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Groundwater/Surface-Water Interactions in the Tunk, Bonaparte, Antoine, and Tonasket Creek Subbasins, Okanogan River Basin, North-Central Washington, 2008

Scientific Investigations Report 2009–5143

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

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U.S. Department of the Interior
KEN SALAZAR, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2009

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Suggested citation:
Sumioka, S.S., and Dinicola, R.S., 2009, Groundwater/surface-water interactions in the Tunk, Bonaparte, Antoine, and Tonasket Creek subbasins, Okanogan River basin, north-central Washington, 2008: U.S. Geological Survey Scientific Investigations Report 2009–5143, 26 p.

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
section (640 acres or 1 square mile)	259.0	square hectometer (hm^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Hydraulic gradient	
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

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

°C= (°F-32)/1.8.

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 1983 (NAD 83).

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

Local and Surface-Water Station Numbers

Wells and other data-collection sites in Washington are assigned so-called local numbers by the USGS that identify their location in a township, range, and section, based on the rectangular subdivision of public land. For example, well number 37N/28E-34A01 indicates, from left to right, the township (37 North), the range (28 East); the 640-acre section (Section 34); and the 40-acre quarter-quarter section (A) within that section. A number follows the quarter-quarter section designation to indicate the sequence in which the well was inventoried in that quarter-quarter section.

Surface-water stations at which streamflows are measured are assigned a number, in downstream order, if there are more than one on a stream. A description of this system of numbering may be found at http://wdr.water.usgs.gov/wy2007/documentation.html#sitenumber.

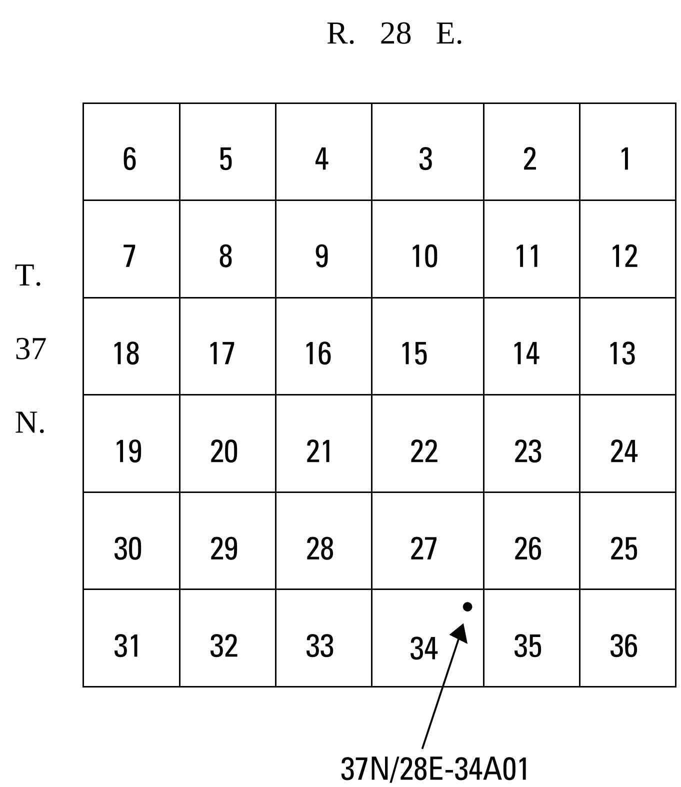

Diagram showing local number site identification system used in Washington State.

Groundwater/Surface-Water Interactions in Tunk, Bonaparte, Antoine, and Tonasket Creek Subbasins, Okanogan River Basin, North-Central Washington, 2008

By S.S. Sumioka and R.S. Dinicola

Abstract

An investigation into groundwater/surface-water interactions in four tributary subbasins of the Okanogan River determined that streamflows and shallow groundwater levels beneath the streams varied seasonally and by location. Streamflows measured in June 2008 indicated net losses of streamflow along 10 of 17 reaches, and hydraulic gradients measured between streams and shallow groundwater indicated potential recharge of surface water to groundwater at 11 of 21 measurement sites. In September 2008, net losses of streamflow were indicated along 9 of 17 reaches, and potential recharge of surface water to groundwater was indicated at 18 of 21 measurement sites. The greatest losses of streamflow occurred near the confluences with the Okanogan River, likely due to the presence of thick layers of unconsolidated deposits in the flood plain of the Okanogan River.

Based on available geologic information compiled from drillers' logs, a surficial geologic map, and streamflow records, the extensive and thick deposits of unconsolidated material in the Tunk and Bonaparte Creek subbasins are factors in sustaining the almost perennial streamflow in those creeks. The less extensive and generally thinner unconsolidated deposits in the Tonasket and Antoine subbasins are contributing factors to the occasional extended periods of zero flow (a dry stream channel) in those creeks.

Even though groundwater withdrawals would affect streamflows, relatively low precipitation in the area, along with limited groundwater storage capacity and the presence of permeable, unconsolidated deposits underlying the stream channels, would likely lead to loss of surface water to the groundwater system without any withdrawals.

Introduction

In recent years, increasing demands for water for domestic, agricultural, recreational, and other uses in watersheds of Washington have created concern that insufficient water resources remain for fish and other uses. The Okanogan River basin includes portions of British Columbia, Canada, and Washington. The Similkameen River is the largest tributary of the Okanogan River and also drains British Columbia and Washington. The drainages of the Okanogan and Similkameen Rivers in Washington constitute Water Resources Inventory Area (WRIA) 49 (fig. 1), one of many watersheds in Washington where local citizens and governments have elected to coordinate with Tribes and State agencies to develop a watershed management plan, according to the guidelines outlined in the Watershed Management Act of 1998 (Washington State Engrossed Substitute House Bill 2514). With leadership from the Okanogan Conservation District (OCD), the planning group is working to implement a long-range sustainable watershed plan to meet the needs of current and future water demands in the basin, while also working to protect and improve its natural resources. In this report, the Okanogan River basin refers to the mainstem of the Okanogan River south of the Canada/United States boundary.

The WRIA 49 planning group needs information regarding the interaction of groundwater and surface water in the tributaries to the Okanogan River as part of the assessment phase. As lead agency for WRIA 49 planning, the OCD selected Tunk, Bonaparte, Antoine, and Tonasket Creek subbasins, tributaries to the Okanogan River (fig. 1) to investigate groundwater/surface-water interactions. The OCD requested that the U.S. Geological Survey (USGS) collect and evaluate data to better understand those interactions in the selected subbasins.

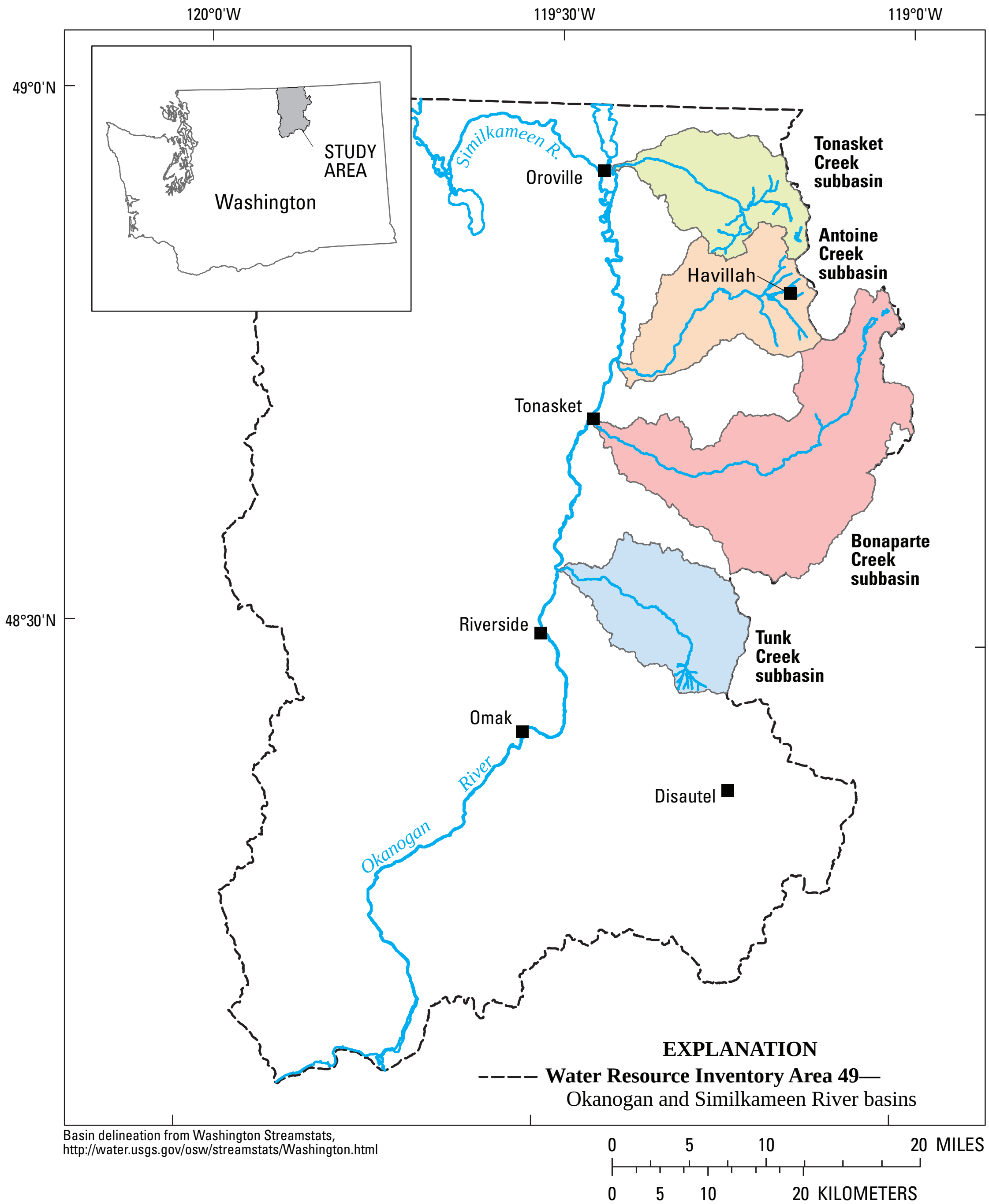

Figure 1. Location of Water Resources Inventory Area 49 and the four study area subbasins, Washington.

Purpose and Scope

This report presents the results of streamflows and shallow groundwater levels measured beneath streams in the Tunk, Bonaparte, Antoine, and Tonasket Creek subbasins of the Okanogan River in Washington. Data were collected in June and September 2008; a low-flow period when water demand is high and water availability is limited. The data were used to identify net streamflow gains and losses along reaches of the creeks and to determine if groundwater is discharging to streams or streamflow is recharging groundwater at measurement locations. In addition, those findings are evaluated with regard to available information about the hydrogeologic framework of the subbasins. Suggestions for additional data collection and interpretation that could refine the understanding of groundwater/surface-water interactions in the subbasins are presented.

Geologic and hydrogeologic information for the subbasins was obtained from previously published reports, from surficial geologic maps published by the Washington State Department of Natural Resources (2005), and from drillers' logs either on file at the USGS Washington Water Science Center or downloaded from the Washington State Department of Ecology (WDOE) website (http://apps.ecy.wa.gov/welllog/textsearch.asp, accessed November 7, 2008).

Previous Water Resources Studies

The water resources for the entire Okanogan River basin were described by Walters (1974), based on water-resources information compiled from various sources. Using existing records of hydrologic conditions (precipitation, streamflow, and groundwater levels), Walters (1974) described, to the extent possible, the amount of water available, the quality or usability of the water, and the frequency of seasonal water shortages or surpluses in the Okanogan River basin and in its tributary subbasins, including the four subbasins of the present study.

Montgomery Water Group, Inc. and others (1995) evaluated existing data and presented an initial assessment of the availability of groundwater and surface water that WDOE could use in making decisions regarding water rights.

A more detailed study of the Bonaparte Creek subbasin (Packard and others, 1983) collected groundwater and surface-water data to describe the relationship between groundwater levels, streamflow, and water levels in several lakes in the subbasin. The study also located the groundwater divide between the Bonaparte Creek subbasin and the Sanpoil River basin to the southeast.

Table 1. Location and selected physical characteristics of four study area subbasins, Washington.

