal warming period and groundwater discharge must be contributing to the stabilization. The segment profiled during this time also displays a very active pool-riffle structure. One of the larger warming structures occurs after 15:30 and is followed by stabilization to 15:43 (fig. 33). Thereafter, there is much more variability in the profile than displayed by most of the previous part of the profile, including the cooling displayed at the end of the profile. This final part of the profile is likely located where the river transitions out of the bedrock-controlled part of the reach through the end of the profile at Thorp. Overall, the reach displays less variability than some of the other reaches, but excluding the rather linear warming in the beginning of the profile, the thermal gradient is small (total change from about 15.4 to 16.7°C with a thermal

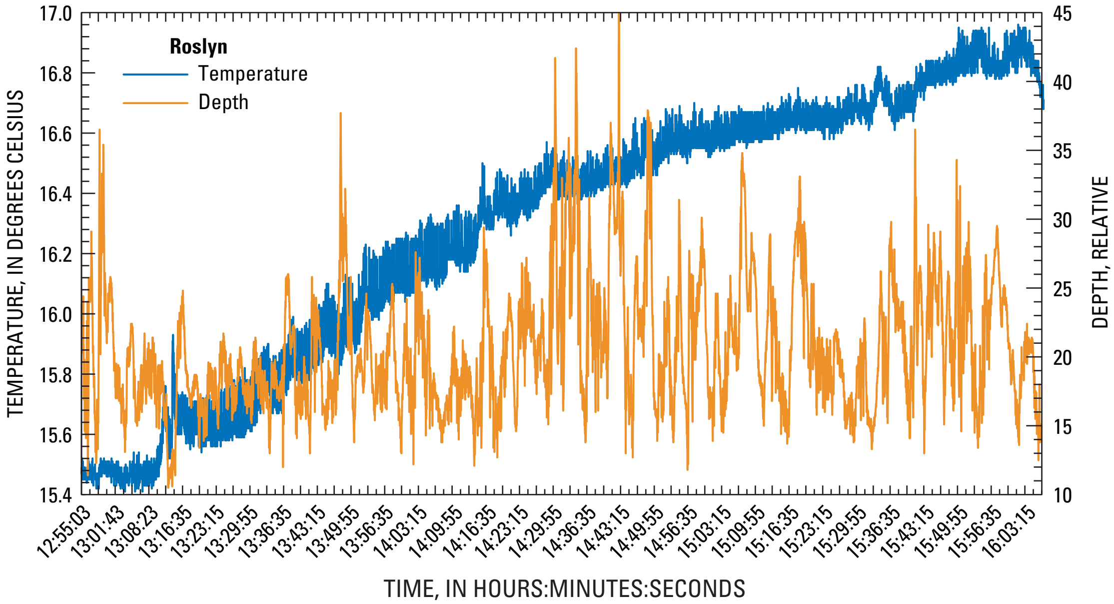


Figure 33. Longitudinal-time gradient of temperature and depth from a thermal profile, Roslyn reach, Yakima River, Washington.

gradient about the same as the Cle Elum reach; table 3) and indicates that focused groundwater discharge derived from the surrounding bedrock uplands in the downstream part of the reach can potentially provide good habitat. This is supported by the fact that the reach had 148 redds or 14 redds/mi in 2004 (A. Dittman, National Oceanographic and Atmospheric Administration, written commun., 2009).

Thorp Reach

The next downstream reach (the 13-mi Thorp reach, fig. 8) has a medium stream gradient (0.0025 ft/ft) relative to the other reaches, a thermal gradient of 0.0005 °C/mi/min (0.09 °C/mi) (nearly the same as the Cle Elum reach), and its streamflow during the profiling was the second highest of the profiles (table 3, estimated using the daily mean discharge for the Yakima River near Horlick—877 ft^3/s). This reach has a relatively complex channel, a large alluvial-valley aquifer, and its profile displays complex diversity and structure (fig. 34). There are numerous diversions, drains (return flows), and several diversion structures in this reach. However, flow during August in this reach averages about 3,200 ft^3/s and total diversions are about 150 ft^3/s; the large regulated August flows derived from the three upstream reservoirs are used to meet downstream uses. The large flow during this period allows for complex exchanges because more water in the side channels, higher river stage, and increased river energy exerting control on bank storage results in a more robust flow system in the alluvial aquifer.

Areas of groundwater discharge are clearly indicated by cooling between miles 2.5–3.2, 4.6–5.0, 5.7–6.0, and 7.8–8.2. In the first segment, the river becomes more constrained due to a hill and a local highway on the left bank, and there also are a couple of drains that discharge; these factors contribute to the cooling, especially the constraining and subsequent narrowing of the alluvial aquifer. The large warming at mile 3.6 between the first two segments occurs in a pool with reduced velocities just upstream of a diversion dam. Within the 4.6–5.0 segment, there was a decrease in temperature of 0.5°C over about 0.2 mi. This segment occurred in a ‘pond’ (relic gravel pit) and its outflow channel. A flood broke through to the pond and created a nearly linear, high-gradient outflow channel that reconnects to the mainstem. During the profiling, many holding spring chinook salmon were observed in the pond. The cooler water likely is attributable to: (1) the bottom of the pond being below the alluvial aquifer water-table (the maximum depth of the reach was measured immediately downstream of the entrance to the pond) and (2) the downgradient, groundwater discharge from the pond area to the outflow channel—the high-gradient channel likely intersects the water table. During the profiling, just downstream of the entrance to the pond on the mainstem was a large pool where YN biologists were snorkeling and counting holding salmon, and they noted that the cool pool contained numerous salmon—further suggesting that in this area the water table is shallow and the river and pond intersect it. For the last two segments (miles 5.7–6.0 and 7.8–8.2), the narrowing of the active flood plain and concurrent constraining of the alluvial aquifer likely leads to the observed streamflow cooling.

Warming structures displayed in the data are caused by either warm return flows (for example, at mile 9.5) or warm groundwater inflows. As an example of the latter, the warming from about mile 7.5 to 7.8 (and at mile 11.3) appears to be

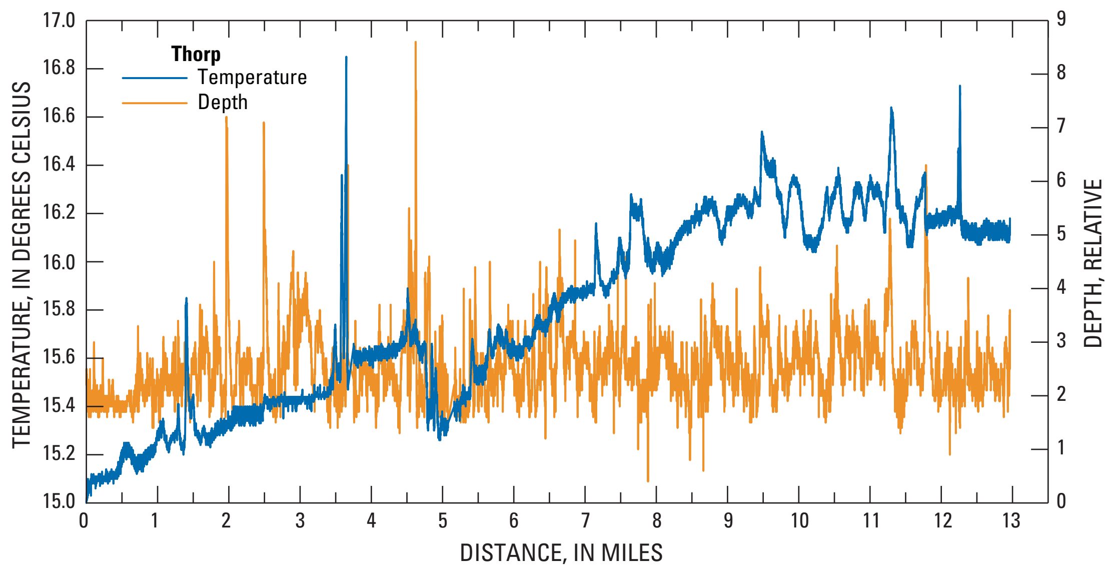


Figure 34. Longitudinal-distance gradient of temperature and depth from a thermal profile, Thorp reach, Yakima River, Washington.

from warm groundwater discharge from a large, shallow pond. Excluding the four warming peaks due to warm surface-water inflows, from about mile 8.8 to the terminus of the profile, there are complex exchanges with the river losing water in some locations followed by gains downstream—typical of an intact, complex braided stream. There is a net gain in this segment (especially over about the last 1 mi) and a thermal gradient of -0.04 °C/mi. Similar to the Easton reach, this long segment was identified as one of the eight priority reaches for restoration based on its intactness and complexity (Snyder and Stanford, 2001). In addition to the presence of holding chinook in this reach, 78 chinook redds (6 redds/mi) were located in this reach in 2004 (A. Dittman, National Oceanic and Atmospheric Administration, written commun., 2009).

Canyon Reach

The 13.5-mi Canyon reach (fig. 8) has a gradient of 0.0018 ft/ft and a thermal gradient of 0.0007 °C/mi/min (0.11 °C/mi) (table 3). The reach lies entirely in the Yakima Canyon, which is a narrow, relatively high canyon contained within tightly-folded ridges of the CRBG. Daily mean discharge in this reach the day of the profile was about 3,850 ft^3/s on the basis of the USGS gaging station Yakima River at Umtanum. The reach appears to display little overall complexity (fig. 35) and was identified as exchange-neutral by seepage runs. However, there are locations of complex exchanges for such a bedrock-controlled reach with a small alluvial aquifer. Over the initial 0.9-mi segment of this reach the profile is relatively smooth compared to the remainder of the reach suggesting some component of groundwater discharge; discharge is expected because the groundwater moving in the basin-fill deposits near the terminus of a structural basin would discharge to the river. From about mile 0.9 to 2.4, there are both warming and cooling segments that display increased variability compared to the initial segment. The cooling structure at mile 1.2 is due to the discharge from Wilson/Cherry Creeks (return flows); the combined daily mean discharge from these creeks during the profiling was about 452 ft^3/s (Hydromet, http://www.usbr.gov/pn/hydromet/yakima/yakwebarcread.html), which was about a 12 percent contribution to the total flow at the USGS Yakima River at Umtanum gaging station (station 12484500) about 7 mi downstream of the mouth of Wilson Creek. The next segment (miles 2.4–3.3) displays a nearly linear, alternating increase-decrease in temperature that suggests a series of springs (the likely source of discharge from the basalt bedrock in this structurally folded area).

The profile for the reach does not display broad areas of cooling (fig. 35), and the areas of stabilization or cooling generally are small, for example, between miles 5.6–5.9, 6.2–6.7 and 8.7–9.0. However, there appears to be a reduction in the thermal gradient from about mile 1.9 to 3.2 (especially between miles 2.4 to 3.2) but it is difficult to discern if this represents a broad area of cooling. Though previously described seepage measurements for this reach indicate that it is near neutral, isolated patches of groundwater discharge are known to occur based on temperature-sensitive radio transmitters implanted in spring chinook salmon (Berman and Quinn, 1991). The canyon reach also contains many large pools that are much less common in the river below the Canyon reach (Berman and Quinn, 1991). Few spring chinook salmon spawn in this reach but it is used for pre-spawning holding. The reach also is well known for its abundant stock of large, wild rainbow trout, some of which may be residualized steelhead trout.

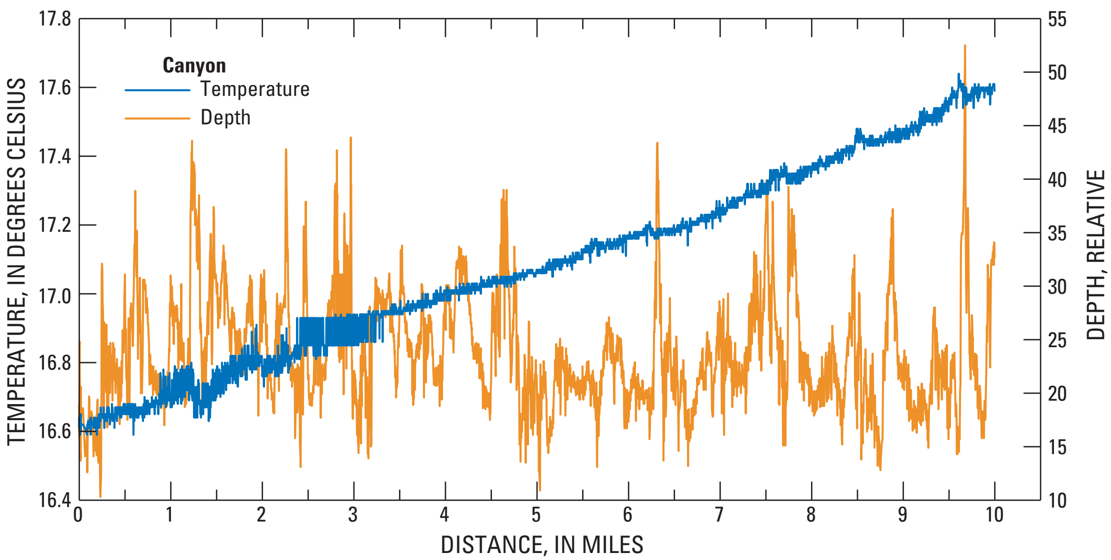


Figure 35. Longitudinal-distance gradient of temperature and depth from a thermal profile, Canyon reach, Yakima River, Washington.