[Location of subbasins are shown in figure 1. Basin characteristics from http://streamstats.usgs.gov/wastreamstats/index.asp, accessed November 26, 2008. Altitudes are given in feet above North American Vertical Datum of 1988 (NAVD 88). mi^2, square mile; ft, foot]

Subbasin name	Location of subbasin mouth (river miles along Okanogan River)	Drainage area (mi^2)	Altitude range (ft)	Average altitude (ft)
Tunk Creek	45.0	71.7	860 – 6,050	3,300
Bonaparte Creek	56.7	161	890 – 7,260	3,550
Antoine Creek	61.2	73.4	900 – 7,250	3,440
Tonasket Creek	77.8	60.1	920 – 5,090	3,300

Description of Study Area

The study area consists of four subbasins located on the eastern side of the Okanogan River in the Okanogan River basin in north-central Washington (fig. 1 and table 1). The Okanogan River flows southward from British Columbia, Canada, to the Columbia River and drains about 8,300 mi^2 in the United States and Canada. WRIA 49 encompasses about 2,100 mi^2 within that area, and the four subbasins make up about 370 mi^2 of the WRIA. The Bonaparte Creek subbasin is the largest of the four subbasins (about 160 mi^2), and the other three subbasins range between about 60 and 70 mi^2. Altitudes of the WRIA range from about 840 ft at the confluence of the Okanogan River and the Columbia River, to about 7,300 ft in the uplands to the east of the Okanogan River.

The climate of WRIA 49 is characterized by warm summers and cold winters and precipitation typical of semi-arid regions. The mean July temperature at Omak, Washington, near the Okanogan River, is about 87°F and the mean January temperature at Omak is about 17°F (Western Regional Climate Center, http://www.wrcc.dri.edu/summary/climsmwa.html, accessed November 25, 2008). Precipitation ranges from about 11 in/yr at Omak to about 16 in/yr at Disautel in the highlands east of the Okanogan River (fig. 1; National Oceanic and Atmospheric Administration, http://www.wrcc.dri.edu/summary/waF.html, accessed November 25, 2008).

The predominant land cover in WRIA 49 and the study area subbasins include shrub/scrub land, evergreen forests, and grassland/pasture/hay (fig. 2). (Land-cover/land-use data were obtained from the National Land Cover Database 2001, downloaded from the Multi-Resolution Land Characteristics Consortium at http://www.mrlc.gov, accessed April 5, 2007). Most agricultural lands in WRIA 49 are in the lowlands adjacent to the Okanogan River. The major population centers also are adjacent to the Okanogan River. Timber operations and recreational land uses generally take place in areas of evergreen forest in the WRIA. Within the study area subbasins, shrub/scrub land cover from about 50 to 60 percent of each subbasin, evergreen forest covers from about 33 to 40 percent of each subbasin, and grassland/pasture/hay cover from about 7 to 18 percent of each subbasin (fig. 2 and table 2). Some of the shrub/scrub land is used for stock grazing. A residential development is currently (2008) under construction in the headwater region of a tributary to Tunk Creek.

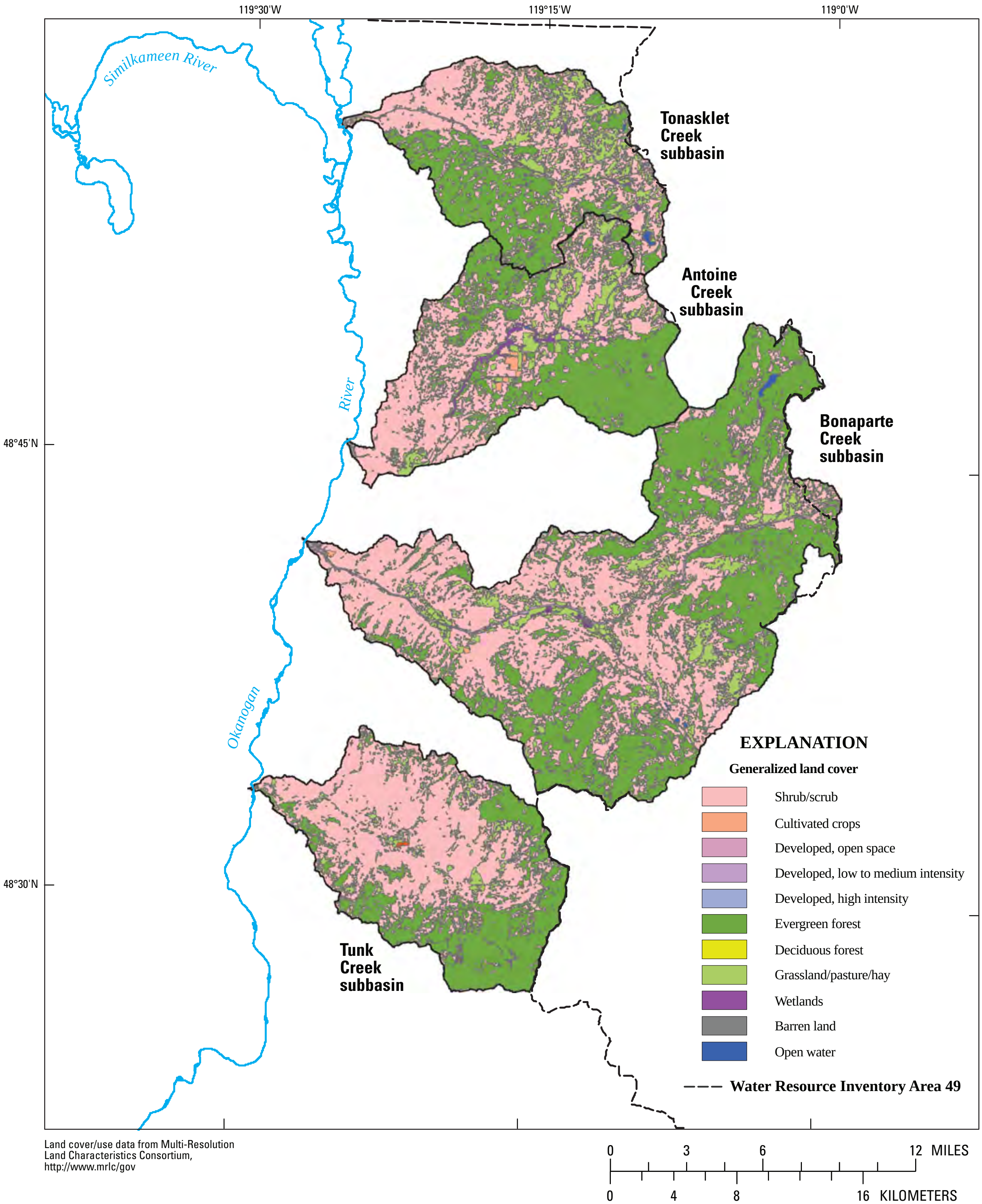

Figure 2. Land cover in the four study area subbasins, Washington.

Table 2. Extents of different land covers in the four study area subbasins, Washington.

[mi^2, square mile]

Subbasin	Land cover	Extent (mi^2)	Percentage of subbasin
Tunk	Shrub/scrub	42.0	58.9
	Cultivated crops	.076	.11
	Developed, open space	.015	.02
	Developed, low to medium intensity	.003	.00
	Evergreen forest	23.9	33.4
	Deciduous forest	.006	.01
	Grassland/pasture/hay	5.15	7.22
	Wetlands	.261	.40
	Open water	.005	.01
Bonaparte	Shrub/scrub	79.5	47.7
	Cultivated crops	.104	.06
	Developed, open space	1.10	.66
	Developed, low to medium intensity	1.28	.77
	Developed, high intensity	.005	.00
	Evergreen forest	66.5	39.9
	Deciduous forest	.004	.00
	Grassland/pasture/hay	17.2	10.33
	Wetlands	.594	.36
	Barren land	.012	.01
	Open water	.305	.18
Antoine	Shrub/scrub	33.9	46.2
	Cultivated crops	.486	.66
	Developed, open space	.459	.63
	Developed, low to medium intensity	.165	.23
	Evergreen forest	27.0	36.8
	Deciduous forest	.011	.02
	Grassland/pasture/hay	10.14	13.8
	Wetlands	1.18	1.61
	Barren land	.000	.00
	Open water	.026	.04
Tonasket	Shrub/scrub	28.9	47.4
	Cultivated crops	.040	.07
	Developed, open space	.436	.72
	Developed, low to medium intensity	.223	.37
	Evergreen forest	19.8	32.6
	Grassland/pasture/hay	11.0	.1
	Wetlands	.403	.66
	Open water	.142	.23

Generalized Hydrogeologic Framework

Unconsolidated deposits, Pleistocene-aged continental drift (table 3) consisting of clay, silt, sand, and gravel generally are the predominant surficial geologic material in the study area. These materials, deposited by the Okanogan Lobe of the Cordilleran ice sheet when it receded following the last, large-scale glaciations in the area (Montgomery Water Group, Inc. and others, 1995), are thickest (in places, several hundreds of feet thick) in the stream valleys. In the upland areas, however, thicknesses may be only a few tens of feet.

Table 3. Areal extents of generalized surficial geologic units in the four study area subbasins, Washington.

[mi^2, square mile]

Subbasin	Unit name	Extent (mi^2)	Percentage of subbasin
Tunk	Unconsolidated deposits	48	66
	Bedrock units	24	34
Bonaparte	Unconsolidated deposits	84	51
	Bedrock units	81	49
Antoine	Unconsolidated deposits	37	51
	Bedrock units	36	49
Tonasket	Unconsolidated deposits	29	48
	Bedrock units	31	52

These materials are the major sources of groundwater in the subbasins, except in those areas where they are thin or are composed of clay or till (a compacted mixture of clay, silt, sand, and gravel). The Tunk Creek subbasin has the highest areal extent (65 percent of the subbasin; fig. 3 and table 3) of surficial unconsolidated deposits of the four subbasins. The areal extent of unconsolidated deposits in each of the other three subbasins is about 50 percent of each subbasin. The unconsolidated deposits are underlain by granitic, andesitic, and metamorphosed rocks forming the bedrock of the Okanogan River basin. Wells that are open in these bedrock units generally provide only enough water to satisfy domestic uses. A part of the southeastern part of the WRIA is underlain by basalts of the Columbia River Basalt Group (Walters, 1974) that can potentially yield more groundwater, but these basalts are not present in the study area subbasins. More detailed information concerning unconsolidated deposits in the subbasins are presented in section, "Subbasin Hydrogeology."

Streamflow-Gaging Stations and Current and Historical Data

During 2008, the WDOE maintained five streamflow-gaging stations in the study area subbasins (fig. 4). Two of the gaging stations (Tunk Creek near Riverside, station 49E080; and Bonaparte Creek near Tonasket, station 49F070) transmit 15-minute interval data by telemetry to WDOE, where they are published on the WDOE website (https://fortress.wa.gov/ecy/wrx/wrx/flows/regions/state.asp). Data are collected intermittently, the interval between visits ranging from biweekly to quarterly, at the remaining three stations (Tonasket Creek near Oroville, station 49H080; Antoine Creek near mouth, station 49G060; and Bonaparte Creek at Aeneas Valley Road, station 49F150), and they also may be found on the WDOE website.

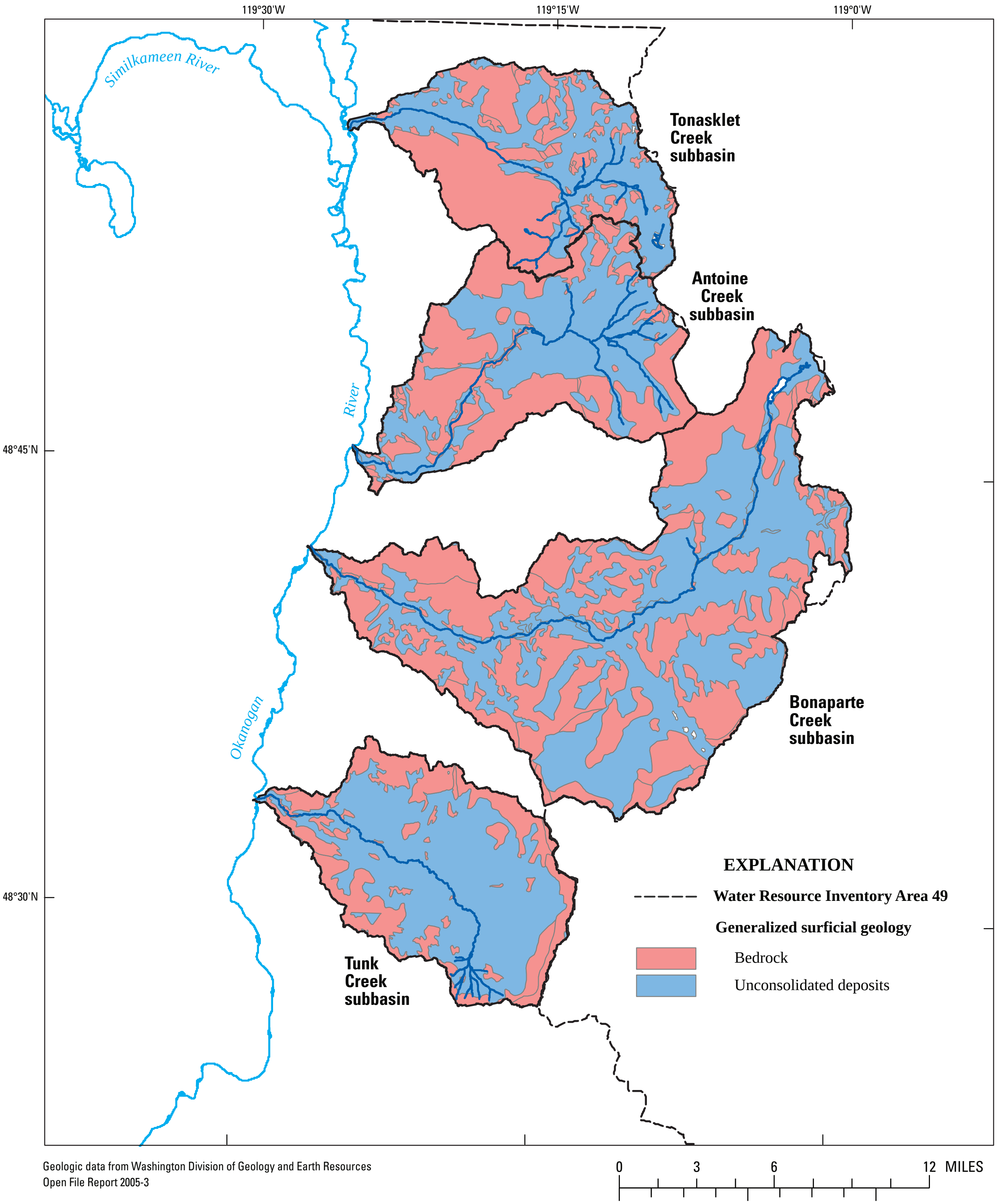

Figure 3. Generalized surficial geology of the four study area subbasins, Washington.

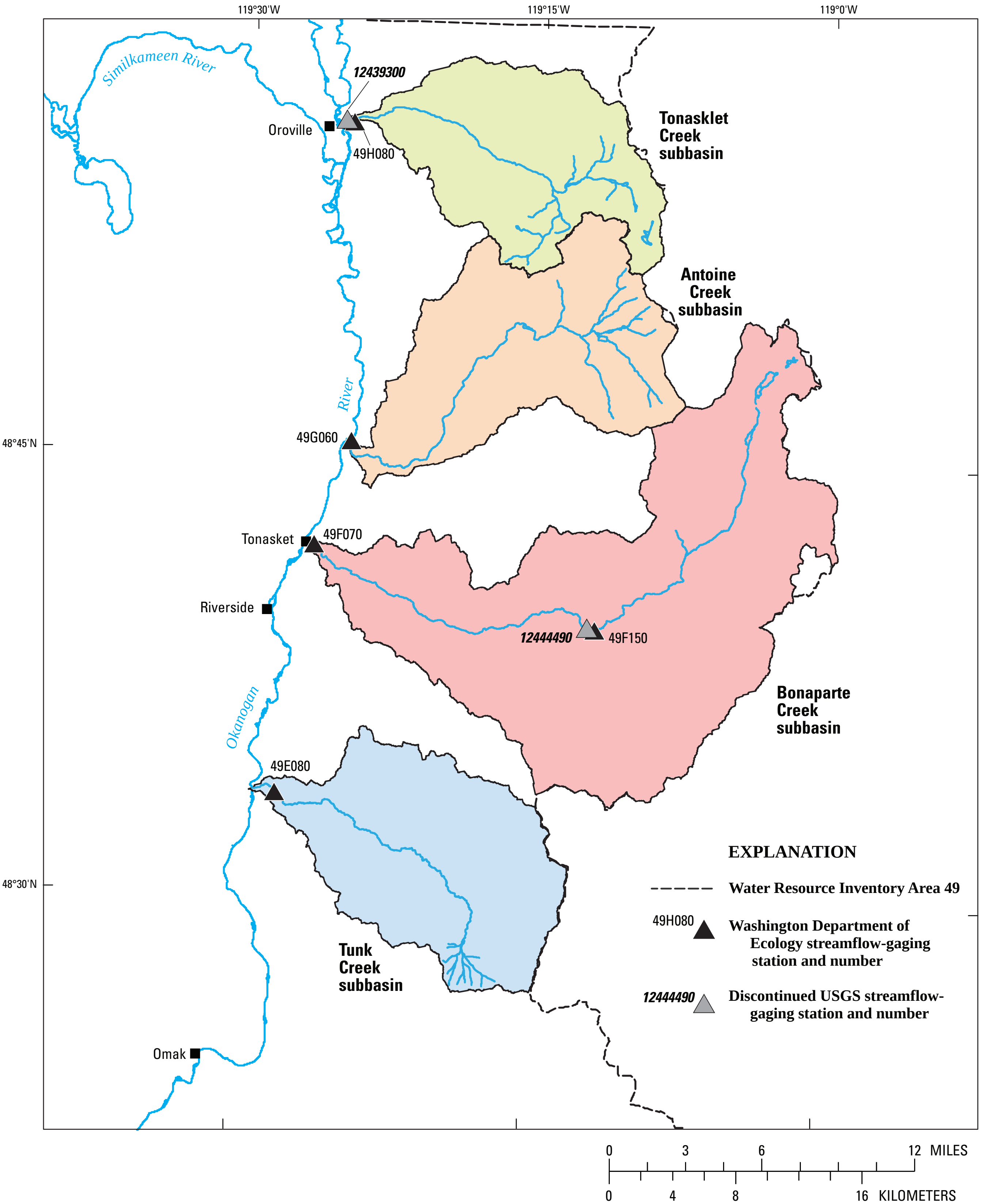

Figure 4. Locations of streamflow-gaging stations maintained by the Washington State Department of Ecology, and historical USGS streamflow-gaging stations in the four study area subbasins, Washington.

In addition, in the past, the USGS operated two continuous-record streamflow-gaging stations in two of the study area subbasins (Tonasket Creek at Oroville, station 12439300; and Bonaparte Creek near Wauconda, station 12444490; fig. 4). Streamflow data for these stations can be accessed at http://waterdata.usgs.gov/wa/nwis/dv. For this investigation, instantaneous streamflow measurements were made at all WDOE and USGS gaging stations except for two in the Bonaparte Creek subbasin (WDOE station 49F150 and USGS station 12444490), where no access was possible.

The gaging station operated by WDOE on Tunk Creek (station 49E080) is about 1.3 mi from the mouth of Tunk Creek and has been operating since August 2002. The annual mean streamflow at the gaging station for water years 2003–07 ranged from an estimated 2 to 7.5 ft^3/s, and the lowest daily mean streamflows (during July, August, or September) ranged from 0.02 to 0.2 ft^3/s. Tunk Creek was never dry at this gaging station.

The WDOE station on Bonaparte Creek (station 49F070) is near the mouth of Bonaparte Creek and has been operating since September 2002. The annual mean streamflow at the gaging station for water years 2003–07 ranged from an estimated 3.4 to 8.2 ft^3/s, and the lowest daily mean streamflows (during July, August, or September) ranged from 0.0 to 0.3 ft^3/s.

The WDOE stations located near the mouths of Antoine Creek (station 49G060) and Tonasket Creek (station 49H080) and on Bonaparte Creek near Aeneas Valley (station 49F150) have been operating since 2002; however, measurements for the Bonaparte Creek gaging station after April 2008 are not listed on the website. Zero flow has been reported at least once during the period of record for each of these gaging stations. The lowest flows occur during the summer and early autumn.

The USGS operated continuous-record streamflow-gaging stations (stream levels recorded every 15 minutes) during 1967–73 on Bonaparte Creek in the central part of the subbasin (station 12444490) and during 1967–91 on Tonasket Creek (station 12439300). The lowest daily mean streamflow in Bonaparte Creek was 0.1 ft^3/s, and zero flow was recorded in Tonasket Creek for many days during the summer and winter.

Methods

Potential sites for streamflow measurements and temporary piezometer installations were identified during a reconnaissance field trip in May 2008. Flow conditions were recorded for streams and their tributaries, as well as accessibility to the streams. About 70 sites were visited in the four study area subbasins and flowing water was observed at about 75 percent of the sites (fig. 5). Sites that were likely to be flowing in late summer and that were accessible for measurement, were chosen for later visits (June and September) to measure stream levels and shallow groundwater levels beneath streams for the purpose of calculating hydraulic gradients (fig. 6).

Measurements of streamflows were made during two field trips in June and September 2008. Streamflows were measured at selected stream sites with an Acoustic Doppler Velocity (ADV) meter in accordance with the surface-water quality-assurance plan for the USGS Washington Water Science Center (Kresch and Tomlinson, 2004). At a few sites in September (site 8 on Tunk Creek and sites 33 and 36 on Bonaparte Creek; fig. 5), flows were low enough that with slight channel modifications, a portable flume was used to measure streamflow depth, which was then converted to streamflow. At site 54 on Tonasket Creek, a volumetric streamflow measurement was made in September. Measured streamflow at the beginning and end of a reach were compared and sites where streamflow was greater than the next upstream site and sites where streamflow was less than the next upstream site were identified.

Measurements of stream levels and shallow groundwater levels beneath streams also were made during two field trips in June and September 2008. Shallow groundwater levels were measured using an electronic tape in temporary piezometers installed about 5-ft deep beneath the streambeds in accordance with the groundwater quality-assurance plan for the USGS Washington Water Science Center (Drost, 2005). Stream levels were measured concurrently relative to the top of the same piezometers. The piezometers consisted of small-diameter pipes with holes drilled near one end that were driven into the streambed near the streamflow-measuring section on the streams. The difference in water levels in the piezometer and the stream is a measure of the head difference, in feet, between groundwater and surface water. Dividing that head difference by the length of pipe beneath the streambed, in feet, gave a value for the hydraulic gradient at that point, in feet per foot. A positive hydraulic gradient indicates the potential for groundwater discharge to the stream, and a negative hydraulic gradient indicates a potential for streamflow recharge to the shallow groundwater system. A zero gradient indicates no net potential flow between surface water and groundwater.

The USGS rates the accuracy of streamflow measurements based on the equipment, character of the measurement section, number of observation verticals, stability of stage, wind and accuracy of depth, and velocity measurements (Rantz, 1982, p. 179). Accuracy ratings of "good" indicate that the measurements are within 5 percent of actual values and "fair" indicate the measurements are within 8 percent of actual values. All streamflow measurements were rated "good" or "fair." Water levels measured in the shallow wells and streams using an electronic tape are assumed to be within 0.01 ft of actual values based on replicate measurements.

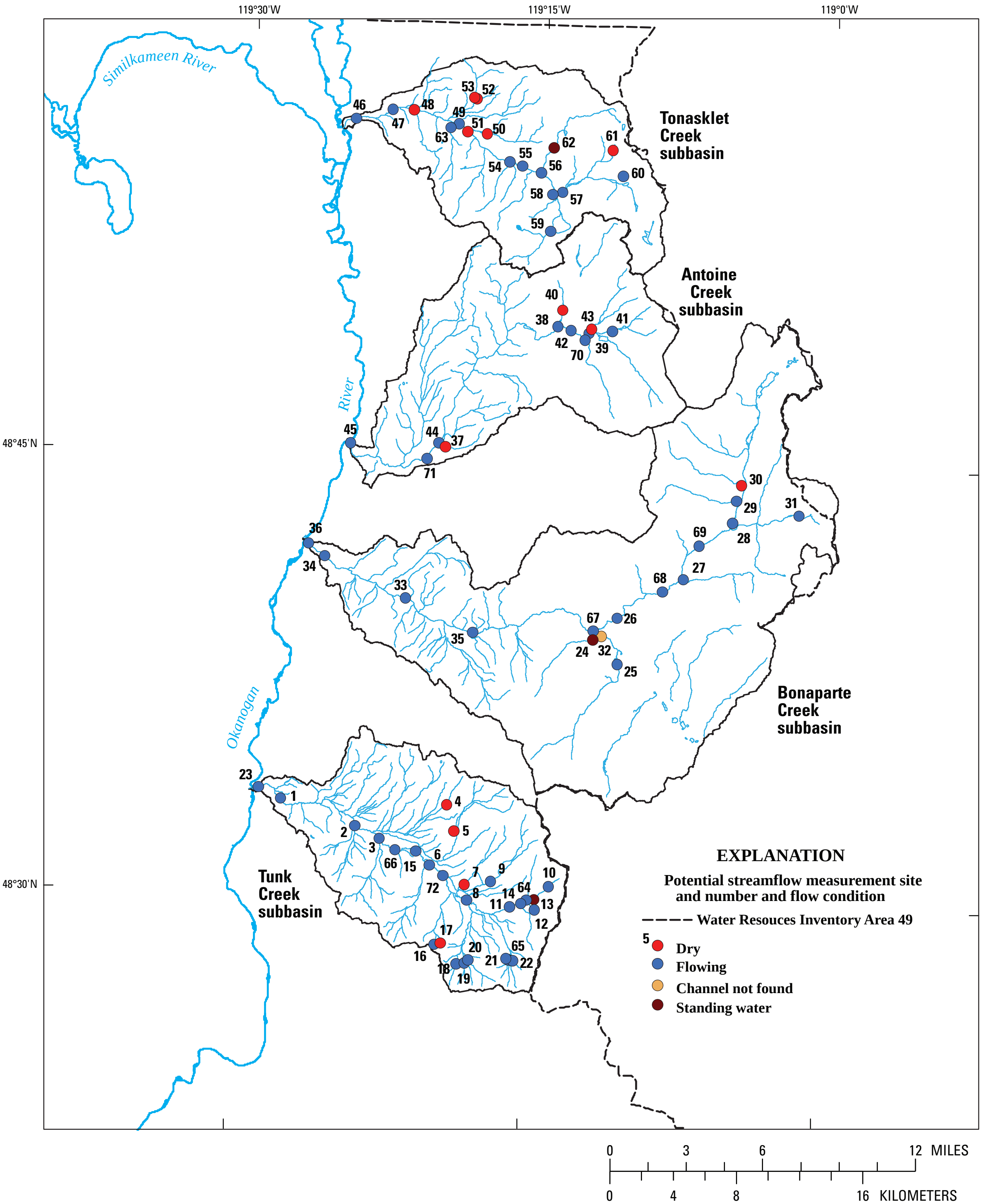

Figure 5. Potential streamflow measurement sites and flow conditions observed by USGS during May 2008 reconnaissance in the four study area subbasins, Washington.