Wapatox Reach

The Wapatox reach (fig. 8) is on the Naches River downstream of the Wapatox diversion dam. This 5.4-mi reach had the third-highest gradient of the reaches profiled (0.0042 ft/ft) and displayed an overall large thermal gradient of 0.0033 °C/mi/min (0.3 °C/mi) (table 3). Daily mean discharge on August 30, 2002 was about 245 ft^3/s based on the Reclamation gaging station the Naches River near Naches. Large cooling is displayed between miles 0.3–0.4 and 0.6–0.7 (fig. 36). The July 2001 profile (reach-average temperature was about 2.5°C warmer than the 2002 profile) displayed a nearly constant temperature over the initial mile of the reach and large cooling structures within a pool from miles 0.3 to 0.4. USGS seepage measurements for this segment showed large gains (59 ft^3/s—a gain of 30 percent), and the USGS mini-piezometer measurement indicated a positive VHG (upward groundwater flow to the channel). Between miles 0.3–0.4, the Tenant ditch wasteway discharges (which contains colder Tieton River water) and the alluvial aquifer (flood plain) on the right bank narrows and terminates. The larger 1-mi segment has several large pools and probably receives alluvial aquifer water originating upstream of the diversion dam, this water may include a component of the Tieton River streamflow losses that enter the alluvial aquifer across the distal end of its terminal alluvial fan. Over-wintering bull trout have been observed in this segment (E. Anderson, Washington State Department of Fish and Wildlife, written commun., 2008). Additionally, juvenile steelheads have been observed in this segment. The differences between the two profiles are attributed to cooler groundwater inflows in the September profile being attenuated because the river temperature was cooler than during the July profile. For example, the July 2001 profile (not shown) displays cooling from mile 1.7 to 2.0, stabilization from mile 5.2 to the end of the reach, and several other segments of reduced warming that are not in the 2002 data. Cary (2006) shows that the groundwater temperature during 2004 in the mini-piezometers in the Naches River were 1-6°C warmer in August compared to October.

Another area of cooling is from about miles 3.4 to 3.9 (fig. 36); data are not available from this segment from the July 2001 profile for comparison. For this segment, the alluvial aquifer narrows and becomes constrained by a highway. Major warming occurs from mile 2.4 to 2.6 and from 3.0 to 3.4, and this warming was also displayed in the July data. These two segments may be losing segments; the mini-piezometer measurement in the latter segment had a negative VHG and the streamflow also would have been reduced in this segment due to diversions. The slight cooling at the terminus of the reach, which is broader in the July data, may be due to the configuration of the alluvial aquifer and river orientation.

Naches Reach

The Naches reach (fig. 8) starts at the terminus of the Wapatox reach and has a higher gradient (0.0044 ft/ft) than the upstream reach (table 3). Most of this reach is contained in a long (12.1 mi) reach that was identified as being a gaining reach from a seepage investigation (see appendix A).

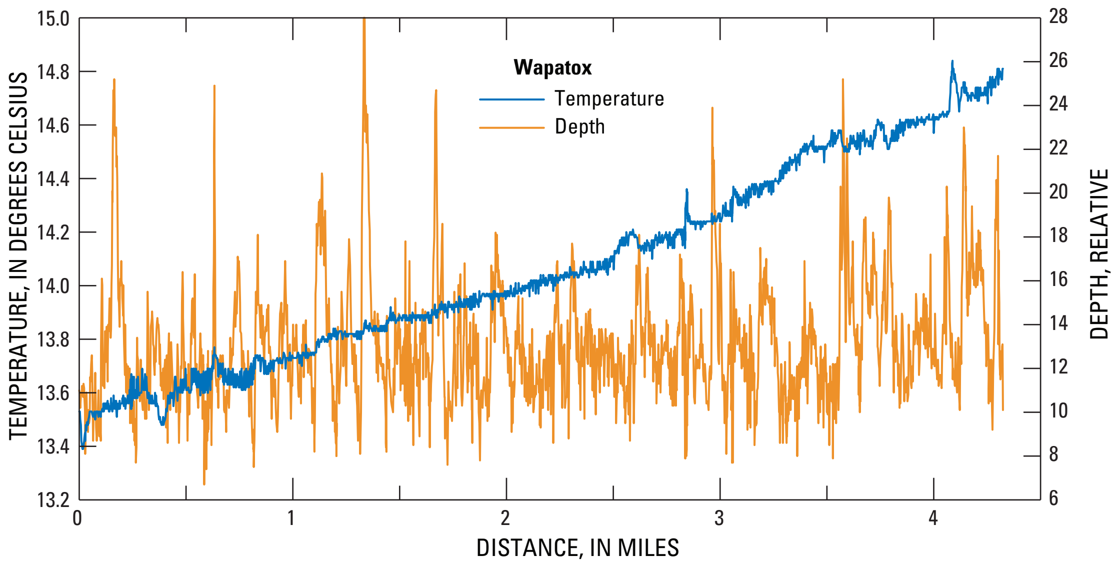


Figure 36. Longitudinal-distance gradient of temperature and depth from a thermal profile, Wapatox reach, Naches River, Yakima River, Washington.

As described previously, the reach has discontinuities in its thermal profile (fig. 37), and a thermal gradient for the complete length of the profile could not be calculated. Based on five segments ranging in length from 0.87 to 2.5 mi that had a total length of 9.54 mi (81 percent of the total 11.8-mi reach length), however, a length-weighted thermal gradient of 0.0009 °C/mi/min (0.38 °C/mi) was calculated (table 3), which is an order of magnitude smaller than that of the Wapatox reach. The August 1, 2001, daily mean discharge in this reach was about 282 ft^3/s. The thermal gradient of the five segments ranged from 0.11 to 0.74 °C/mi. Of these five segments, the initial 0.65 mi displayed broad stabilization, which is consistent with the stabilization observed at the terminus of the upstream Wapatox reach—indicating about a 1-mi segment where the river gains water. Mini-piezometer data for this area show a large positive VHG (0.06 ft/ft) at the beginning of the reach that reversed to negative at about mile 1. Therefore, the segment appears to reverse from gaining to losing by mile 1.0. A 1-mi long gaining segment in August should provide good salmonid habitat in this area of the Naches River.

Another segment displaying stabilization was from mile 10.1 to the end of the reach (fig. 37); this segment had the lowest thermal gradient (0.11 °C/mi) of the five. The river in this section becomes more constrained with a large narrowing of the alluvial aquifer, which would result in increased groundwater discharge. A mini-piezometer measurement showed a positive (upward) VHG of 0.049 ft/ft near the end of the profile. The alluvial valley aquifer expands downstream of this constrained section and streamflow losses would be expected, which is indicated by the mini-piezometer measurements in this area. The segment with the largest thermal gradient extends from mile 1.25 to 3.5. The first 1.55 mi of this segment displays some complexity with structure, and the remaining part displays a nearly linear profile without structure but with a decreased thermal gradient.

A segment not included in the above discussion extends from mile 3.8 to 4.5 and its profile displays interesting temperature variations (fig. 37). The profile began at the end of CTD equilibration that was identified by a rise in temperature. That is, a rise in streamflow temperature measured by the CTD indicates it has reached equilibrium with the streamflow temperature because the temperature of the CTD is cooling during equilibration after it gained thermal heat during downloading of data—readings are typically 1-1.5°C higher than streamflow temperature on hot days. From mile 3.8 to 4.25, the streamflow temperature only increased by 0.04°C and had a thermal gradient of 0.09 °C/mi, which is the same as the thermal gradient for the Easton and Thorp reaches. A temperature decrease of about 1°C occurs over the next 0.04 mi that is followed by nearly constant temperature over the next 0.2 mi that results in this 0.7-mi segment (mi 3.8–4.5) having a gradient of -1.4 °C/mi. The 1°C cooling occurs where the alluvial aquifer narrows and becomes constrained by a highway, and there are four return flow/wasteways in this segment, including the Wapatox power return that would be carrying colder, upstream water; mini-piezometer data also indicated positive VHGs in this segment. This segment thus should contain good summer thermal attributes for holding and rearing salmonids.

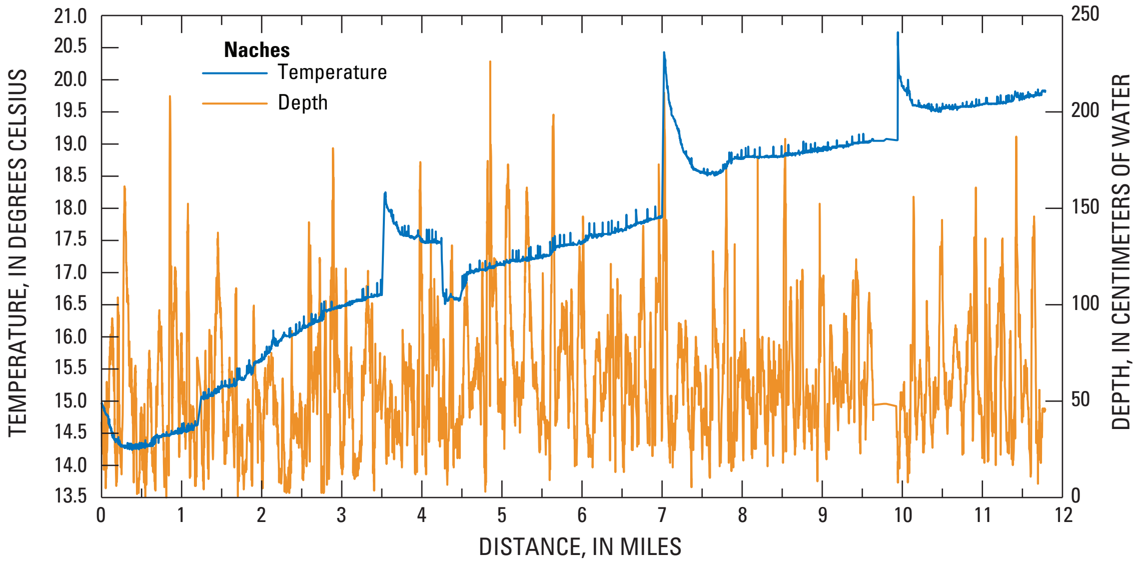


Figure 37. Longitudinal-distance gradient of temperature and depth from a thermal profile, Naches reach, Naches River, Yakima River, Washington.

Parker Reach

The 14.2-mi Parker reach (fig. 8) begins immediately downstream of two large diversions (total daily mean discharge for the diversions was 2,205 ft^3/s on the day of the profile—leaving about 317 ft^3/s in the river (Hydromet, http://www.usbr.gov/pn/hydromet/yakima/yakwebarcread.html). The reach has a stream gradient of 0.0029 ft/ft (table 3) that is indicative of a braided reach; gradients greater than about 0.001 ft/ft generally indicate braided or bedrock constrained reaches. The thermal profile (fig. 38) has both areas and patches of complex thermal regimes. Also typical in extensively developed basins, warming structures (short-temporal positive-warming deviations from the diurnal trend) are prevalent in this reach and in the other lower-basin reaches (figs. 38-46). These structures are caused by anthropogenic inputs (for example, return flows and wastewater discharges), and are nearly absent from most of the upstream reaches. The Parker reach, however, is part of a longer reach that was identified as one of the eight priority reaches for restoration based on its intactness, especially because it contains the largest intact flood plain in the basin (Snyder and Stanford, 2001).

The September thermal gradient was 0.0007 °C/mi/min and 0.26 °C/mi (table 3). Based on two segments, the August profile had a thermal gradient of 0.0006 °C/mi/min (0.20 °C/mi) (table 3). The first segment ended at mile 4.98 where a stop was completed to download data; this segment had a gradient of 0.33 °C/mi. The second segment extended through the remainder of the reach and had a gradient of 0.12 °C/mi. The smaller gradient in the latter 9.2-mi segment is caused by a distinctive cooling at about 15:00 (mile 10.3) on August 28 that is followed by an overall cooling to the end of the profile (fig. 38); this cooling also was displayed by the September profile. The cooling was initiated at about where information from shows indicates there is a ‘Drain-Slough Discharge’ (Bureau of Reclamation, 1974). A linear trend through the smoother, earlier part of the data suggests an expected ending temperature for the profile on the order of 2°C higher than the observed value of 22.6°C. For the September profile, the ending temperature was about 21.4°C, and a trend line also suggests an expected ending value of about 2°C higher. The timing of the cooling for the two profiles indicated that the cooling is opposite of the diurnal cycle (during this time of year the maximum water temperatures are reached at about hour 17:00 and stabilizes to about hour 18:50—much later than the observed cooling). The cooling also is dissimilar from the more typical downstream diurnal warming displayed by most of the downstream reaches. Based on the August and September GPS data, the cooling was initiated at about the same location. Thus, under two different thermal loadings (August in contrast to September), the repeated measurements indicate a consistent cooling over this segment. Seepage measurements were later made for this segment and the measurements identified a large, 240 ft^3/s, gain (see figs. 18 and A1). This long segment contains several spring discharges (Bureau of Reclamation, 1974) and spring brooks (Stanford and others, 2002). The flood plain also narrows at about mile 10.1 and the alluvial aquifer becomes more constrained by Interstate 82. The interaction of side channel re-connections, narrowing of the alluvial aquifer, and channel orientation appear to provide the framework for such large exchanges. The four mini-piezometer measurements in this segment were equally divided between negative and positive VHGs. However, the locations of the negative VHGs are in areas where the river may be locally losing water across gravel bars.

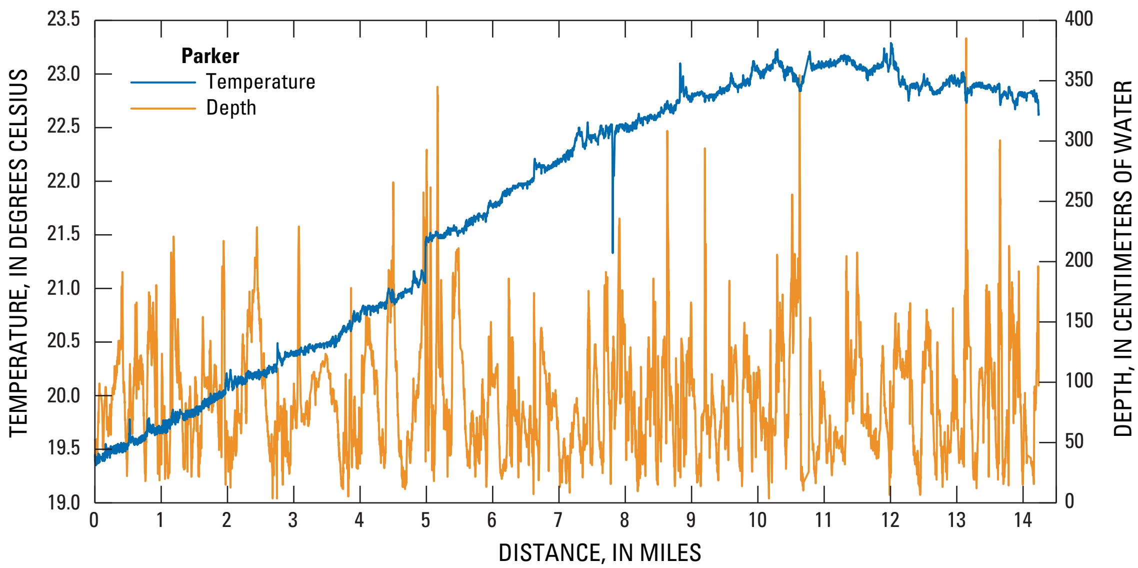


Figure 38. Longitudinal-distance gradient of temperature and depth from a thermal profile, Parker reach, Yakima River, Washington.

A more detailed view of the cooling reach for the August data shows much diversity and structure with complex exchanges of different waters. The pool-riffle structure displayed by the CTD's depth data is not correlated to this cooling, but suggests that potential habitat for different salmonid life-stages may be available, albeit at temperatures that are not preferred (Brett, 1956, Burrows, 1963; Jobling, 1981; Beschta and others, 1987; Berman and Quinn, 1991; Eaton and others, 1995). The volume of water measured by the CTD is mainly river water and a measurement of the water just at or below the sediment-water interface would have lower temperatures. These exchanges, represented by both overall cooling and cooling structures, may be refugia, and relative to surrounding segments, this segment may well represent the preferred thermal regime for holding and rearing salmonids, especially because most of the preferred side-channel habitat was de-watered during the 2001 drought year. The groundwater discharge also could provide good thermal habitat for the fall chinook stock.

Stabilization of temperature also occurred from about mile 4.0 to 4.3 (fig. 38). Three spring brooks, which typically have moderated temperature compared to the river water, occur in this segment (Stanford and others, 2002) and a side channel reconnects. A mini-piezometer measurement near the end of this segment had a small negative VHG. A major, well-defined cooling structure occurs at mile 7.8, and depicts more than a 1°C decrease in streamflow temperature. A mini-piezometer measurement just upstream of this location showed a negative VHG—streamflow loss, and thus, the cooling is likely associated with cooler water discharged from the Roza Canal Wasteway to the river near this location. Warming structures such as at mile 8.8 occur where channel complexity increases and streamflow diverges to several channels.

Toppenish Reach

The 12.2-mi Toppenish reach (fig. 8) has a stream gradient of 0.0013 ft/ft and during the September 14, 2001, profile, a thermal gradient of 0.0007 °C/mi/min (0.17 °C/mi) (table 3); the August profile had a thermal gradient of 0.0006 °C/mi/min and 0.23 °C/mi. The pool-riffle-run structure in this reach changes and becomes less complex at about mile 4.0 (fig. 39), which is related to the gradual transition of the Yakima River to a meandering stream. The profile displays complexity with both warming and cooling structures starting about mile 5.9. For the first 5.9 mi, some cooling occurs between miles 1.5–1.7 where a side channel reconnects. A warming structure occurs at mile 4.7 where the river abuts a pond, and cooling and stabilization then occurs through mile 5.1. The latter likely is caused by the channel orientation changing orientation (it becomes more perpendicular to the alluvial aquifer). At mile 5.9 there is warming due to a farm-drain discharge that is followed by cooling and stabilization through mile 6.7, which is due to the narrowing of the alluvial aquifer and flood plain in this segment. The large heat structure between miles 6.9–7.1 appears to be related to both effluent from a drain and the streamflow losses in this shallow segment. The orientation of the river downstream of this segment allows the river to gain water from the alluvial aquifer. The stabilization between miles 8.9–9.4 is where the river traverses the alluvial aquifer. Where the alluvial aquifer and flood plain greatly narrow (miles 9.9–10.2), stabilization also is displayed by the profile because groundwater typically discharges to streams under such conditions. Numerous drain discharges and streamflow losses contribute to the high rate of warming and the warming structures from miles 10.2–10.6.

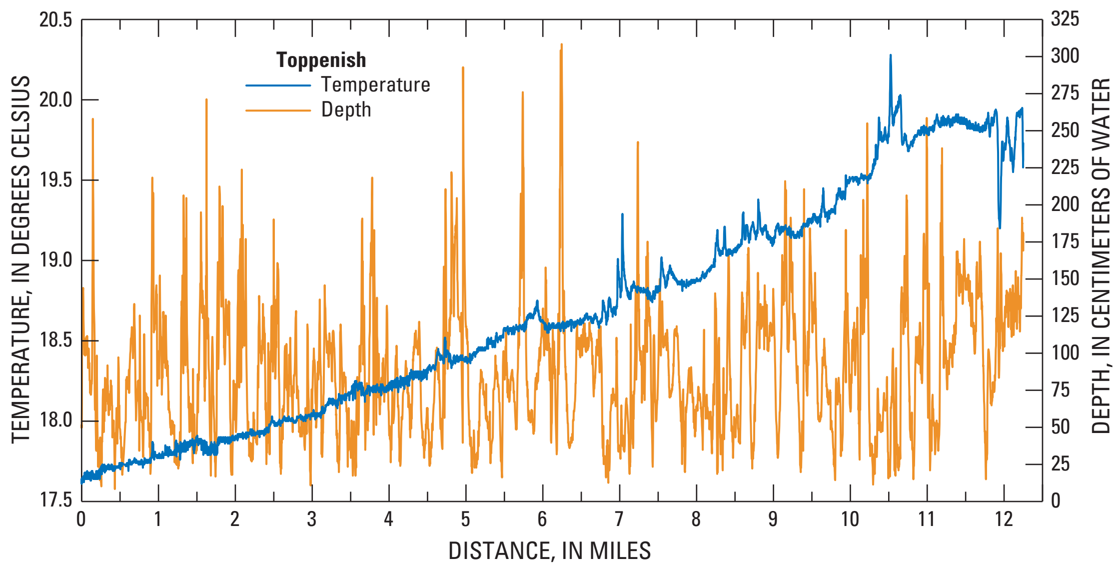


Figure 39. Longitudinal-distance gradient of temperature and depth from a thermal profile, Toppenish reach, Yakima River, Washington.

The profile for the ending 1.6-mile segment displays stabilization and large cooling structures (fig. 39). In this area, the alluvial aquifer greatly narrows and abuts a terrace (left bank), resulting in groundwater discharging to the river. From mile 11.2 to the end of the profile, the river also contains large, deep pools that likely penetrate the water table. The very large cooling structures at mile 11.9 and 12.1 suggest a large groundwater source; the source probably is the springs because springs are observed along the face of the terrace. This segment also is in an area where the structural Toppenish basin becomes more subdivided due to Toppenish Ridge and Snipes Mountain near Granger, Washington, and thus, mimics the terminus of a structural basin; that is, topographic and structural control greatly limits down-valley groundwater flow in the basin-fill deposits as shown by water-table contours in Vaccaro and others (2009). For migrating, holding, or rearing salmonids, this 1.6-mi segment may provide the best summer thermal habitat in the reach, especially because of the presence of the large, deep pools. Similar to the Parker reach, this reach is part of a longer reach that was identified as part of one of the eight priority reaches for restoration based on its intactness, and because it also contains the largest flood plain in the basin (Snyder and Stanford, 2001).

Granger Reach

The Granger reach (fig. 8) has the lowest stream gradient (0.0007 ft/ft) for the profiles of the Yakima River upstream of Benton City, a length of about 185 mi. The reach also had one of the largest measured thermal gradients of 0.0015 °C/mi/min (0.37 °C/mi) (table 3). The 8.1-mi long profile (fig. 40*A*) displays a more typical (expected) profile for a downstream reach in a large river basin. Excluding the first 0.5-mi segment, cooling structures are nearly absent and warming structures, mainly due to surface-water return flows (there are at least 14 drains in this reach), are present (fig. 40*A*). Diversity is less pronounced but nonetheless is present and complex. The highly-variable structure in the first part of the profile also was displayed in the most downstream segment of the contiguous, upstream Toppenish reach (fig. 39). This part of the Granger reach also abuts the high terrace (the only segment of the reach to be so), and the bed material consists of large-angular-rugged clasts of eroded and landslide siltstone. Deeper pools and groundwater springs (observed along the face of the terrace) contribute complexity to the profile in this area; the complexity was reproduced in both the August 29 and September 14 profiles for the Toppenish reach. Both reaches are used by the fall chinook stock for spawning, and this stretch may represent a pre-spawning holding area, as its thermal regime is cooler and more stable. The Granger profile shows reasonably long stretches of stabilization with some cooling, indicating broad areas of groundwater discharge; examples of stabilization/cooling occur between miles 3.2–3.7 that is followed by cooling between miles 3.7–4.0, and stabilization between miles 7.4–7.8 (fig. 40*A*). In the first segment, there is a distinctive narrowing of the flood plain and the orientation of an oxbow in the latter part of this segment is conducive to intercepting groundwater flowing down-valley.