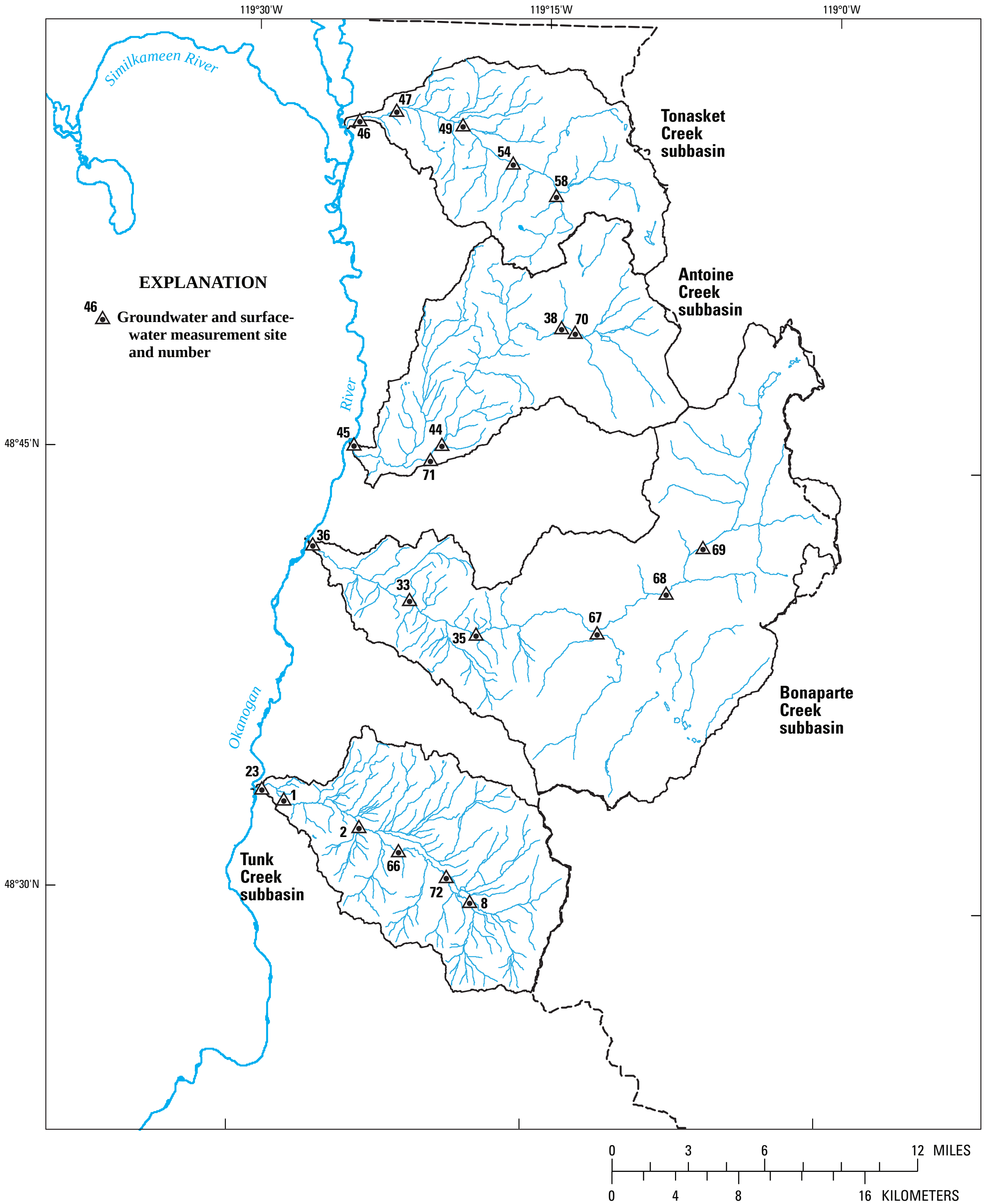

Figure 6. Selected sites for measuring streamflows, stream levels, and shallow groundwater levels beneath streams in the four study area subbasins, Washington.

Streamflow and Water-Level Measurements

About 70 sites were visited in the four study area subbasins in May 2008 and flowing water was observed at about 75 percent of the sites (fig. 5). During this May reconnaissance, estimated streamflows ranged from less than 1 to about 10 ft^3/s. Streamflow was measured at 21 sites in June and September 2008 and ranged from dry and 7.05 ft^3/s (table 4). Location information and calculated streamflow per unit area for each measurement site also are presented in table 4. One site measured in September was not accessible in June, one site measured in June was flooded by backwater (likely from a beaver dam) in September, and four sites were dry. Streamflows also are available on-line at the USGS National Water Information System http://waterdata.usgs.gov/wa/nwis/measurements.

The streamflow measurements are presented again with coincident hydraulic gradient related measurements for June and September 2008 (table 5). Additional metrics related to groundwater/surface-water interactions were calculated, including:

- net differences in streamflow between sequential sites,
- net differences in streamflow per river mile between sequential sites,
- identification of the reach between sequential sites as gaining or losing, where gaining sites had net increased streamflow downstream and losing sites had net decreased streamflow, and
- vertical hydraulic gradients beneath the streambed.

The measurements have some limitations that need to be considered when evaluating groundwater/surface-water interaction. First, the two sets of measurements were made several months apart and represent conditions existing at the specific times only, although the measurements within each set were all made within a few days. Atypical activities occurring during a measurement, such as exceptionally high, short-term pumping from a near-stream well would result in atypical measurements for the time of year. Furthermore, gains or losses of streamflow, as described in this report, refer to the cumulative or net gain or loss in streamflow between two measurement sites. It was beyond the scope of this study to locate and measure the potentially numerous small tributaries and surface-water diversions and returns in the subbasins, so the reported losses and gains in streamflow may be due to processes other than groundwater/surface-water interactions. For example, unmeasured surface-water diversions along a reach identified as losing could potentially be large enough to mask or reduce streamflow gains from groundwater discharge, and unmeasured tributaries and return flows could mask or reduce streamflow losses along a reach identified as gaining. In addition, there could be many localized areas of streamflow losses to and gains from groundwater within a reach that overall had a net gain or loss of streamflow. Regardless of these limitations, some general patterns appear in the data that provide useful insight into groundwater/surface-water interactions in the study area.

Table 4. Site information and measured streamflows in four study area subbasins, Washington, June and September 2008.

[Latitude and longitude are referenced to North American Datum of 1983 (NAD83). USGS, U.S. Geological Survey; mi^2, square mile; ft^3/s, cubic foot per second; (ft^3/s)/mi^2, cubic foot per second per square mile; –, no data]

Map No. (see fig. 6)	Site name	USGS site No.	Drainage area (mi^2)	River mile	Latitude	Longitude	Local No.	Measurement date	Streamflow (ft^3/s)	Streamflow per unit area [(ft^3/s)/mi^2]
	Tunk Creek subbasin									
23	Tunk Creek at Keystone Road, near Barker	12445400	71.7	0.39	48 33 44.6	119 28 44.4	35N/27E-04E	06-16-08	3.75	0.052
								09-16-08	.09	.0013
1	Tunk Creek at Tunk Creek Road, near Barker	12445390	70	1.71	48 33 22.4	119 27 34.6	35N/27E-04R	06-17-08	4.10	.059
								09-18-08	.18	.0026
2	Tunk Creek at Knox Road, near Synarep	12445200	58.6	5.72	48 32 30.7	119 23 43.5	35N/27E-12R	06-17-08	3.97	.068
								09-18-08	.29	.0049
66	Tunk Creek at Ed Figlenski Road, near Synarep	12445190	33.4	7.75	48 31 44.2	119 21 37.3	35N/28E-17L	06-17-08	3.90	.12
								09-18-08	.36	.011
72	Tunk Creek at Soriano's, near Synarep	12445150	19.1	10.68	48 30 54.5	119 19 07.4	35N/28E-22L	09-18-08	.3	.016
8	Tunk Creek at Clough Homestead Road, near Synarep	12445100	15.6	12.37	48 30 05.8	119 17 53.1	35N/28E-26L	06-17-08	3.46	.22
								09-18-08	.079	.0051
	Bonaparte Creek subbasin									
36	Bonaparte Creek at Tonasket	12444550	161	0.35	48 42 05.7	119 26 32.8	37N/27E-16P	06-17-08	3.24	0.020
								09-19-08	.13	.0008
33	Bonaparte Creek below Bannon Creek, near Tonasket	12444530	140	5.24	48 40 19.7	119 21 28.4	37N/28E-30N	06-18-08	2.99	.021
								09-16-08	.022	.0002
35	Bonaparte Creek above Bannon Creek, near Tonasket	12444510	131	8.46	48 39 13.0	119 17 58.5	36N/28E-02D	06-18-08	3.97	.030
67	Bonaparte Creek below Peony Creek, near Wauconda	12444488	109	14.23	48 39 23.9	119 11 58.0	37N/29E-32P	06-18-08	4.41	.040
								09-16-08	1.69	.0155
68	Bonaparte Creek below Little Bonaparte Creek, near Wauconda	12444475	57.2	18.14	48 40 46.7	119 08 17.2	37N/29E-26D	06-18-08	5.92	.10
								09-16-08	.15	.0026
69	Bonaparte Creek above Little Bonaparte Creek, near Wauconda	12444440	44.7	21	48 42 23.3	119 06 27.2	37N/29E-13G	06-18-08	6.65	.15
								09-16-08	.54	.012

Table 4. Site information and measured stream discharges in four study area subbasins, Washington, June and September 2008.—Continued

[Latitude and longitude are referenced to North American Datum of 1983 (NAD83). USGS, U.S. Geological Survey; mi^2, square mile; ft^3/s, cubic foot per second; $(ft^3/s)/mi^2$, cubic foot per second per square mile; –, no data]

Map No. (see fig. 6)	Site name	USGS site No.	Drainage area (mi^2)	River mile	Latitude	Longitude	Local No.	Measurement date	Streamflow (ft^3/s)	Streamflow per unit area [$(ft^3/s)/mi^2$]
	Antoine Creek subbasin									
45	Antoine Creek at U.S. Highway 97, near Ellisford	12444290	73.4	0.23	48 45 33.2	119 24 32.9	38N/27E-27R	06-20-08	0.69	0.009
								09-19-08	.23	.0031
71	Antoine Creek at Whiskey Creek Road, near Ellisford	12444225	54.5	4.29	48 45 05.6	119 20 36.0	38N/38E-31H	06-20-08	.56	.010
								09-17-08	dry	–
44	Antoine Creek at Antoine Breaks Road, near Ellisford	12444220	52.8	5.11	48 45 38.7	119 20 00.5	38N/28E-29L	06-20-08	6.38	.12
								09-17-08	1.6	.030
38	Antoine Creek at Mt Hull Road, near Havillah	12444175	19.3	13.78	48 49 43.0	119 14 02.5	38N/28E-01A	06-19-08	6.56	.34
								09-17-08	.44	.023
70	Antoine Creek near Havillah	12444150	19.1	14.36	48 49 35.9	119 13 21.6	38N/29E-06C	06-19-08	7.05	.37
								09-17-08	.58	.030
	Tonasket Creek subbasin									
46	Tonasket Creek at Oroville	12439300	60.1	0.73	48 56 36.2	119 24 47.7	40N/27E-27A	06-19-08	0.44	0.007
								09-17-08	dry	–
47	Tonasket Creek at Chesaw Road, near MP3 near Oroville	12439280	58.2	2.39	48 56 57.6	119 22 53.2	40N/27E-24M	06-19-08	.64	.011
								09-17-08	dry	–
49	Tonasket Creek at West Corral Road, near Oroville	12439260	42.3	5.26	48 56 32.0	119 19 27.8	40N/28E-29A	06-19-08	.79	.019
								09-17-08	.01	.00024
54	Tonasket Creek at Forest Service Road 3525, near Oroville	12439240	32.2	7.95	48 55 17.5	119 16 47.1	40N/28E-34J	06-19-08	.36	.011
								09-17-08	.006	.00019
58	Tonasket Creek above Dry Creek, near Oroville	12439180	6.46	10.43	48 54 12.7	119 14 31.3	39N/28E-01Q	06-19-08	dry	–
								09-17-08	dry	–

Table 5. Measured streamflows and stream and groundwater levels, and calculated hydraulic gradients and metrics related to groundwater/surface-water interactions at sites in the four study area subbasins, Washington, June and September 2008.