The diversity present in the profile for the Granger reach is less than that displayed by the other reaches, but a complex thermal regime is still exhibited. The thermal regime in the downstream reaches typically is controlled by atmospheric conditions (Mohseni and Stefan, 1999), and thus, would be representative of fixed station meteorological

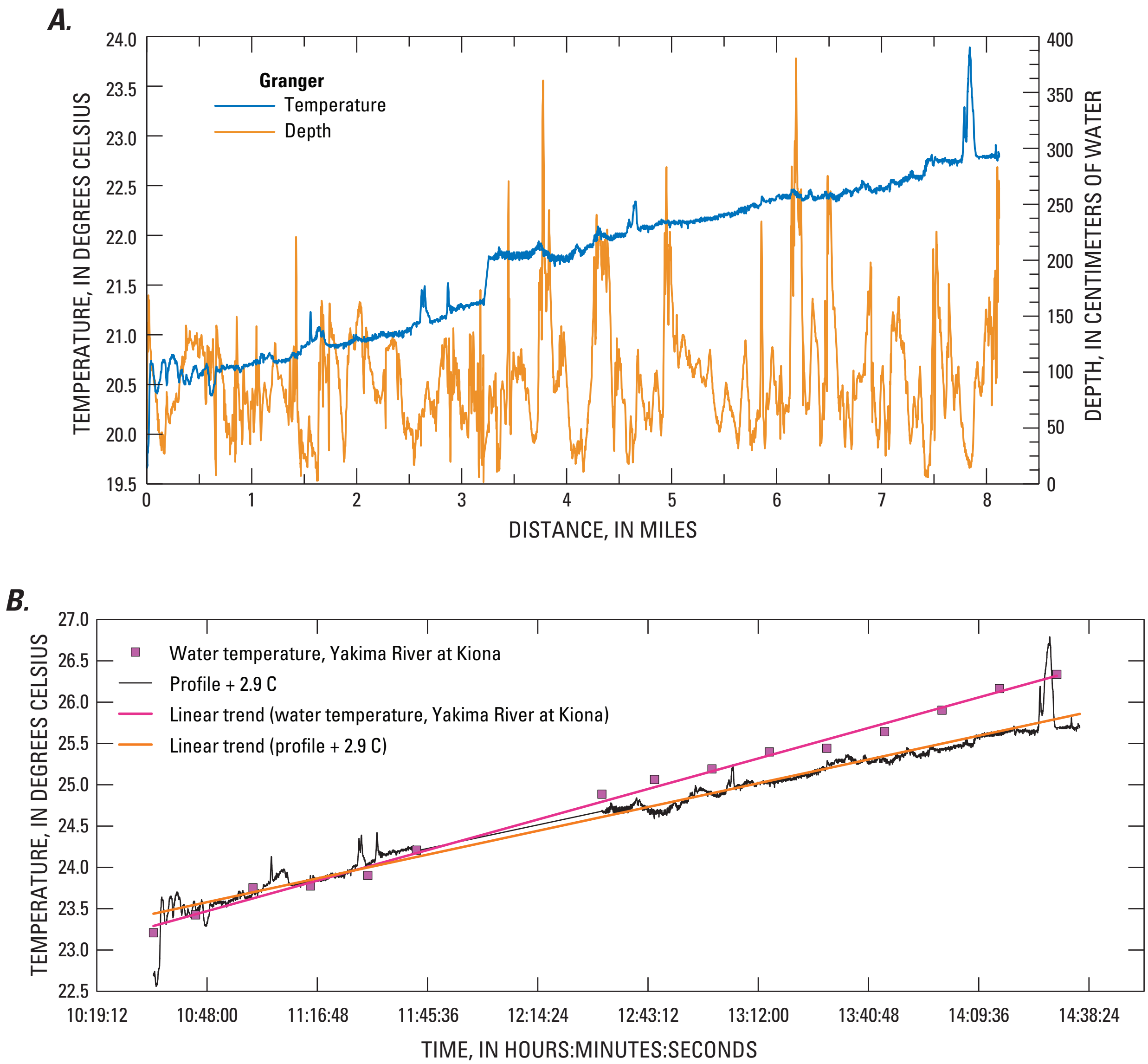


Figure 40. (*A*) longitudinal-distance gradient and (*B*) longitudinal-time gradient of temperature and depth from a thermal profile, Granger reach and streamflow temperature measured at the Yakima River at Kiona gaging station, Yakima River, Washington.

data. Comparing streamflow temperature data from the most downstream gaging station in the basin (Yakima River at Kiona) to the thermal profile indicates the inherent richness in the complexity of the thermal profile (fig. 40*B*). The profile data were adjusted by adding 2.9°C to the time series so that temperatures are equal at time 11:42; linear trend lines have been fitted to both data series. Obviously, the profile is controlled by atmospheric conditions, but advective heat transfer associated with surface-water and groundwater inflows also exert control. The variations from the trendline show the influence of warming structures that are present in modified basins, and clearly indicate areas of stabilization, cooling, and a change in slope in the thermal response. The changes in slope represent a third category of deviations from an expected thermal response. Slope changes are more difficult to identify because of natural variability, and represent advective inflows that are less influential than those that induce stabilization or cooling (the other two categories). The change in slope is not related to the depth structure, which is functionally related to velocity and surface area—important variables in thermal modeling, and thus, would not be able to be accounted for using only fixed station data. In these partial thermal transition reaches, the end-member temperature is attenuated by subtle effects of groundwater discharge.

Prosser Reach

The 12.3-mi Prosser reach (fig. 8) was the most downstream reach profiled by the USGS and starts just below the Prosser diversion dam for the Chandler Canal. During the profiling, streamflow diverted to Chandler Canal ranged from about 910 to 955 ft^3/s and the discharge entering the reach, as measured at the Reclamation's gaging station the Yakima River near Prosser (Hydromet, http://www.usbr.gov/pn/hydromet/yakima/yakwebarcread.html), was about 610 ft^3/s. Although it is a downstream reach, its stream gradient (0.0015 ft/ft) was similar to that of the Canyon reach, principally because most of the reach (like the Canyon reach) is bedrock controlled by the permeable CRBG in the stream valley and surrounding uplands. The alluvial aquifer in the reach is not extensive and is thin (Jones and others, 2006). The smallest thermal gradient of all the reaches was in the Prosser reach (0.00002 °C/mi/min [0.007 °C/mi]) (table 3). At mile 10.3, the 20.9°C water temperature (air temperature was about 27°C) was the same as the starting temperature at mile 0.0. Water-level contours (Vaccaro and others, 2009) indicate that groundwater from the surrounding uplands (Horse Heaven Hills to the south and the intensively irrigated Rattlesnake Hills to the north) is directed towards the stream valley in this reach. Two of the seepage investigations indicate that the reach gains an estimated 8–41 percent in segments that include part or all of this reach. Thus, like the Teanaway reach, the physical setting and hydrogeology predicate the magnitude and type of exchanges in the Prosser reach, but unlike the Teanaway reach, the exchanges are enhanced. The discussion of the data for the reach is more detailed than the discussions for the other reaches because of the potential importance of exchanges in the lower basin where human impacts are largest, and air and water temperatures are highest. The exchanges in this reach are important for migrating salmonids and may contribute to maintaining favorable habitats for fall chinook redds.

The thermal profile displays stabilization from the start to about mile 3.6 (fig. 41*A*). In this segment, there are temperature stable parts (miles 0.0–0.75 and 2.9–3.5), cooling parts (miles 0.75–1.3, 1.7–2.2), and warming parts (miles 1.3–1.7 and 2.2–2.9). The cooling and stabilization parts are caused by both groundwater discharge and return flows, such as the Chandler Fish flow return. Major cooling starts again at about mile 3.7 and continues to about mile 4.4. The cooling is due to groundwater input from Rattlesnake Hills from irrigation return flows, and also likely contains a component of leakage from Chandler Canal that parallels the river in this area. The spike with a 0.5°C drop in water temperature is attributed to either spring flow or drain discharge (there are two drains in this general location). Thus, after 4.4 mi (about 2 hours), the streamflow temperature is about 0.45°C cooler than the initial temperature. Streamflow temperature from two gaging stations (Yakima River near Prosser and at Kiona) show nearly linear increases in streamflow temperature during this time (fig. 41*B*). In the following warming reach (miles 4.4–5.2) the profile warms at the same rate as the streamflow temperature at the two gaging stations. This initial 4.4-mi segment is used by fall chinook for spawning, likely because streamflow velocities, bed sediment, and groundwater discharge conditions create favorable habitat.

Stabilization occurs from mile 5.2 to 6.2 (the combined Spring/Snipes Creeks flow, which is colder surface-water in these wasteways, discharges at about mile 5.7) and is followed by a very large cooling from miles 6.2–6.3 (fig. 41*A*). The cooling appears to be derived from a constraining of the small alluvial aquifer. After mile 6.3, warming principally occurs through mile 7.8 with one segment of cooling between miles 6.8–7.0; in this area Chandler Canal is close to the river and thus, may provide leakage into the shallow groundwater system. Cooling then occurs from mile 7.8 to 8.4 with a large cooling structure at about mile 8.3 that appears related to both to a series of springs and the presence of a large pool. Downstream of this segment, there is warming to about mile 8.8 that is followed by stabilization through mile 10.0. A large cooling (0.45°C) occurs between miles 10.0–10.15, and its cause is unknown but may be related to an unidentified return flow, which is consistent with a return flow identified by Appel (http://www.yakimacounty.us/YBWRA/PowerPoint/TempProfile_LV_files/frame.htm). Streamflow warming is then observed through mile 10.7, with stabilization through 10.8. Two very large warming structures (one in a riffle and another in a pool) occur through mile 11.4, followed by stabilization through mile 11.6. A series of warming, stabilization, and cooling segments that contain structure occur to mile 12. The cooling/stabilization between RMs 12.0–12.26 was where an irrigated terrace to the north that diminished in size and likely enhanced groundwater discharge from the terrace. The warming at the end of the profile is attributed to the profile being in shallow water near the take-out just above the Chandler Power return.

Prosser-Banks Reach

The Prosser-banks reach starts about 1.8-mi downstream of the starting location of the Prosser reach. The Prosser-banks reach includes most of the Prosser reach (fig. 8) and has two profiles, left and right bank, in contrast to the Prosser reach thermal profile that generally was run in the thalweg. The 11.4-mi long reach had September thermal gradients of 0.00056 and 0.00054°C/mi/min (0.18 and 0.17°C/mi) for the left and right bank profiles, respectively (table 3). Daily mean discharge on the day of the profile was about 485 ft^3/s, which was about 20 percent less than during the August profile of the Prosser reach. For the Prosser-banks reach and the following four reaches, the discussion of the profile is as detailed as the previous discussions because the profiles were previously described by Appel (Benton Conservation District, written commun., http://www.yakimacounty.us/YBWRA/PowerPoint/TempProfile_LV_files/frame.htm, 2008).

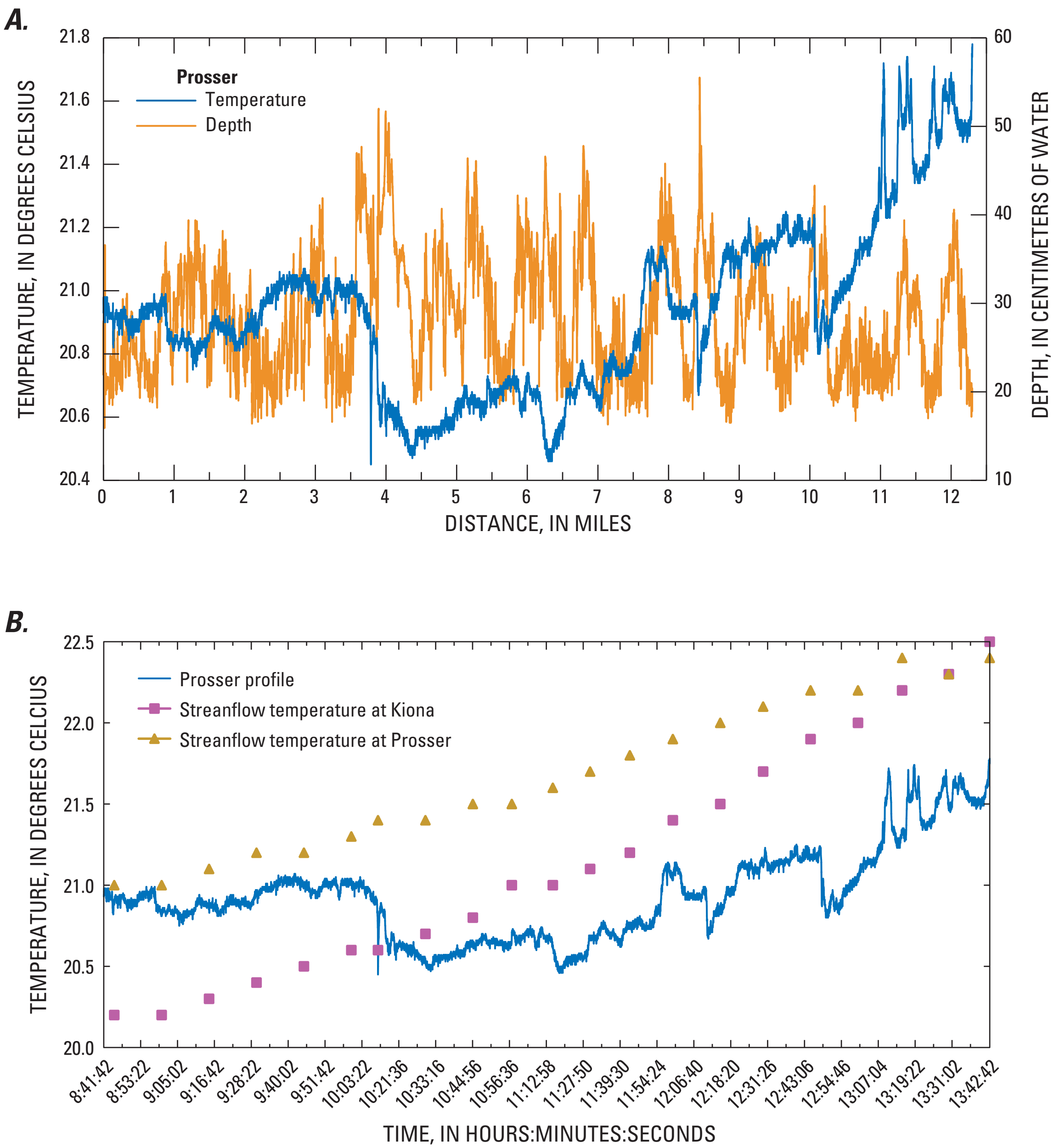


Figure 41. (*A*) longitudinal-distance gradient and (*B*) longitudinal-time gradient of temperature from a thermal profile, Prosser reach, and streamflow temperature measured at the Yakima River near Prosser and the Yakima River at Kiona gaging stations, Yakima River, Washington.

There are distinct differences between the profile for the Prosser reach (fig. 41*A*) and these two profiles (figs. 42*A*, *B*). The differences can be attributed to a variety of factors, especially the proximity to inflows including return-flows and springs, due to conducting the profiles near the banks in contrast to the thalweg profile with its attendant mixing of these inputs. However, the relatively small temperature change (0.7°C) from about mile 2.4 to the end of the reach is consistent with the data for the Prosser reach, that is, large inputs of both cool return flows and groundwater result in near stabilization of streamflow temperature over about 9 miles (a thermal gradient of only about 0.08 °C/mi).

Differences between the right and left bank profiles are related to location of return flows and springs/seeps. However, the overall trends in the two profiles after mile 2.4 (figs. 42*A*, *B*) indicate a relative abundance of groundwater inflow because point sources cannot account for continual stabilization and or cooling. This is shown clearly by the nearly constant temperature between miles 3.6–6.5, and miles 7.3–10.8, especially for the right bank profile; these segment profiles are very different from the profiles for the initial 2.4 mi that display a gradient on the order of 0.45 °C/mi which was one of the largest of all the profiles (table 3). For the left-bank profile, cooling after about mile 7.7 is caused by a series of springs. All of the large cooling and warming structures are related to localized inflows (there are at least 16 return flows in this reach) and show the importance of such inputs in modified river basins. Indeed, some of these structures show changes ranging from 0.5 to 1°C. The stabilization, cooling, patches, and groundwater input suggest that thermal refugia likely can be found for rearing and holding salmonids. However, improved irrigation efficiencies with concomitant decreases in groundwater discharge derived from surface-water irrigation and decreased discharge quantities of cool return flows may have a large impact on the presence and size of thermal refugia in this reach.

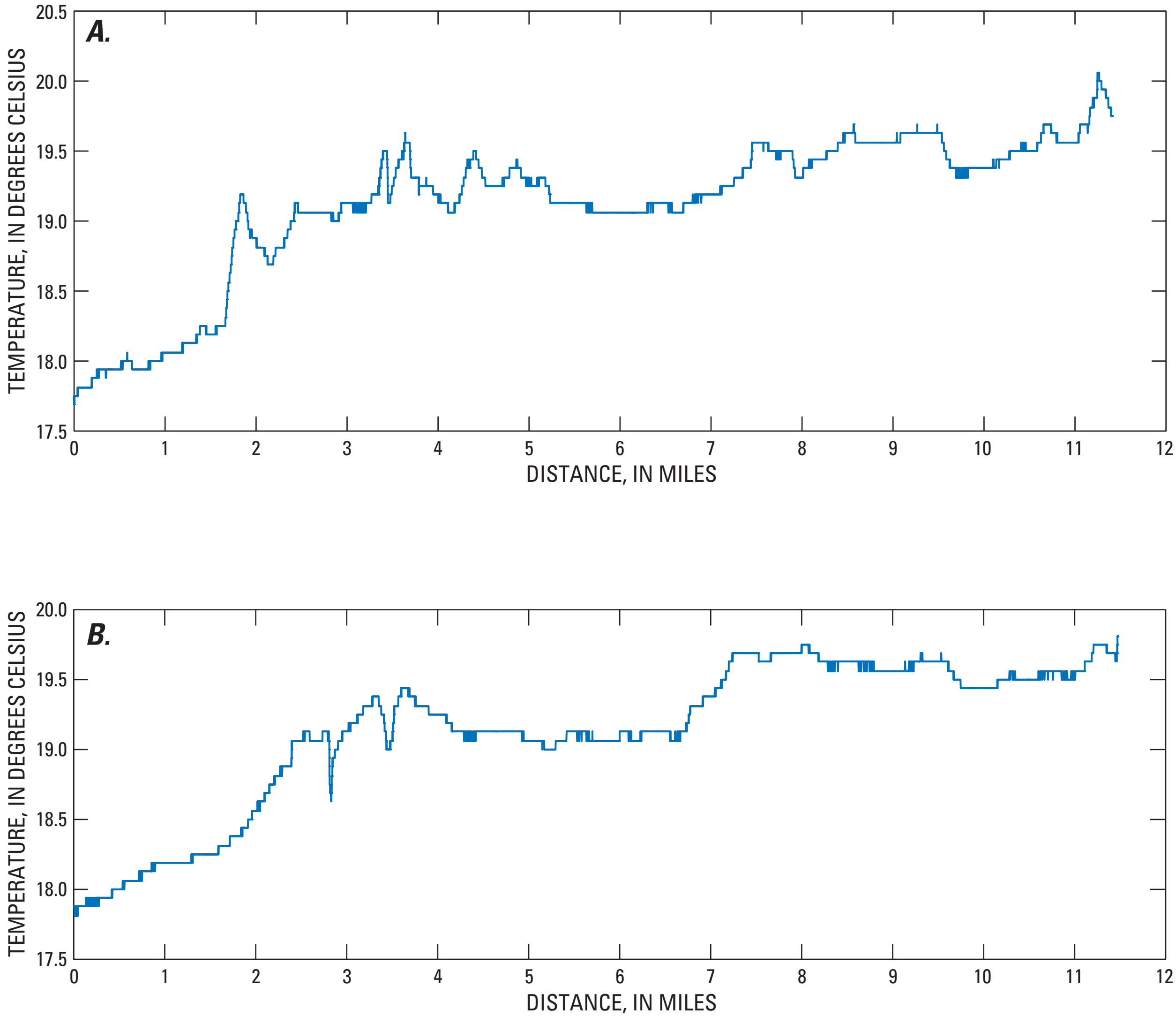


Figure 42. Longitudinal-distance gradient of temperature from a thermal profile for the (*A*) left bank and (*B*) right bank, Prosser-banks reach, Yakima River, Washington.

Chandler Reach

The 7-mi Chandler reach starts below the Chandler power return; on the day of the profile, the daily mean discharge from the power return was about 850 ft^3/s and daily mean flow in the reach was about 1,370 ft^3/s. The reach has a stream gradient of about 0.0012 and a thermal gradient of 0.00145 °C/mi/min (0.25 °C/mi) (table 3). The thermal gradient along this thalweg profile was much larger than the gradient for the Prosser-banks reach. The larger thermal gradient is attributed to less total irrigated area in the surrounding uplands that contributes to local groundwater recharge in the uplands (and therefore groundwater discharge) and to fewer return flows.

Seepage investigations identified this reach as having a significant gain (appendix A). Excluding the first 0.17 mi of the profile, there are five distinct segments in this gaining reach; note that the large rise in temperature over the first part of the reach was likely an artifact of the probe equilibrating to ambient streamflow temperature (M. Appel, Benton Conservation District, written commun., 2007). The first segment (mile 0.17–0.8) displays a small thermal gradient, with only about a 0.1°C increase (0.15 °C/mi) (fig. 43); the small increase may be due to the effects of the cooler power return discharge. The next segment ending at mile 1.3 shows a large gradient of 1.12 °C/mi. This large gradient may be related to streamflow losses or a decrease in the depth, in either case, there is an obvious lack of cooler groundwater discharge. The next segment (mile 1.3–4) has a nearly flat thermal gradient (0.016 °C/mi) that is partially caused by inputs from return flows such as Swiss Corral and Corral Canyon Creeks (locations identifiable in the profile by the two large cooling structures at miles 1.7 and 2.7), but the well-defined temperature recession from the two major cooling structures to a nearly flat gradient suggests a large contribution of groundwater. This segment is followed by an initial large increase in temperature with stabilization through about mile 6.3, and the remaining part of the profile (the last segment) also displays stabilization (fig. 43). Except for the short segments, the thermal profile for this reach displays remarkable stabilization for a lower basin reach, which is consistent with the Prosser and Prosser-bank reaches. The stabilization is not related to streamflow temperature reaching equilibrium temperature conditions because the following reach (the Benton reach, fig. 44) clearly shows a nearly linear increase in temperature. The overall physical setting of the Prosser/Prosser-banks and this reach is a large-scale, bedrock-controlled area as defined by the hydrogeology of this area (Jones and others, 2006). In these reaches, groundwater in the surrounding basalt uplands likely discharges along the surface-water drainage features, especially the Yakima River, and groundwater in the limited alluvial aquifer would be supported by this discharge and by streamflow moving through the thin gravel sediments. Downstream of the bedrock-controlled part of the reach, the last three miles of the Chandler reach abuts irrigated areas on the left bank that would contribute to groundwater discharge. The physical habitat (gravels) and the groundwater input likely contributes to the presence of numerous fall chinook redds in these reaches.

Benton Reach

The 10.2-mi Benton reach has a stream gradient of about 0.0006 and a center (thalweg)-profile thermal gradient of 0.00068 °C/mi/min (0.17 °C/mi) (table 3). This reach extends from Benton City (RM 28.4) to near the Horn Rapids diversion dam (RM 18.2), and the reach is a documented losing reach based on the seepage investigations (appendix A) and the work of Drost and others (1997). Throughout most of this reach, the river stage is higher than the water table resulting in streamflow losses and groundwater levels also show movement of water to the east (away from the river) for part, but not all, of this reach (Vaccaro and others, 2009). Groundwater movement towards the river would occur from the basalt uplands on Rattlesnake Hills to the west, as identified by the mapped water levels (Vaccaro and others, 2009). Some groundwater discharge to the river likely also would occur through about mile 5 from the irrigated lands abutting the left bank.

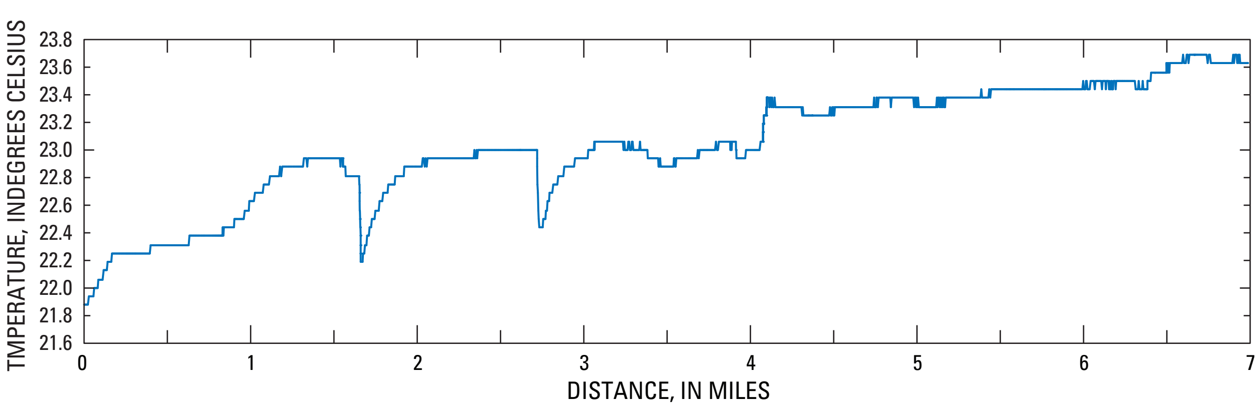


Figure 43. Longitudinal-distance gradient of temperature from a thermal profile, Chandler reach, Yakima River, Washington.