[**Hydraulic gradient**: A positive gradient indicates the potential for groundwater discharge to the stream. The reverse, a negative hydraulic gradient, indicates the potential for streamflow recharge to the groundwater system. mi^2, square mile; ft^3/s, cubic foot per second; $(ft^3/s)/mi$, cubic foot per second per mile; ft btp, feet below top of piezometer; ft/ft, foot per foot; –, no data; na, not applicable]

Map No. (see fig. 6)	Drainage area (mi^2)	River mile	Measurement date	Streamflow (ft^3/s)	Net difference in streamflow (ft^3/s)	Net difference in streamflow per river mile [$(ft^3/s)/mi$]	Gaining or losing reach?	Stream water level (ft btp)	Groundwater level (ft btp)	Hydraulic gradient (ft/ft)
				Tunk Creek subbasin						
June 2008										
23	71.7	0.39	06-16-08	3.75	-0.35	-0.27	losing	2.99	5.05	-0.82
1	70	1.71	06-17-08	4.10	.13	.03	gaining	3.64	3.95	-.17
2	58.6	5.72	06-17-08	3.97	.07	.03	gaining	3.69	3.48	.12
66	33.4	7.75	06-17-08	3.90	.44	.10	gaining	2.46	2.33	.04
72	19.1	10.68	06-17-08	–	–	–	–	–	–	–
8	15.6	12.37	06-17-08	3.46	na	na	na	2.97	2.85	.04
September 2008										
23	71.7	0.39	09-16-08	0.09	-0.09	-0.068	losing	2.5	3.98	-0.74
1	70	1.71	09-18-08	.18	-.11	-.027	losing	3.78	3.89	-.06
2	58.6	5.72	09-18-08	.29	-.07	-.034	losing	3.26	3.3	-.01
66	33.4	7.75	09-18-08	.36	.06	.020	gaining	3.37	3.43	-.03
72	19.1	10.68	09-18-08	.30	.221	.13	gaining	1.9	1.84	.02
8	15.6	12.37	09-18-08	.079	na	na	na	2.96	2.89	.02
				Bonaparte Creek subbasin						
June 2008										
36	161	0.35	06-17-08	3.24	0.25	0.05	gaining	3.97	4.53	-0.28
33	140	5.24	06-18-08	2.99	-.98	-.30	losing	3.11	3.83	-.33
35	131	8.46	06-18-08	3.97	-.44	-.08	losing	1.86	1.67	.05
67	109	14.23	06-18-08	4.41	-1.51	-.39	losing	2.00	2.00	.00
68	57.2	18.14	06-18-08	5.92	-.73	-.26	losing	2.36	2.30	.02
69	44.7	21	06-18-08	6.65				3.08	2.97	.01
September 2008										
36	161	0.35	09-19-08	0.13	-0.09	-0.018	losing	3.66	3.86	-0.09
33	140	5.24	09-16-08	.022	–	–	–	2.84	3.83	-.35
35	131	8.46	09-19-08	–	–	–	losing	–	–	–
67	109	14.23	09-16-08	1.69	1.54	.39	gaining	3.14	3.22	-.07
68	57.2	18.14	09-16-08	.15	-.39	-.14	losing	2.01	2.08	-.02
69	44.7	21	09-16-08	.54	na	na	na	3.78	3.79	-.002

Table 5. Measured stream discharges and stream and ground-water levels, and calculated hydraulic gradients at sites in the four study area subbasins, Washington, June and September 2008.—Continued

[**Hydraulic gradient**: A positive gradient indicates the potential for groundwater discharge to the stream. The reverse, a negative hydraulic gradient, indicates the potential for streamflow recharge to the groundwater system. mi^2, square mile; ft^3/s, cubic foot per second; $(ft^3/s)/mi$, cubic foot per second per mile; ft btp, feet below top of piezometer; ft/ft, foot per foot; –, no data; na, not applicable]

Map No. (see fig. 6)	Drainage area (mi^2)	River mile	Measurement date	Streamflow (ft^3/s)	Net difference in streamflow (ft^3/s)	Net difference in streamflow per river mile [$(ft^3/s)/mi$]	Gaining or losing reach?	Stream water level (ft btp)	Groundwater level (ft btp)	Hydraulic gradient (ft/ft)
Antoine Creek subbasin										
June 2008										
45	73.4	0.23	06-20-08	0.69	0.13	0.03	gaining	3.16	5.05	-0.80
71	54.5	4.29	06-20-08	.56	-5.82	-7.10	losing	2.04	1.95	.02
44	52.8	5.11	06-20-08	6.38	-.18	-.02	losing	3.00	3.00	.00
38	19.3	13.78	06-19-08	6.56	-.49	-.84	losing	1.98	2.08	-.03
70	19.1	14.36	06-19-08	7.05	na	na	na	2.29	2.33	-.01
September 2008										
45	73.4	0.23	09-19-08	0.23	0.23	0.06	gaining	3.75	3.84	-0.04
71	54.5	4.29	09-17-08	0	-1.6	-2.0	losing	–	–	<0
44	52.8	5.11	09-17-08	1.6	1.16	.13	gaining	2.56	2.6	-.02
38	19.3	13.78	09-17-08	.44	-.14	-.24	losing	2.4	2.54	-.04
70	19.1	14.36	09-17-08	.58	na	na	na	2.68	2.59	.03
Tonasket Creek subbasin										
June 2008										
46	60.1	0.73	06-19-08	0.44	-0.2	-0.12	losing	3.49	5.05	-0.72
47	58.2	2.39	06-19-08	.64	-.15	-.05	losing	2.48	5.65	-.92
49	42.3	5.26	06-19-08	.79	.43	.16	gaining	2.75	2.75	.00
54	32.2	7.95	06-19-08	.36	.36	.15	gaining	2.41	2.93	-.07
58	6.46	10.43	06-19-08	0	na	na	na	–	–	<0
September 2008										
46	60.1	0.73	09-17-08	0	0	0	neutral	–	–	<0
47	58.2	2.39	09-17-08	0	-.01	-.0035	losing	–	–	<0
49	42.3	5.26	09-17-08	.01	.004	.0015	gaining	3.13	3.25	-0.12
54	32.2	7.95	09-17-08	.006	.006	.0024	gaining	2.01	2.16	-.15
58	6.46	10.43	09-17-08	0	na	na	na	–	–	<0

Groundwater/Surface-Water Interactions

Groundwater/surface-water interactions generally were characterized for the study area subbasins based on changes in measured streamflows between June and September, net gains and losses of streamflow along the lengths of the streams, and hydraulic gradients between surface water and shallow groundwater at measurement sites. Streamflows and hydraulic gradients represent groundwater/surface-water interactions at different spatial scales. A measured net gain or loss of streamflow is a cumulative value for an entire reach that spans between two measurement points. In contrast, a positive (potential upward flow) or negative (potential downward flow) hydraulic gradient represents conditions at a specific point at the beginning or end of a reach. Thus, it is possible to identify seemingly conflicting conditions such as a losing reach that is bounded at one of both ends with sites that have positive hydraulic gradients. Such data indicate that the losing areas of the reach are located somewhere between the two measurement points. The interactions were further evaluated with regard to available information on the hydrogeologic framework of the subbasins and the distribution of known existing wells.

General Streamflow Characteristics

The most obvious difference between the June and September streamflow measurements (table 4) is that there was substantially less streamflow in all subbasins during September 2008 than in June 2008. Beyond that, streamflow in each of the subbasins had unique characteristics.

Tunk Creek subbasin.—Measured streamflow changed very little along the length of Tunk Creek during June and September, although the September streamflows were about an order of magnitude smaller than the June streamflows (table 4 and fig. 7*A*). As is typical for drainage basins with moderate topographic relief, the June streamflow per unit area decreased in a downstream direction, which is likely a result of more precipitation-driven runoff and groundwater recharge in the high-altitude areas of the Tunk Creek subbasin. During September, however, streamflow per unit area at the uppermost measurement site (site 8, RM 12.37) was about the same as at a mid-basin measurement site (site 2). That change was likely a result of either limited groundwater storage capacity and streamflow to the stream in the upper basin with presumably thinner unconsolidated deposits, or possibly relatively greater consumptive use of water in the upper basin. Given that the unconsolidated deposits in Tunk Creek generally are less than 100-ft thick and have relatively low permeability (Walters, 1974), the upper basin likely does have limited groundwater storage capacity and discharge to the stream. The streamflows measured by USGS in June and September 2008 at site 1 in Tunk Creek were consistent with the 2003–07 June and September streamflows from WDOE streamflow-gaging station 49E080, Tunk Creek near Riverside, which is adjacent to site 1.

Bonaparte Creek subbasin.—In contrast to Tunk Creek, measured June streamflow in Bonaparte Creek decreased consistently from the uppermost to the lowermost measurements sites (table 4 and fig. 7*B*). The September streamflows were substantially smaller than those measured in June, although changes in streamflow along the length of the creek were quite variable. Similar to Tunk Creek, the June streamflow per unit area decreased in a downstream direction, although the amount of streamflow per unit area was only about one-half that measured in Tunk Creek. Assuming similar amounts of precipitation for Tunk and Bonaparte Creek subbasins, these data indicate that in Bonaparte Creek, more runoff either goes into groundwater storage or is used consumptively (lost to evapotranspiration). Given the potentially large volume of groundwater storage in the mid-basin parts of Bonaparte Creek subbasin (the Aeneas Valley area located to the southeast of site 67, fig. 6) and a correspondingly large amount of groundwater pumping (Walters, 1974), there appears to be substantial consumptive use of groundwater in the Bonaparte Creek subbasin.

Antoine Creek subbasin.— Measured streamflows and calculated streamflows per unit area during June in Antoine Creek at and upstream of RM 5.11 were substantially larger than comparable streamflows in the other subbasins (table 4, fig. 7*C*). In contrast, June streamflows at the two measurement sites downstream of RM 5.11 in Antoine Creek were substantially smaller than streamflows in the lower reaches of Bonaparte and Tunk Creeks. The substantial decrease in June streamflow occurred downstream of a long canyon and upstream of an intensively irrigated area, about 4 mi upstream of the mouth of Antoine Creek. The agricultural area is irrigated with groundwater (Walters, 1974). There are a number of very productive irrigation wells in the area between Antoine and Siwash Creeks near the Okanogan River (Walters, 1974). It is possible that groundwater pumping was at least partly responsible for the rapid decrease in Antoine Creek streamflow during June. However, the largest decrease in streamflow was measured at site 71 (RM 4.29; fig. 6) that is upstream of the irrigated area and at the mouth of the canyon where unconsolidated deposits are likely of limited thickness. Thus, a surface-water diversion for irrigation may be a more likely explanation for the decreased June streamflow.