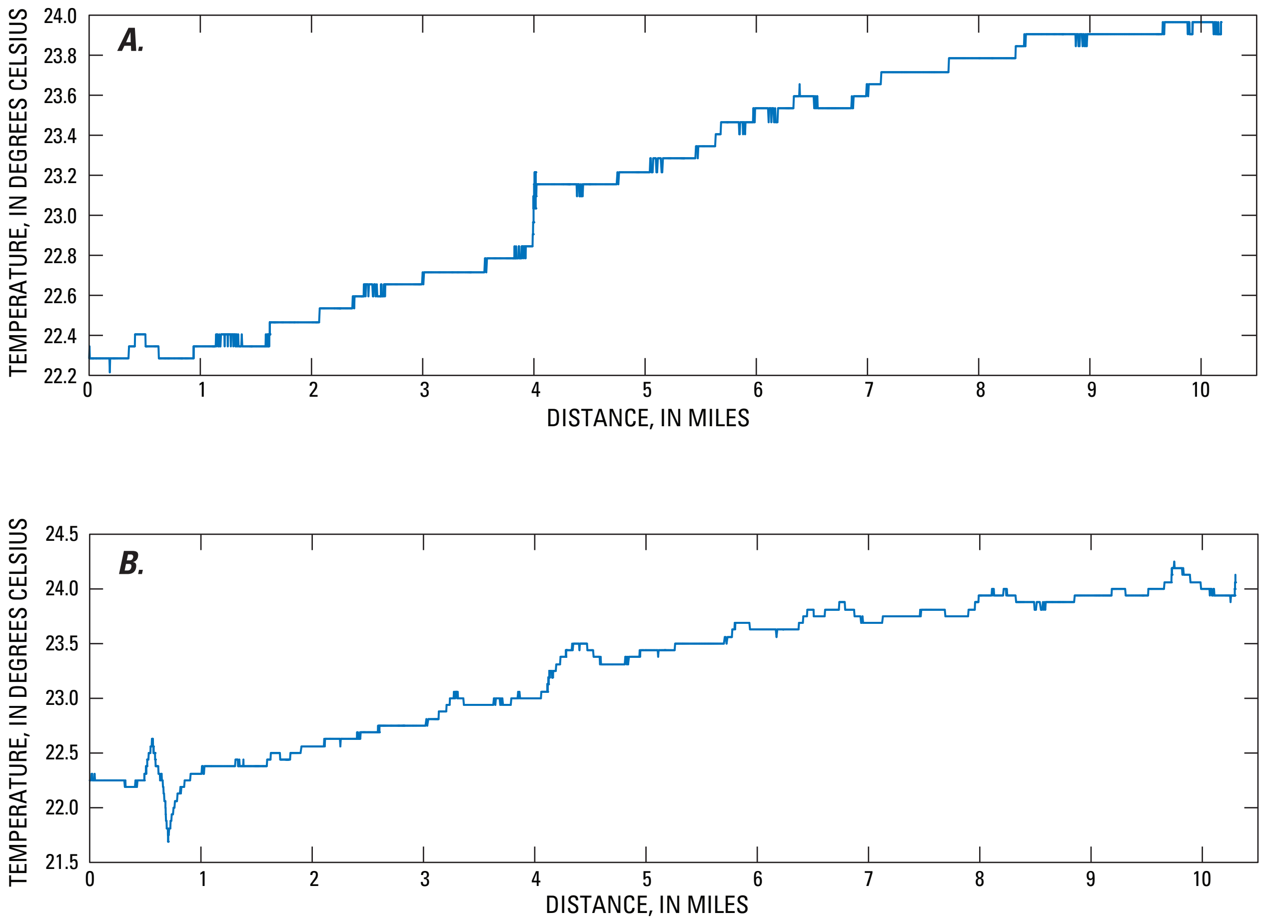


Figure 44. Longitudinal-distance gradient of temperature from a thermal profile for the (*A*) center channel and (*B*) left bank, Benton reach, Yakima River, Washington.

Except for a large cooling structure at mile 0.67, which occurred in a side channel (http://www.yakimacounty.us/YBWRA/PowerPoint/TempProfile_LV_files/frame.htm), the left bank profile, does not have cooling structures (fig. 44*B*). Warming structures, where present, are mainly displayed in the left-bank profile, which is likely related to lower velocities and shallower depths compared to the center-channel profile. More variability also is displayed by the left-bank profile compared to the center-channel profile (fig. 44*A*), and indicates that near-shore thermal habitat during this time-period is minimal. However, from about mile 8.3 to the end of the profile, the center-channel profile displays stabilization; this stabilization appears to have been initiated at about mile 7.2 because the profile shows a decrease in the temperature gradient from mile 7.2 to 8.3. For this segment, surface-water irrigated areas to the southeast may have raised groundwater levels resulting in the river intercepting the water table and there also may be groundwater flow from the basalt uplands to the west; groundwater level contours for these areas indicate some flow towards the river (Vaccaro and others, 2009). Of interest is that the thermal gradient for this reach is much smaller than the Teanaway reach (table 3) located in the upper basin; the thermal gradient also was consistent with the Parker and Toppenish reach gradients, suggesting there should be some localized, good thermal habitat for salmonids. As described previously, the quantity of streamflow affects the warming of a parcel of water as it moves downstream, and the relatively large discharge on the day of the profile (1,220 ft^3/s), which includes the Chandler power return, contributes to decreased warming in this lower basin reach compared to the Teanaway reach. The diurnal warming, however, is nearly the same as measured at the Yakima River at Kiona gaging station.

Snivley Reach

The 11.4-mi Snivley reach has a stream gradient of about 0.0007 and a thermal gradient of 0.00072 °C/mi/min (0.20 °C/mi) (table 3). Discharge in the reach on the day of the profile was about 1,140 ft^3/s—similar to that for the Chandler reach. The reach also has been identified as being in a losing reach based on seepage investigations (appendix A) and mapped groundwater levels (Vaccaro and others, 2009).

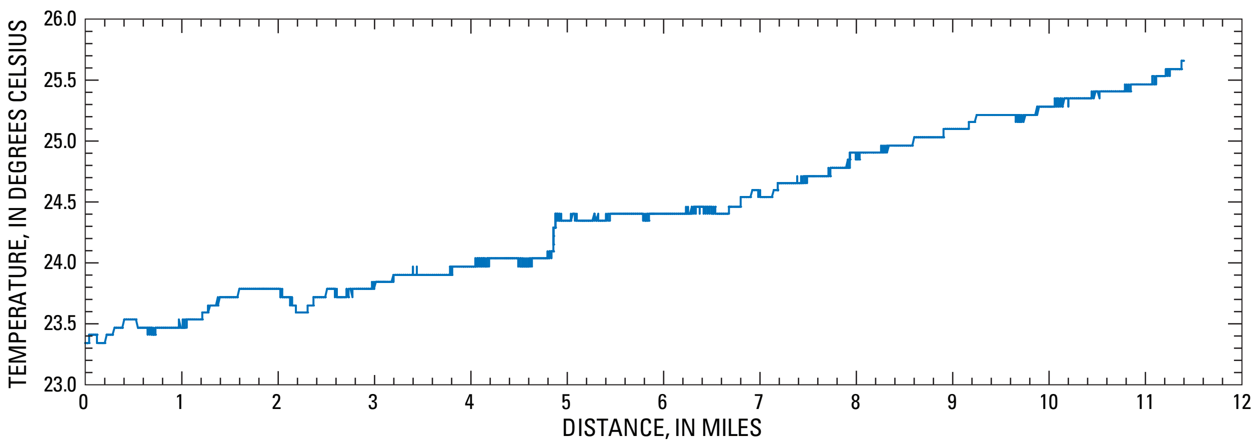


Figure 45. Longitudinal-distance gradient of temperature from a thermal profile, Snivley reach, Yakima River, Washington.

The profile displays a nearly linear increase in temperature (a linear trend line fit to the data has an R-squared value of 0.98) with about a 2.3°C increase in temperature over the length of the profile (fig. 45). However, downstream of the distinctive warming from mile 4.7 to 4.9, the profile stabilizes through mile 6.6, and has a low thermal gradient of 0.06 °C/mi. The stabilization over this 1.7-mi segment indicates that localized groundwater discharge occurs from the surface-water irrigated areas that surround this segment. Appel (http://www.yakimacounty.us/YBWRA/PowerPoint/TempProfile_LV_files/frame.htm) shows stabilization over this segment for left- and right-bank profiles; these profiles also display more structure than the center profile. The left-bank profile has more cooling structures than the right-bank profile, which is consistent with the irrigated areas to the east above the left bank providing some localized groundwater discharge; the right-bank profile principally displays warming structures in contrast to cooling structures. Given the large stream discharge quantity on the day of the profile, a reasonable amount of groundwater discharge in this 1.7-mi segment would be required to prevent typical diurnal warming and allow for stabilization. Therefore, there likely are local areas at the streambed interface with cool groundwater discharge that can provide thermal refugia in such a warm reach.

Confluence Reach

Two profiles are presented and described for the Confluence reach (fig. 46*A*, *B*), a 4.9-mi center profile and a 6-mi right-bank profile; note that Appel's profiles (http://www.yakimacounty.us/YBWRA/PowerPoint/TempProfile_LV_files/frame.htm) extended into the Columbia River, but only the part of the profiles in the Yakima River are presented. The reach has the lowest stream gradient (0.0002 ft/ft) of the profiles (table 3), and the gradient is consistent with the Confluence reach being the terminal reach for the Yakima River before it enters the Columbia River. The center and right-bank profiles had thermal gradients of 0.00033 °C/mi/min (0.07 °C/mi) and 0.00053°C/mi/min (0.11 °C/mi), respectively (table 3). The very low thermal gradient for the center profile suggests that the streamflow temperature is approaching thermal equilibrium in the lower reach. The slightly higher thermal gradient for the right-bank profile is attributed to the lower temperature at the start of the profile. On the day of the profile, discharge was about 891 ft^3/s on the basis of the daily mean discharge for the USGS gaging station, Yakima River at Kiona.

There are large differences between the two profiles (fig. 46*A*, *B*) because the right-bank profile captures near bank temperature changes derived from irrigation-return flows and groundwater discharge. Additionally, an irrigation canal runs just west of the right bank through more than one-half of the profile, and Drost and others (1997) showed that the canal leakage can be an important component of groundwater recharge in this area. The canal leakage would raise groundwater levels and result in subsequent groundwater discharge. The right-bank profile displays large variability with structure throughout. The first major structure (a cooling of more than 5°C) starts at mile 0.8 (fig. 46*B*) where a side channel enters. Note that the left-bank profile of Appel does not display most of the cooling structures displayed in the right-bank profile, but in the vicinity of the side channel it displays some cooling that further indicates that this area is receiving a reasonable amount of cooler groundwater discharge. Appel (http://www.yakimacounty.us/YBWRA/PowerPoint/TempProfile_LV_files/frame.htm) identifies a spring in the side-channel area, but the cooling occurs throughout the side channel, suggesting continuous discharge of cooler water derived from a series of springs and (or) by a high water table adjacent to the river that can be attributed to canal leakage to the west. After re-entering the main channel, the temperature of the right-bank profile reach the center-channel temperature until 0.5 mi downstream, further indicating that this area along the right bank is receiving groundwater discharge. The next cooling structure at about mile 1.9 is where the downstream end of the side channel

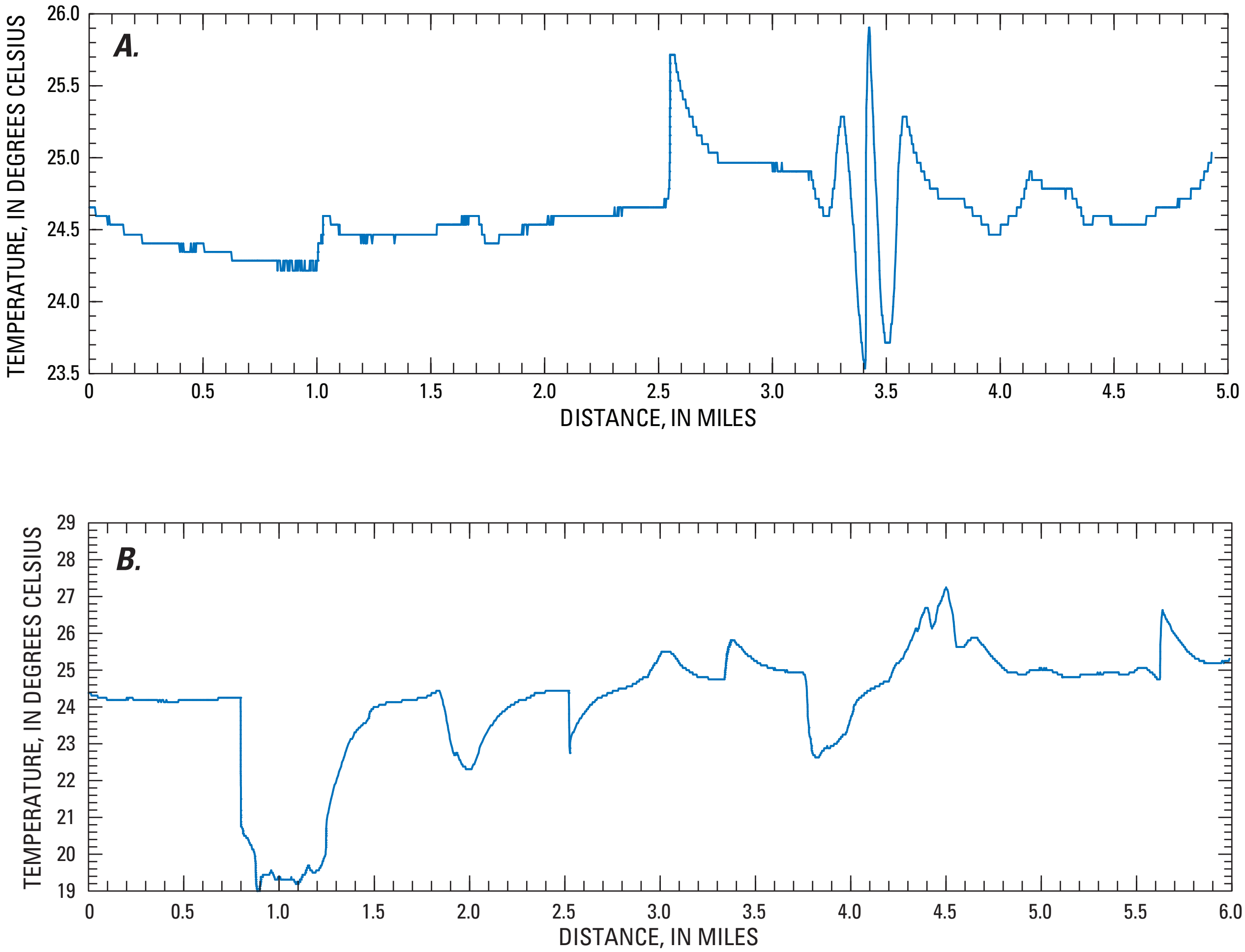


Figure 46. Longitudinal-distance gradient of temperature from a thermal profile for the (*A*) center channel and (*B*) right bank, Confluence reach, Yakima River, Washington.