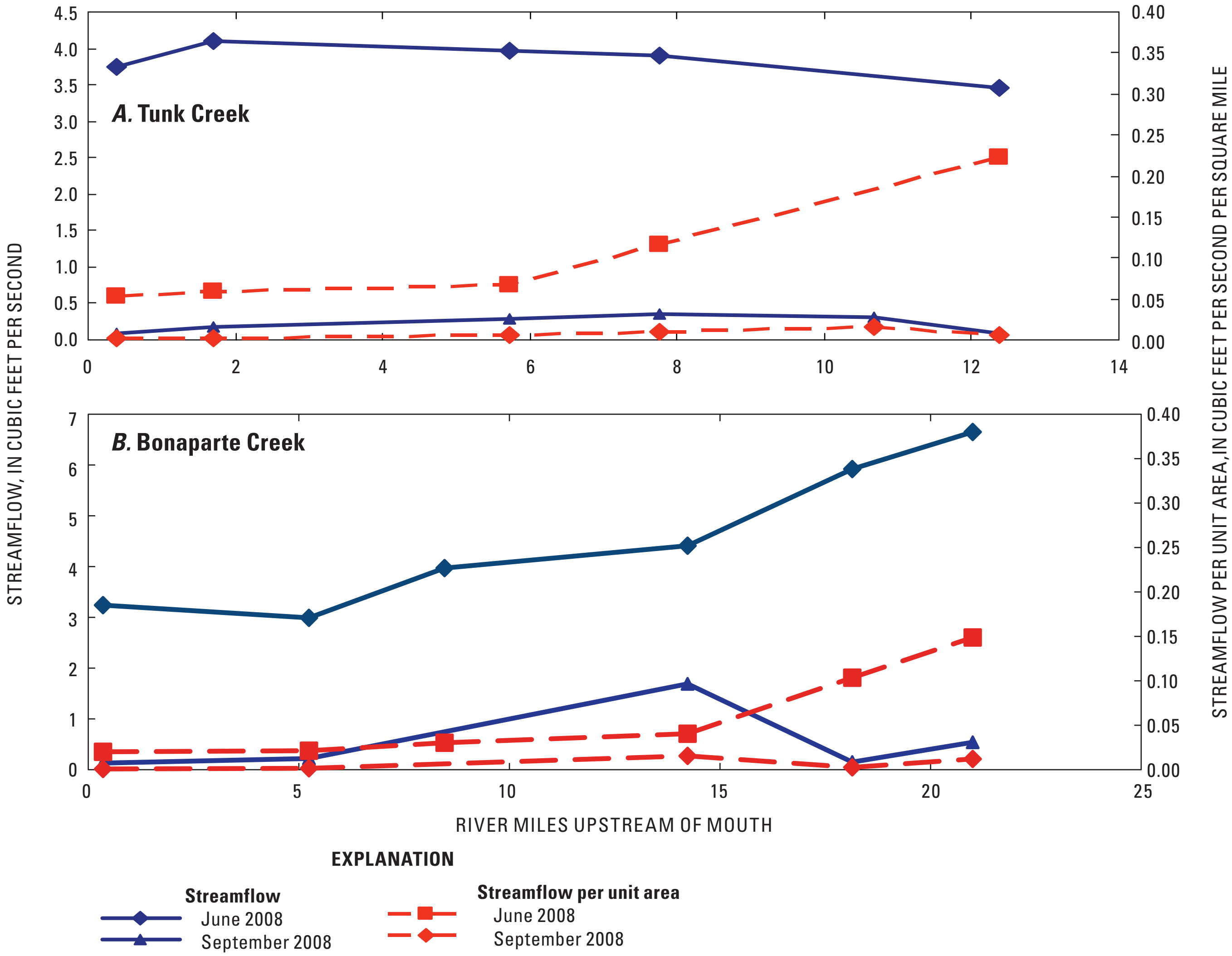

Figure 7. Streamflow and streamflow per unit area in the four study area subbasins, Washington, June and September 2008.

Tonasket Creek subbasin.—Measured streamflows and calculated streamflow per unit area in Tonasket Creek were substantially less than those in the other subbasins (fig. 7D). Even in June, the uppermost measurement site in Tonasket Creek was dry, and the largest value of streamflow per unit area [0.019 (ft^3/s)/mi^2] was only about one-eighth of the largest value for the other three subbasins. The highest altitudes in Tonasket Creek subbasin are 1,000 to 2,000-ft lower than altitudes in the other subbasins (table 1), so precipitation in Tonasket Creek subbasin may be slightly less, but that cannot account for the substantial difference in streamflow per unit area during June and September. These data indicate that in Tonasket Creek, there is very limited groundwater recharge from winter/spring runoff and generally little groundwater discharge and storage. Additionally, data are consistent with the hypothesis of exceptionally large consumptive use of groundwater and (or) surface water in the subbasin. Because there are not an exceptional number of wells in the subbasin and there does not appear to be an appreciable volume of groundwater storage (Walters, 1974), naturally limited groundwater resources in the subbasin are indicated. The instantaneous streamflows measured by USGS in June and September 2008 at the lowermost site in Tonasket Creek (0.44 and 0 ft^3/s) were lower than the average monthly June and September streamflows reported for 1967–79 for the discontinued USGS streamflow-gaging station at the same location (2.5 and 1.0 ft^3/s). However, the range of average daily streamflows during June and September for 1967–79 at the discontinued USGS streamflow-gaging station was 0.0 to greater than 10 ft^3/s, and the 2008 measurements fall within that range.

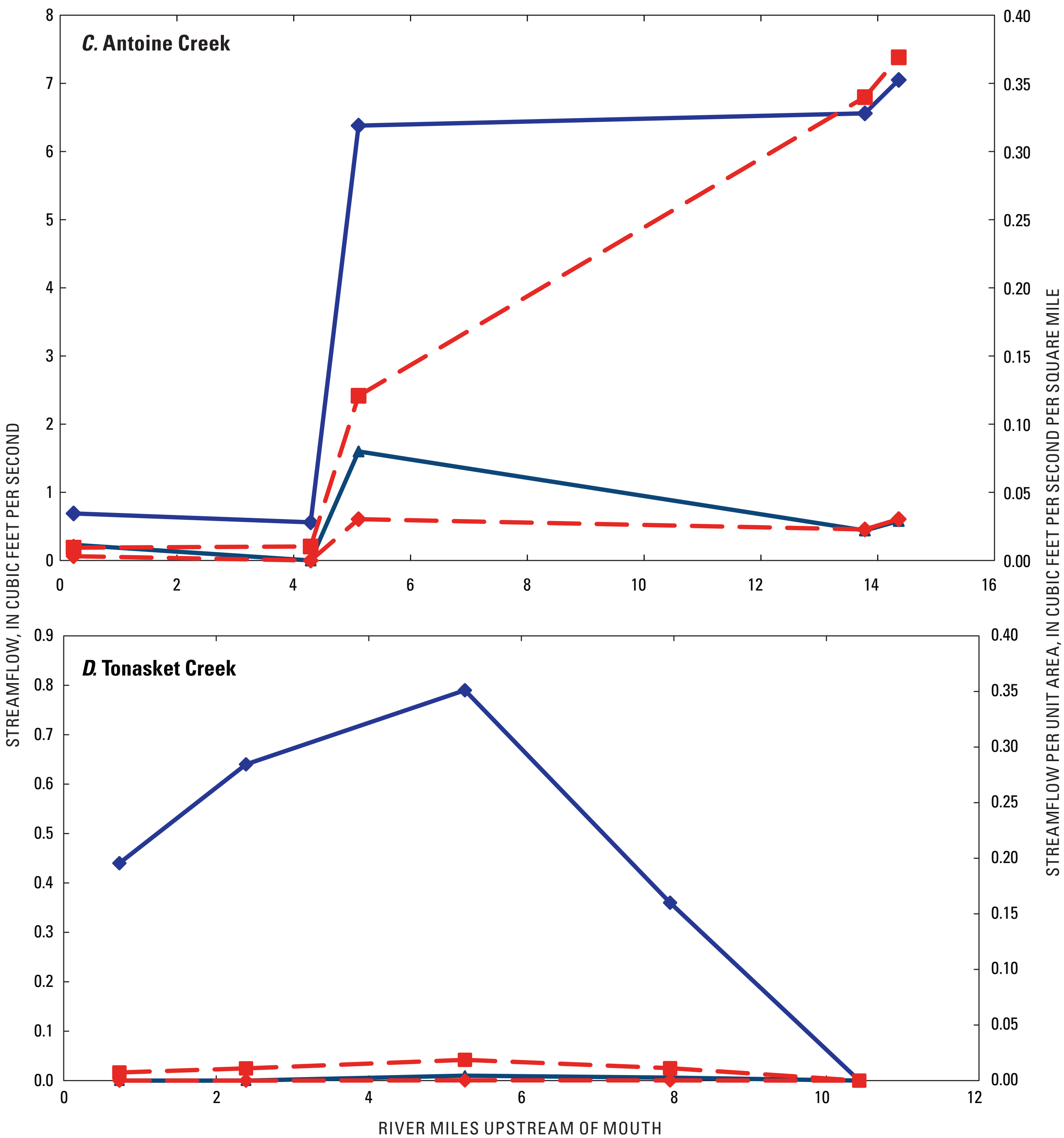

Figure 7.—Continued.

Streamflow and Hydraulic Gradient

Changes in measured streamflow between sites indicated net gains or losses along the reach of stream between the sites that were at least in part due to groundwater discharge to the stream or streamflow recharge to groundwater. The direction of the hydraulic gradient at a measurement site indicated groundwater discharge to surface water (positive gradients) or surface-water recharge to groundwater (negative gradients) at that specific point, which corresponds to either end of a reach.

During June 2008, 10 of 17 reaches were identified as losing, and 11 of 21 measurement sites had negative hydraulic gradients (table 5, fig. 8). During September 2008, 9 of 17 reaches were identified as losing, and 18 of 21 measurement sites had negative hydraulic gradients. All four streams appeared to lose water to the groundwater system as they neared the Okanogan River. The most substantial losses were for Antoine Creek, as previously discussed. It is likely that regardless of groundwater pumping, streamflow losses would occur as the streams flow across the relatively permeable floodplain deposits of the Okanogan River. The losses possibly are exacerbated by pumping from the relatively abundant wells along the Okanogan River, but measured streamflow data alone cannot determine the effects of pumping. Overall, there was good correspondence between losing reaches and negative hydraulic gradients at the sites at the ends of the reaches. The only neutral reach (lack of a gain or loss in streamflow) identified was in lower Tonasket Creek in September when both measurement sites (sites 46 and 47) were dry. This does not necessarily indicate a lack of groundwater and surface-water interaction, but rather the cumulative gains and losses between measurement sites equal to 0.0 ft^3/s.

In June, hydraulic gradients in Tunk and Bonaparte Creeks at upstream sites (sites 66 and 2 on Tunk Creek, and sites 69 and 68 on Bonaparte Creek) were positive, indicating groundwater was flowing into the stream at these sites. The hydraulic gradient at site 35 on Bonaparte Creek (RM 8.46) also was positive. Hydraulic gradients at other sites on the two creeks were less than or equal to zero. The hydraulic gradient at site 71 (RM 4.29) on Antoine Creek was positive in June. All other sites on Antoine Creek exhibited negative hydraulic gradients and were near zero, or slightly less than zero, indicating no or little water movement between the stream and the groundwater system. All streams had negative hydraulic gradients at the sites near their mouths. In September, most sites had negative hydraulic gradients, the exceptions being a few upper basin sites. It is not possible to quantify the hydraulic gradient at sites with zero flow, but it is known that the gradient is negative. Thus, zero flows at the two downstream-most sites on Tonasket Creek (sites 46 and 47, fig. 6) indicate negative hydraulic gradients.

In Tunk Creek during June (fig. 8*A*), groundwater discharged to the creek at the upstream sites and streamflow was lost from the creek at the downstream sites. Tunk Creek flows through a thick layer of unconsolidated deposits from about RM 12.37 (site 8) to slightly upstream of RM 5.72 (site 2), and the stream gained water from these sediments in June and lost water to these sediments during September. Downstream of RM 5.72 (site 2), the unconsolidated deposits thin and the creek flows through an area where bedrock is near or at land surface. Near RM 1.71 (site 1), unconsolidated deposits again forms the near-surface geologic material and the creek lost water from that point to its mouth during June and September.

Hydraulic gradients measured in Bonaparte Creek were similar in June and September (fig. 8*B*). Site 33 (RM 5.24), downstream of the ‘bedrock sill segment’ defined by Packard and others (1983) had a relatively large negative hydraulic gradient in June and September. Site 33 is located in a losing reach (Packard and others, 1983). Downstream of site 33, the gradient was less steep but still negative.

Antoine Creek lost water between the two most upstream measurement sites (sites 70 and 38, fig. 6; RM 14.36 and 13.78, fig. 8*C*) during June and September. Based on drillers’ logs, the thickness of unconsolidated deposits in this part of the subbasin appears to be as much as about 200 ft. About 10 river miles downstream, after the creek emerges from the narrow, bedrock canyon, the gradients were slightly less negative (sites 44 and 45, fig. 6). In June, the gradient was zero at site 44 (RM 5.11), positive about 0.8 mi downstream (site 71 at RM 4.29), then strongly negative near the mouth of the creek (site 46 at RM 0.73). The positive to neutral hydraulic gradients, combined with the large loss of streamflow at RM. 4.29, indicates that a surface-water diversion may be the cause of the decreased streamflow.