was profiled. Right-bank temperatures do not reach the same temperatures of the center channel profile before another cooling structure where return flow is encountered at mile 2.5. The lower temperatures from the side channel to the return flow likely are caused by canal leakage. The 2°C cooling displayed by the right-bank profile from mile 3.7 to about 4.1 appears to be related to discharge from drains and low-lying areas in a triangular-shaped (constrained by highway 240 and a smaller road) large vegetated area to the southeast. Over the last 0.6 mi of the reach, the difference between the right-bank and center-channel profiles appears to be related to the variations in depth between the two profiles; it would also require a large amount of cool groundwater discharge to affect the main channel temperature because of the large quantity of streamflow (note the overall smoothness of the center-channel profile shown on figure 46*A*). Overall, the temperatures displayed in this reach are high and do not provide good thermal habitat for salmonids. However, the existence of the localized cooling structures indicates that cooler refugia may be found and that these few areas may be candidates for preservation.

Summary And Conclusions

Several types or categories of information can be used to identify the locations of and to estimate the magnitude of the exchanges of water between stream channels and adjacent or underlying aquifers (river-aquifer exchanges) in the Yakima River basin. The information comprises data on the chemical isotopic composition of streamflow and groundwater; gains and losses in flow along a specified reach of a stream channel (seepage runs); vertical hydraulic gradients within a stream channel; concurrent water levels and temperatures in a stream and nearby wells; and longitudinal profiles of streamflow temperatures.

Isotope Data

The groundwater and surface-water isotope data showed that the ultimate source of surface and groundwater is meteoric water derived from atmospheric precipitation. Water in deep wells had a different isotopic composition than both shallower groundwater and surface water, which indicates that surface water contains, at most, only a small component of discharge from the deep flow system. The isotope data confirmed that river-aquifer exchanges involve primarily modern streamflow and modern, shallow groundwater. The range in tritium concentrations of shallow groundwater indicates that groundwater discharging to the river may be very recent water (less than 1 year) to as much as 65 years old. More detailed age-dating analyses are needed to improve the accuracy and increase the confidence in the indicated age of groundwater discharging to the rivers and the groundwater in shallow flow paths, particularly for areas of the Yakima River basin downstream of the humid uplands. Such analyses would improve the understanding of the relation between the shallow groundwater-flow system and river-aquifer exchanges. It may be that inferred relations such as those described for the flood plain include hydrologic controls exerted many years ago that no longer occur. Such understanding has implications related to best management practices and nutrient loadings to the streams and drains in the basin.

Seepage Investigations

The analyses of 470 discharge measurements for 46 stream sections, which included 167 subsections, or reaches, ranging in length from 0.4 to 206 mi (median of 7.6 mi), provide the most direct evidence and measure of streamflow gains and losses in the large Yakima River basin. Because of the importance of groundwater discharge to salmonid habitat, the gaining reaches may suitable for restoration or preservation of such habitat and thus the health and survival of the fish populations in the streams of the basin. The multiple repetitive seepage investigations, which included discharge measurements in the same sections, highlighted the importance of conducting such investigations over short distances. In several cases, long reaches identified as being either net gaining or net losing reaches in one seepage investigation were shown to have highly variable exchange conditions based on seepage investigations that subdivided these reaches: that is, an identified gaining (losing) reach based on only a single seepage investigation was shown to contain locally gaining and losing segments in another investigation that subdivided the reach. Although the net exchange was gaining (or losing) for such a reach, the alternation of gains and losses within the reach further refine the locations and quantity of the exchanges. The magnitude of many of the larger exchanges was not expected—more than 40 percent of the gains were more than 10 (ft^3/s)/mi. Such large exchanges were not confined to the reaches in the upper basin, but occurred throughout the river system. The data also verified the concept that most of the gains or losses occurred over a small part of a reach, and that the river system continually gains and loses water as it flows from the headwaters to the mouth. That is, the groundwater in the alluvial aquifer flows longitudinally downgradient in the aquifer, generally parallel to the river, with gains and losses conditioned on streambed/water-surface elevation, elevation of the water table, variations in the lateral and vertical extent of the aquifer, lithology contrasts, and channel complexity and orientation. Of importance is the fact that the natural river-aquifer exchanges have been greatly modified throughout large areas due to the effects of anthropogenic activities, and as result, the reaches and or segments with functional river-aquifer exchanges are important for a viable aquatic ecosystem that supports salmonids.

Vertical Hydraulic Gradients

Mini-piezometer measurements provided an estimate of the vertical hydraulic gradients (VHGs) between the river and the shallow groundwater. Measured VHGs are representative of local conditions only, however, and may not be representative at the reach scale. For example, a negative gradient, indicating local losses of water from a stream channel to the adjacent aquifer, may be determined for a site that is in a reach that has a net gain. Variations and changes in direction of VHGs also occur across individual river transects (cross sections). Single measurements do not capture seasonal variations, and seasonal or temporal changes in the direction of the VHG may be dependent on streamflow quantities. However, in some areas groundwater levels in piezometers can mimic the surface-water levels due the pressure effects of the river stage, and the VHG can be maintained over a reasonably large range of flows.

Ninety-nine measurements of VHG were available for analysis; 70 values were negative (indicating streamflow losses), 29 were positive (indicating streamflow gains). The VHGs ranged over four orders of magnitude, and in terms of absolute values, 17 percent were less than 0.01 ft/ft, 50 percent were less than 0.05 ft/ft, 65 percent were less than 0.1 ft/ft, and 94 percent were less than 1 ft/ft. Thus, VHGs tend to be small and larger values are less common. Indeed, 90 percent of the values (absolute terms) were less than 0.5 ft/ft, suggesting that larger VHG values reflect extremely local geologic conditions, for example, sites may be in areas of more vigorous exchanges dominated by lateral groundwater discharge or where a fine-grained geologic unit locally underlies the streambed. The complexity of exchanges measured at a local scale in contrast to overall segment/reach exchange was clearly shown by the data. The percentile distribution of the data, which was similar to the shape of the seepage data distribution, showed that beyond the 80th percentile, the positive VHG values become much larger, indicating that the largest VHGs have a different controlling mechanism, that is, lateral rather than vertical groundwater discharge likely dominates large exchanges. Therefore, occurrences of large positive VHGs may indicate the potential for a large component of lateral groundwater discharge in that area.

The VHGs were formulated in terms of fluxes per unit area; the negative VHGs ranged from 0.005 to 24 in/d and 96 percent were less than 3 in/d. It was determined that river losses can support such values. For the 29 positive VHGs, fluxes ranged from 0.01 to 19.3 in/d, and 86 percent were less than 2.3 in/d. Formulating the values in terms of normalized discharge (cubic feet per second per mile) highlighted the fact that the very large positive VHGs were not the controlling factor for exchanges and that other mechanisms, such as lateral inflow, dominate the hydrologic exchange process. The concept that a VHG can be formulated in terms of a normalized discharge is important because several measurements can be used to estimate the potential quantity of gains or losses in the area where VHGs were measured.

Concurrent Water Level and Temperature Data

Water level and temperature data from the monitoring sites in and along streams in the Yakima River basin displayed highly-variable characteristics that reflect complex relations with respect to both groundwater levels and temperature, between the shallow groundwater system and streamflow, surface-water bodies, alluvial aquifer flow, and irrigation (infiltration of irrigation water and return flows). In many cases, the fluctuation of groundwater levels mimicked river stage at both gaining and losing sites, and shows the effects of river stage pressure on the adjacent groundwater system. These pressures may raise groundwater levels to the extent that they intercept the land surface in depressions and sloughs. Thermographs can be clearly identified as being either surface-water or groundwater dominated on the basis of the magnitude of the annual amplitude. Amplitudes were as large as 16°C and as small as 1°C, and depending on the physical setting, the annual maximum groundwater temperature lagged streamflow temperature from less than one month to more than two months. Vertical variations of water levels and temperature in the shallow groundwater system occur over distances as small as 10 ft. At sites where streams are losing water, temperature effects on groundwater were attenuated at distances as small as 50 ft from the river. The temperature data show that bank storage is not as important as the inundation of side channels and sloughs in supplying relatively cool water to the shallow groundwater system. The magnitude of streamflow is an important control on water levels and temperature in the shallow groundwater system, with rain-on-snow events being more important than the spring-runoff season because the former events can produce higher discharges. Differences in groundwater levels and temperatures between wet and dry years were distinctive, and the differences show the importance of the type of year (dry, average, or wet) on river-aquifer exchanges throughout the Yakima River basin. The increased releases from the Naches River arm reservoirs usually beginning in September resulted in identifiable changes in both groundwater temperature and water levels downstream of the reservoirs.

Thermal Profiles of Streams

Variations in local river-aquifer exchanges were identified over some 160 river miles on the basis of thermal profiles of the water. Short variations (thermal structure) and long variations (thermal diversity) were displayed in all the profiles, including those in the lower, or downstream, part of the basin. The temperature data display much inter- and intra-profile diversity and structure, and detailed views of parts of the profiles also exhibit such features. The interaction of short and long variations results in a templet for thermal habitat for salmonids. The 22 recorded thermal profiles show stabilization/cooling segments that typify broad areas of groundwater discharge, whereas structures are indicative of local discharge. Four categories of local groundwater discharge were identified and are components of the basins' temperature templet that is predicated on river-aquifer exchanges. The first category includes small, commonly dry tributary streams beneath which groundwater is flowing through underlying coarse-grained alluvial sediments and discharges to a larger stream at the mouth of the tributary. The second includes de-watered river channel braids (side channels) that function as alluvial aquifers that discharge where they reconnect to the main channel. The third category includes deep pools that are incised into the alluvial aquifer or in bedrock-controlled segments that receive upstream discharge from thinning or terminating river alluvium. The fourth category of discharge is that from groundwater springs. The first two categories were readily identified because the small tributary creeks and most side channels were dry in the drought year 2001, when many of the profiles were recorded. Alluvial aquifer discharge also would be occurring when the smaller tributary streams are flowing. However for that case, the groundwater discharge from the mouth (usually represented by its alluvial fan) of the tributary may not be detectable on a thermal profile because the temperatures of the tributary streamflow and groundwater may be similar; in any case, however, this discharge would provide temperature conditions favorable for rearing or holding salmonids; rearing fish appear to use the habitat near the mouth of tributary creeks. In the case of flowing side channels, groundwater discharge during the summer low-flow/high-temperature period should be detectable because the groundwater may be much cooler than the river water and thus, this groundwater discharge would provide improved habitat. The third category is displayed by temperature-depth data that indicates cooler water at the bottom of pools. The fourth category generally was inferred, although one spring, with a measured water temperature about 6°C lower than ambient stream temperature, was physically located at the end of the Granger reach, and at least one profile clearly showed local cooling effects of springs. During low-flow years or low-flow periods, these four types of environments may provide important habitat with respect to summer thermal refugia for holding or rearing and winter refugia for rearing.

Areas of temperature stabilization and cooling, and cooling structures displayed in the thermal profiles are indicative of river-aquifer exchanges, and represent the deviations (anomalies) from the overall thermal response. These areas or "patches" are most prevalent in the upstream reaches of Yakima River basin streams and diminish, in relation to total reach length, in the lower river basin, which is consistent with the thermal processes and the overall basin hydrology—more groundwater discharge occurs in the hydrologically active and humid uplands. The connectivity of these patches is crucial for salmonids. Warming structures, caused primarily by human activities such as irrigation and the consequent return flows, are nearly absent in the profiles for the upper reaches of streams and are common in the profiles for the downstream reaches, in the heavily modified lower river basin. The thermal profile information reflects the complex interactions of different waters. Thus, the thermal processes leading to the end-member temperatures of the reaches could not have been identified using standard techniques, such as using streamflow temperature data from fixed stations. Thermal modeling of these reaches to define the thermal habitat would also be difficult in view of the local-scale processes acting to warm or cool stream water.