The uppermost site on Tonasket Creek (site 58, fig. 6; RM 10.43, fig. 8*D*) was observed flowing only during the May reconnaissance (it was dry in June and September), and the number of measurement sites on Tonasket Creek with zero flow increased from one to three between June and September. The next two downstream sites on Tonasket Creek (site 54 at RM 7.95 and site 49 at RM 5.26) had negative or neutral hydraulic gradients in June and September (fig. 8*D*). At the downstream sites (site 47 at RM 2.39 and site 46 at RM 0.73) in June, the hydraulic gradients were more negative, and in September both sites had zero flow. Considering the surficial geology of the subbasin, it is possible there are reaches of the creek that are gaining. Between sites 49 and 54, bedrock approaches land surface or may be exposed, which could lead to groundwater moving upward and entering the creek. Very few drillers’ logs were available for this area to confirm this interpretation. Downstream of site 49 to the mouth, the creek channel is underlain by unconsolidated deposits, with thicknesses greater than 150 ft in some places, that would be expected to coincide with negative hydraulic gradients and streamflow losses to groundwater.

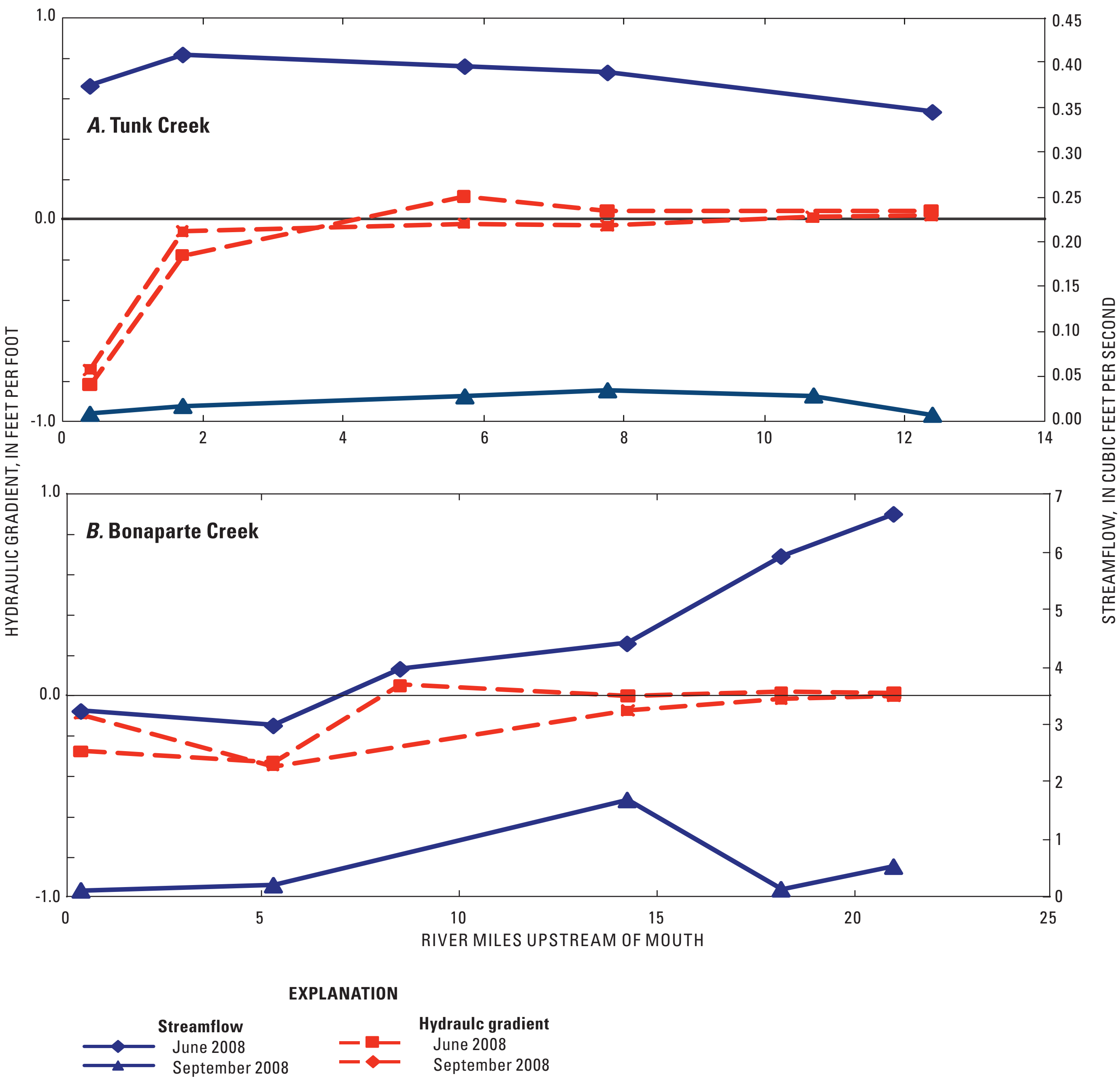

Figure 8. Hydraulic gradients and streamflow for four study area subbasins, Washington, June and September 2008

Subbasin Hydrogeology

A summary evaluation of subbasin hydrogeology was completed by compiling information from available well logs and recent surficial geologic maps and comparing it to previously published descriptions (Walters, 1974) to refine understanding of hydrogeologic features. The logs are not an ideal source of information largely because different drillers' describe subsurface materials differently, and because there is inherent uncertainty in the driller-provided well locations on the well logs that are, in most cases, accurate to a 40-acre quarter-quarter section (the well-log information was not field checked by USGS). In spite of these limitations, logs were of value because the vast majority of the 1,041 logs reviewed were for wells constructed after the Walters (1974) report was published.

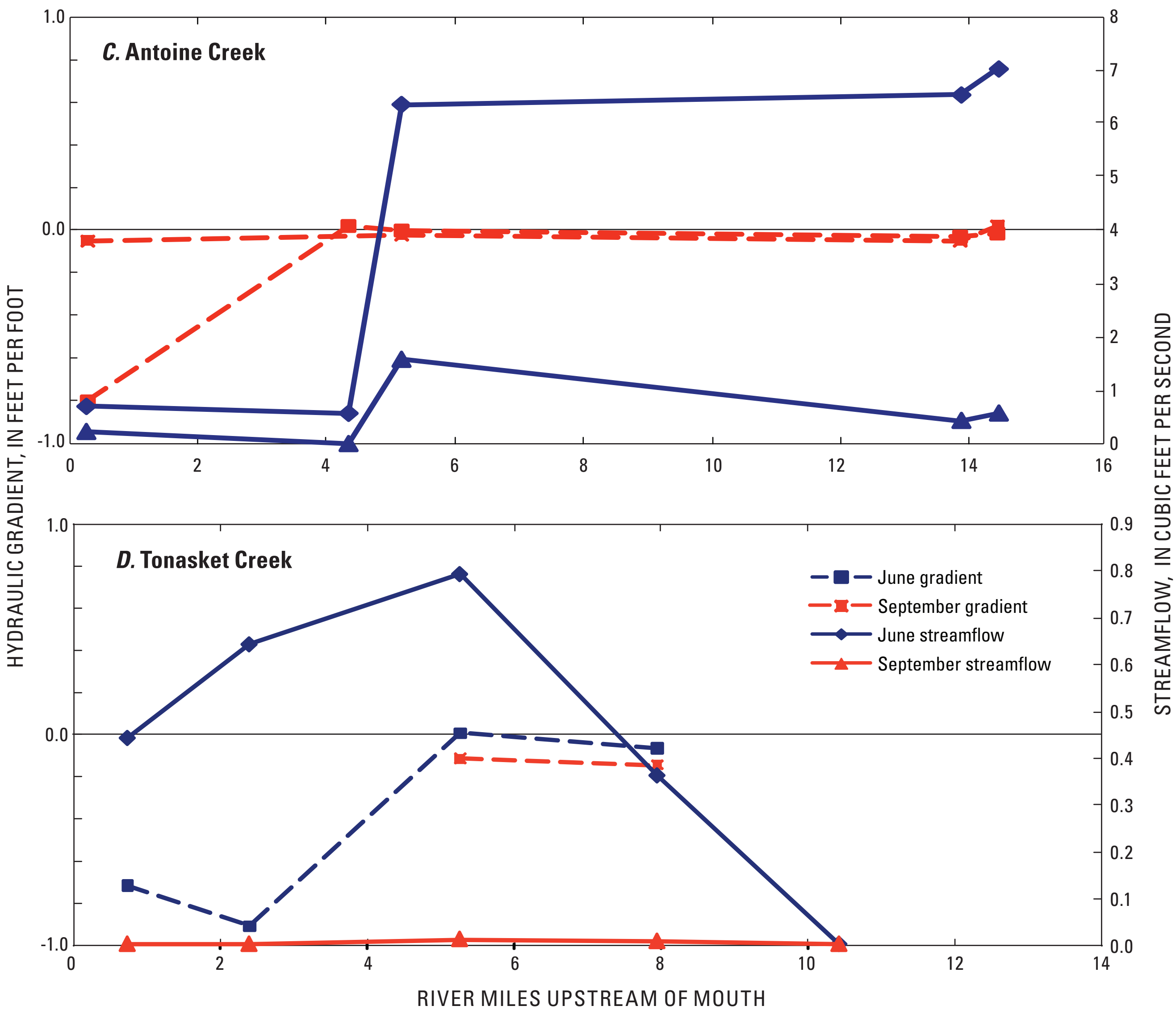

Figure 8.—Continued.

There is a substantially greater extent of unconsolidated surficial deposits in the study area subbasins, shown by the 2005 maps (Washington Department of Natural Resources, 2005; fig. 3) compared to plate 1 in Walters (1974). However, the distribution of wells in study area subbasins for which drillers' logs were reviewed (fig. 9) generally coincides with the extent of quaternary alluvium and terrace deposits mapped by Walters (1974). The Washington Department of Natural Resources (2005) maps likely include significant areas of mapped unconsolidated deposits that are unsaturated or very thin, so the expanded surficial extents of unconsolidated deposits do not likely reflect newly found expanded groundwater storage.

Wells constructed in study area subbasins after 1974 were compiled according to depth to bedrock (fig. 10) for comparison to information presented by Walters (1974). Depth to bedrock is essentially equivalent to thickness of unconsolidated deposits. Overall, the Bonaparte Creek subbasin stands out as having about three times more wells in total and wells deeper than 99 ft compared to the other subbasins. This is indicative of Bonaparte Creek subbasin having the most ample groundwater resources. This is consistent with Walters' estimates of groundwater storage in the Siwash-Bonaparte-Chewiliken subarea of 200,000 acre-ft, in the Tunk-Omak subarea of 60,000 acre-ft and in the Tonasket-Antoine subarea of 70,000 acre-ft. Tonasket Creek subbasin has the fewest and the shallowest wells, which is indicative of having the most limited groundwater resources. This is consistent with the extremely low streamflow per unit area values calculated from streamflows measured in June and September 2008, that are in turn indicative of naturally limited groundwater storage and streamflow needed to sustain summer low flows.