The apparent downstream-decrease in diversity and occurrence of cooling structures is typical of large riverine systems. In a downstream direction, stream discharge and channel width (and thus total surface area and surface area exposed to direct solar radiation) typically increase, and the number of tributaries, degree of canopy shading, and bed sediment size decrease. However, in the Yakima River basin, stream discharge does not increase systematically in a downstream direction due to diversions. Such reductions in streamflow can contribute to an increase in warming. The energy balance ultimately determines how the interaction between these longitudinal changes affects the temperature. The longitudinal temperature profile varies by distance—starting with upstream temperature control on water temperature, transitioning to a combination of upstream temperature and climate control, and ultimately to climate control. The locations of the transition areas vary seasonally by travel time and therefore, by discharge. Overlaid on this longitudinal templet is the reach behavior concept, which holds that in some reaches temperatures are affected only by atmospheric conditions and that 'thermal transition reaches' are present in which advective inflows have a residual effect. This temperature templet results in the movement of salmonids to find suitable habitat for their different life-history stages. Fish assemblages in the basin are also arrayed along this gradient.

A more diverse thermal regime that is influenced by river-aquifer exchanges leads to a more diverse aquatic ecosystem. The basin's large diversity in water temperatures documented in the thermal profiles is consistent with the large diversity in algal, benthic invertebrate, and fish communities observed in the basin. However, locally the decreased thermal diversity in the downstream reaches likely is related to the decrease in aquatic diversity in these downstream reaches.

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Appendix A. Streamflow Gains and Losses for Selected Stream Reaches, Yakima River Basin, Washington

Table A1. Streamflow gains and losses for selected stream reaches in the Yakima River basin, Washington.

[River mile locations from E. Young, Bureau of Reclamation, written commun., 2007. River miles are miles from the mouth of the river. Toppenish Creek measurements are averages of 56 total measurements split unevenly during the identified months. Only gains or losses greater than 5 percent of measured streamflow are presented. Data from Magirl and others, 2009. **Abbreviation**: ft^3/s, cubic foot per second; **Symbol**: –, not applicable]

River miles	Net gain (ft^3/s)	Net loss	Date	Stream name
214.4 to 182.5	137	–	July 1988	Yakima River
202.3 to 195.4	27	–	September 2001	Yakima River
182.5 to 165.4	–	137	July 1988	Yakima River
182.5 to 165.4	–	33	February 2005	Yakima River
176.0 to 165.4	–	22	February 2005	Yakima River
165.4 to 155.9	381	–	August 1999	Yakima River
165.4 to 148.4	101	–	February 2005	Yakima River
165.4 to 140.4	224	–	July 1988	Yakima River
155.9 to 140.4	–	213	August 1999	Yakima River
127.7 to 124.4	–	16	September 2005	Yakima River
127.7 to 124.4	–	25	March 2006	Yakima River
124.4 to 123.5	60	–	August 1999	Yakima River
124.4 to 123.5	21	–	March 2006	Yakima River
124.4 to 123.5	28	–	September 2005	Yakima River
107.3 to 103.7	370	–	August 1999	Yakima River
107.3 to 103.7	124	–	October 2008	Yakima River
107.3 to 103.7	93	–	March 2006	Yakima River
103.6 to 102.7	62	–	September 2005	Yakima River
103.6 to 102.7	101	–	March 2006	Yakima River
102.7 to 93.1	–	29	July 2003	Yakima River
102.7 to 93.1	109	–	September 2005	Yakima River
102.7 to 100.3	–	41	September 2005	Yakima River
102.7 to 100.3	90	–	March 2006	Yakima River
100.3 to 93.1	144	–	September 2005	Yakima River
100.3 to 98.0	–	176	March 2006	Yakima River
98.0 to 93.1	240	–	March 2006	Yakima River
93.1 to 82.9	253	–	July 2003	Yakima River
86.2 to 82.9	62	–	July 2004	Yakima River
82.9 to 78.1	53	–	July 1988	Yakima River
82.9 to 75.6	–	144	March 2006	Yakima River
82.9 to 75.6	–	52	September 2005	Yakima River
82.9 to 73.0	103	–	July 2004	Yakima River
80.0 to 72.4	69	–	July 2003	Yakima River
78.2 to 72.4	57	–	July 1988	Yakima River
72.4 to 55.0	56	–	July 1988	Yakima River
72.4 to 55.0	312	–	August 1999	Yakima River
61.5 to 55.0	–	69	July 2004	Yakima River
55.0 to 43.9	164	–	July 2004	Yakima River
46.3 to 29.9	218	–	August 1999	Yakima River
43.9 to 29.9	421	–	July 2004	Yakima River
43.0 to 29.9	421	–	July 2004	Yakima River
43.0 to 29.9	71	–	July 1988	Yakima River
29.9 to 8.4	–	391	July 2004	Yakima River
43.5 to 36.0	17	–	August 2002	Naches River
43.5 to 43.0	–	12	July 2004	Naches River
43.0 to 42.0	61	–	July 2004	Naches River
41.1 to 40.0	–	23	July 2004	Naches River
36.0 to 34.0	22	–	July 2004	Naches River
28.9 to 28.0	74	–	July 2004	Naches River
26.6 to 23.9	–	57	July 2004	Naches River
23.9 to 20.8	64	–	July 2004	Naches River
20.8 to 17.6	23	–	July 2004	Naches River
17.6 to 16.0	–	34	July 2004	Naches River
17.2 to 16.3	59	–	August 2002	Naches River
16.0 to 12.8	–	26	July 2004	Naches River
12.8 to 0.5	95	–	July 2004	Naches River
13.3 to 5.7	11	–	September 2003	American River
5.7 to 0.6	4	–	September 2003	American River
6.1 to 4.0	–	16	July 2004	Tieton River
4.0 to 3.0	17	–	July 2004	Tieton River
2.2 to 1.5	–	18	July 2004	Tieton River
1.5 to 0.4	26	–	July 2004	Tieton River
10.0 to 4.0	5.9	–	June 2005	Taneum Creek
10.0 to 7.9	–	2	July 2005	Taneum Creek
7.9 to 4.0	3.1	–	July 2005	Taneum Creek
4.0 to 2.0	–	2.4	July 2005	Taneum Creek
10.0 to 7.9	–	2.1	August 2005	Taneum Creek
5.9 to 0.1	–	.5	July 2005	Swauk Creek
22.6 to 20.0	8.1	–	June 2005	Naneum Creek
22.6 to 20.0	2.3	–	July 2005	Naneum Creek
22.6 to 20.0	.9	–	August 2005	Naneum Creek
22.6 to 20.0	1.1	–	October 2005	Naneum Creek
20.0 to 17.4	–	2.2	August 2005	Naneum Creek
17.4 to 3.4	1.7		June 2005	Cooke Creek
3.4 to 3.0	.4	–	June 2005	Cooke Creek
3.4 to 3.0	.6	–	July 2005	Cooke Creek
4.6 to 0.2	.4	–	June 2005	Umtanum Creek
4.6 to 0.2	.3	–	October 2005	Umtanum Creek
4.2 to 1.1	35.6	–	December 2008	Wilson Creek
1.7 to 0.3	15.1	–	December 2008	Cherry Creek
24.6 to 22.8	–	13	December 1897	Ahtanum Creek
22.0 to 18.5	10	–	December 1897	Ahtanum Creek

Table A1. Streamflow gains and losses for selected stream reaches in the Yakima River basin, Washington.–Continued

[River mile locations from E. Young, Bureau of Reclamation, written commun., 2007. River miles are miles from the mouth of the river. Toppenish Creek measurements are averages of 56 total measurements split unevenly during the identified months. Only gains or losses greater than 5 percent of measured streamflow are presented. Data from Magirl and others, 2009. **Abbreviation**: ft^3/s, cubic foot per second; **Symbol**: –, not applicable]

River miles	Net gain (ft^3/s)	Net loss	Date	Stream name
18.5 to 16.2	–	4	December 1897	Ahtanum Creek
20.8 to 17.3	17	–	March 2009	Marion drain
17.3 to 10.9	73	–	March 2009	Marion drain
15.3 to 12.9	29	–	March 2009	Marion drain
12.9 to 1.2	95	–	March 2009	Marion drain
10.9 to 6.3	40	–	March 2009	Marion drain
6.3 to 1.2	43	–	March 2009	Marion drain
45.1 to 41.6	–	15	July-September	Toppenish Creek
45.1 to 41.6	–	13	October-December	Toppenish Creek
45.1 to 41.6	–	11	January-March	Toppenish Creek
45.1 to 41.6	–	15	April-June	Toppenish Creek
41.6 to 40.2	.4	–	July-September	Toppenish Creek
41.6 to 40.2	2.4	–	October-December	Toppenish Creek
41.6 to 40.2	3.2	–	January-March	Toppenish Creek
41.6 to 40.2	1.7	–	April-June	Toppenish Creek
37.7 to 24.7	–	4.3	September 2003	Satus Creek
9.5 to 8.0	–	1	September 2003	Satus Creek
8.0 to 3.2	12	–	September 2003	Satus Creek

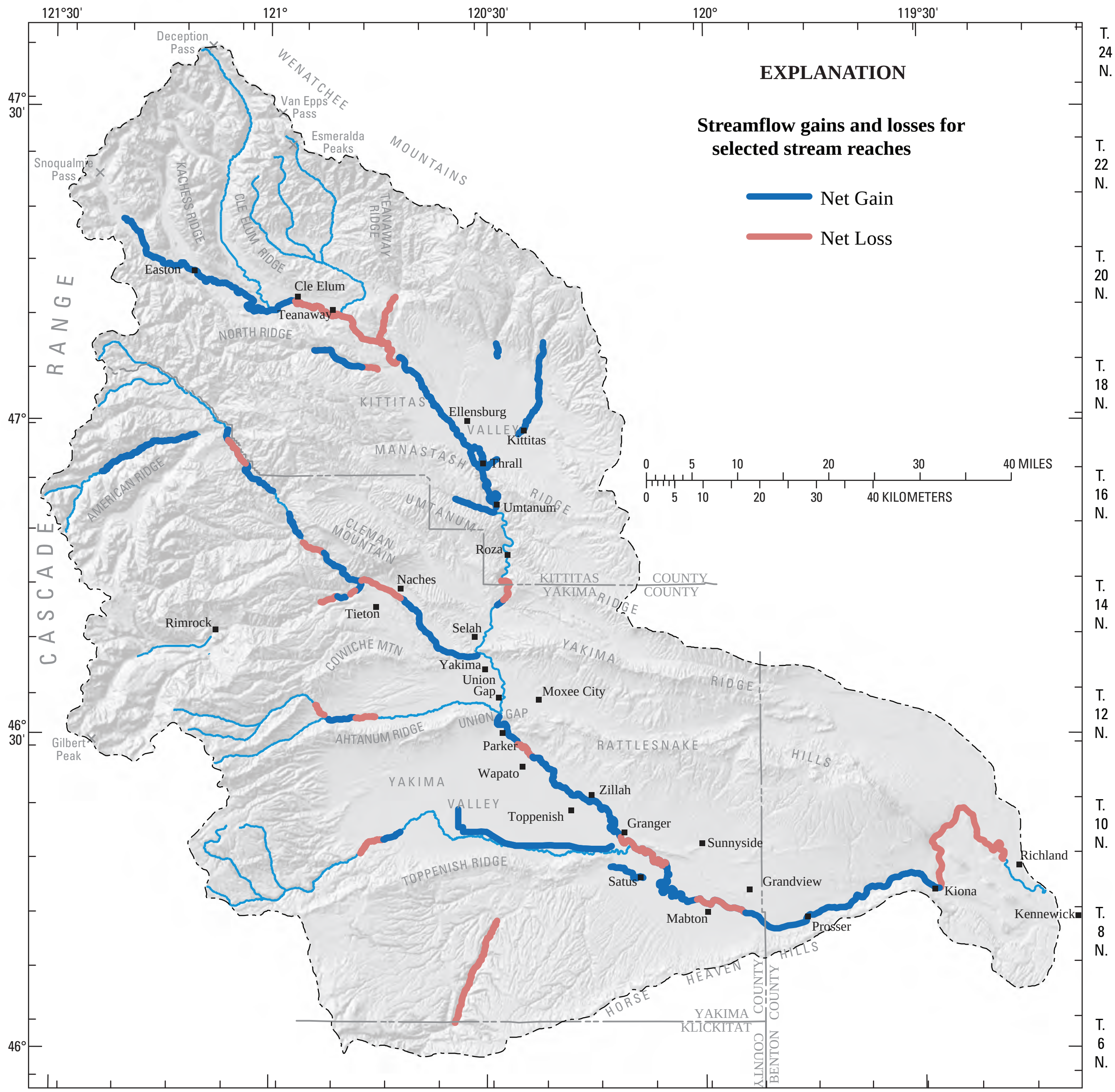

Figure A1. Map showing streamflow gains and losses for selected stream reaches in the Yakima River basin, Washington.

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