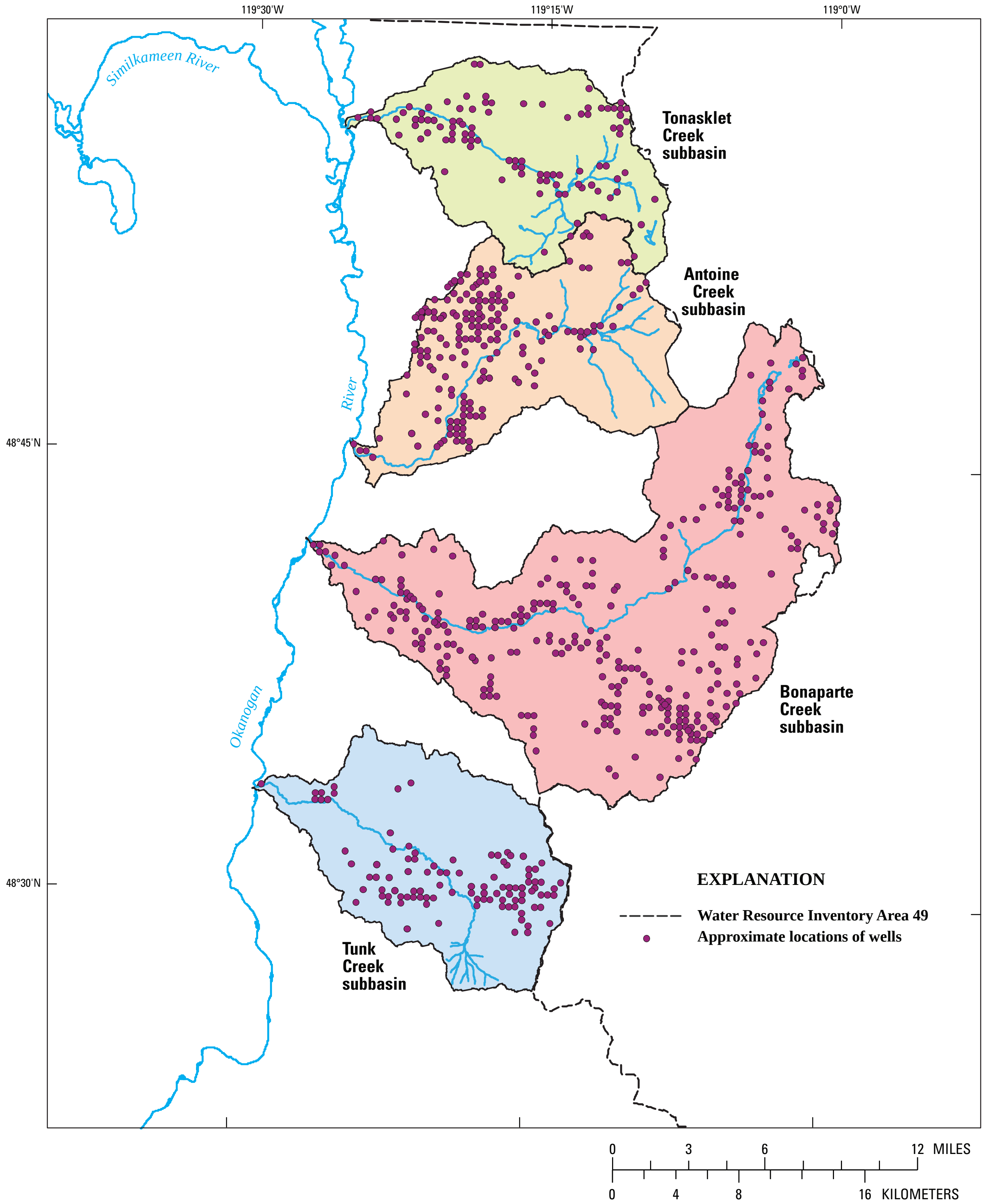

Figure 9. Approximate locations of wells for which driller's logs were reviewed in the four study area subbasins, Washington.

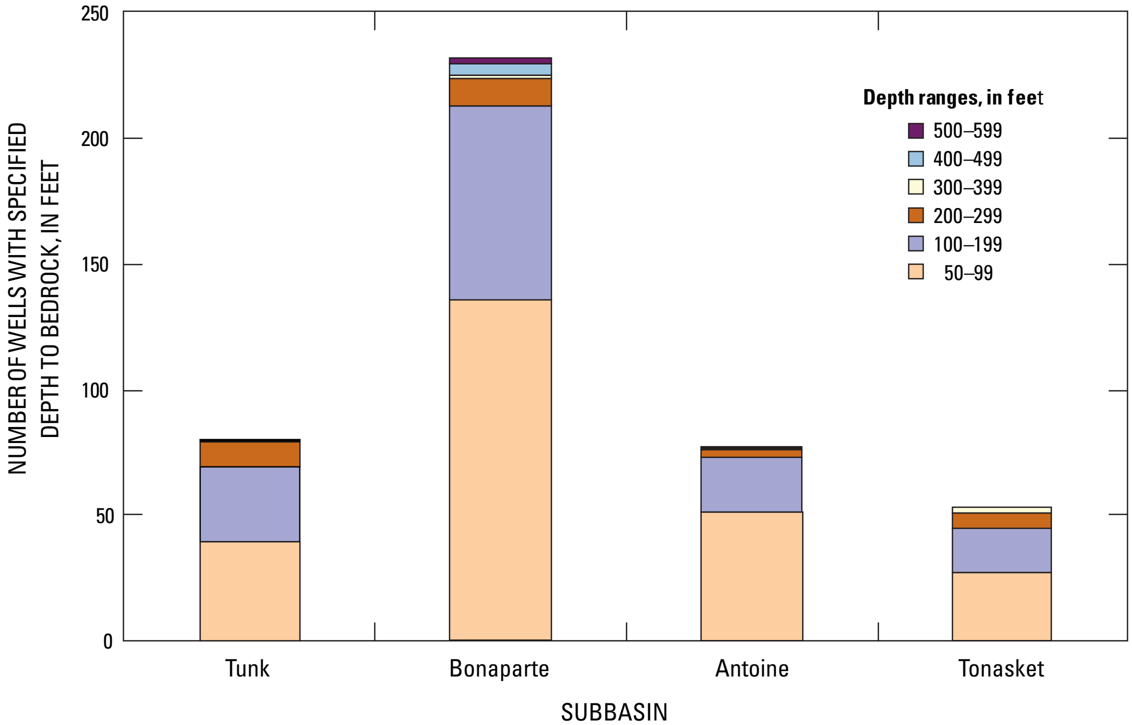

Figure 10. Numbers of post-1974 constructed wells with specified ranges in depth to bedrock in the four study area subbasins, Washington.

One conclusion from the Initial Watershed Assessment (Montgomery Water Group, Inc. and others, 1995) was that some locations in the study area may have deep confined aquifers within unconsolidated deposits that may not be in connection with nearby surface water. Most drillers' logs showing well depths greater than 100 ft indicate multiple potential confining layers, such as blue or gray clays or various cemented units, but evaluating the continuity and hydraulic characteristics of confining layers was beyond the scope of this investigation.

About 66 percent of the Tunk Creek subbasin is mantled with unconsolidated deposits, the highest percentage of the four study area subbasins. The relatively high percentage of unconsolidated deposits in the subbasin is consistent with the relatively constant streamflow measured along the length of the creek in June and September 2008. This is because the extensive deposits can store groundwater along most of the length of the Tunk Creek mainstem. Because nearly one-half of the drillers' logs for wells in the subbasin indicate sediment thicknesses of less than 100 ft, there is a high potential for groundwater withdrawals to affect groundwater discharge to streams.

About one-half of the Bonaparte Creek subbasin is mantled with unconsolidated deposits, and depths to bedrock may exceed 300 ft especially near the center of the subbasin following the course of the Bonaparte Creek streambed. Most well logs with depths to bedrock greater than 300 ft for the Bonaparte Creek subbasin were located in the lowlands immediately adjacent to the Okanogan River and are not typical of unconsolidated deposits farther upstream in the subbasin.

About one-half of the Antoine Creek subbasin is mantled with unconsolidated deposits. Most of these deposits are in the upper basin, although about 16 percent lies within about 5 river miles of the mouth of the creek (fig. 3). Drillers' logs indicate that the unconsolidated deposits in this lower part of the subbasin may be relatively thin, about 100 ft thick or less. Measured streamflows abruptly decreased by a substantial amount in this lower part of the subbasin. Antoine Creek flows through a deep and narrow canyon upstream of this location; the downstream end of which is about 5.5 mi from the mouth of the creek. The canyon is about 4.6 mi long and about 150–200 ft deep. Based on the available logs, the thickest layer of unconsolidated deposits exist around the town of Havillah, Washington, near RM 14. Thicknesses exceed 200 ft in this area.

Again, about one-half of the surface is mantled with unconsolidated deposits in the Tonasket Creek subbasin, and most of those deposits are in the northern and eastern parts of the subbasin. Surface and near-surface bedrock is in the southwestern part of the subbasin. Based on information contained in the drillers' logs, the thickest layer of unconsolidated deposits, exceeding 300 ft, is between 2 and 5 mi from the mouth of the creek. Thicknesses in most other areas of the subbasin range from a few feet to greater than 100 ft.

Data Gaps and Suggestions for Further Study

Low summer streamflows that have a high potential for being impacted by groundwater withdrawals appear to indicate that groundwater storage may be limited in most parts of the study area subbasins. However, given the limited precipitation and groundwater storage capacity, together with permeable unconsolidated deposits along most of their lengths, the creeks measured during this investigation also would likely lose summer streamflow to groundwater over much of their lengths even without groundwater withdrawals. These conditions make it difficult to parse out the specific effects of groundwater pumping on streamflow without intensive measurements and evaluations.

Given those difficulties, it would be expedient to select more limited, high-interest areas where detailed quantitative assessments of groundwater/surface-water interactions would be of most use. The USGS Bonaparte Creek study (Packard and others, 1983) is a reasonable starting point for what a detailed quantitative assessment of groundwater/surface-water interactions would include. In addition, it would be informative to field-locate surface-water diversions and pumping wells with estimates or measurements of the diversion and pumpage amounts, and to use pressure transducers and recorders in selected near-stream wells to measure pumping-induced changes in water levels.

Characterizing possible deep, confined aquifers within unconsolidated deposits that may not be in connection with nearby surface water also would require investigation that again would benefit by focusing on a few limited, high-interest areas. As previously described, most drillers' logs showing well depths greater than 100 ft indicate multiple potential confining layers, such as blue or gray clays or various cemented units. However, the presence of such layers alone is not indicative of an unconnected deep aquifer. It seems unlikely that a deep, confined, unconnected aquifer exists in the relatively limited unconsolidated deposits of the subbasins. That is because the underlying and surrounding bedrock generally is of low permeability, so recharge to a deep aquifer with any appreciable groundwater resource would have to originate from the overlying sediments, and streamflow from a deep aquifer would need to be through the overlying sediments in different locations. By definition, the deep aquifer would thus be in connection with nearby surface water. It would be possible to better characterize the nature and timing of groundwater/surface-water interactions, such as when pumping groundwater at a given time may affect streamflow. A numerical groundwater-flow model would greatly assist in the evaluation, as was done for WRIA 59 in Stevens County (Kahle and others, 2003). Such a characterization would require more intensive evaluations of the hydrogeologic framework of the unconsolidated deposits and their hydraulic properties. It is unlikely that there are enough existing wells to definitely characterize any deep confined aquifers, so drilling of new monitoring wells would be required. Geophysical logging methods could be used to further characterize the lithology at those locations. Again, it would likely be difficult to parse out the specific effects on streamflow of groundwater pumping from a deep, confined aquifer compared to the existing pumping from shallower unconfined aquifers, even with new monitoring wells.

Summary and Conclusions

The Okanogan Conservation District (OCD) is the lead agency of a group of local government agencies and citizens undertaking the planning and implementation of a long-range watershed plan for the Okanogan River basin in north-central Washington. The plan will be used to meet the needs of current and future water demands in the basin while also working to protect and improve its natural resources. Part of the planning phase includes an assessment of the groundwater/surface-water interactions in tributaries to the Okanogan River. The OCD selected four subbasins tributary to the Okanogan River (Tunk, Bonaparte, Antoine, and Tonasket Creeks) and requested that the U.S. Geological Survey (USGS) collect and evaluate data to better understand groundwater/surface-water interactions in those subbasins.

The objective of this study was to describe the groundwater/surface-water interactions in unconsolidated deposits in the tributary subbasins. Fieldwork included streamflow measurements and shallow groundwater level measurements beneath the streams in the subbasins. In addition, geologic and hydrogeologic information for the subbasins was obtained from previously published reports, surficial geologic maps produced by the Washington State Department of Natural Resources (WDNR), and from drillers' logs on file at the USGS Washington Water Science Center or downloaded from the Washington State Department of Ecology database of drillers' logs.

Granitic, andesitic, and metamorphosed rock underlie most of the Okanogan River basin. Wells open in these bedrock units generally provide only enough water to satisfy domestic uses. The Okanogan Lobe of the Cordilleran ice sheet overrode the bedrock units and as the ice sheet receded, it deposited layers of clay, silt, sand, and gravel in the river and stream valleys. These unconsolidated deposits represent the primary sources of groundwater.

The extent of unconsolidated deposits near or at land surface ranges from 48 to 66 percent of the subbasins. Drillers' logs suggest that the thickness of these materials ranges from less than 20 feet in the upland areas to several hundreds of feet in the river and stream valleys.

About 70 stream sites in the four subbasins were visited during a reconnaissance trip to the study area in May 2008. Flowing water was observed at about 75 percent of the sites. Estimated streamflows at the sites during May ranged from less than 1 to about 10 ft^3/s. A subset of these sites was selected for streamflow and groundwater level measurements.

Streamflow was measured at 21 sites in June and September 2008. Shallow groundwater levels were measured at the same time as the streamflow measurements, using a small-diameter piezometer temporarily installed during the site visit. Measurements of the water level in the piezometer and the distance from the top of the piezometer to the stage of the stream were used to compute the hydraulic gradient between surface water and groundwater at that point.

Streamflows in June in all streams were higher than in September. Streamflow per unit area was calculated for each measurement site. For Tunk Creek, the streamflow per unit area decreased in a downstream direction in June. In September, streamflow per unit area at the uppermost measurement site was less than at mid-basin sites. This is likely due to limited groundwater storage capacity and subsequent streamflow to the stream resulting in less water entering the stream later in the year. An alternative is greater consumptive use in the upper basin, but given that the thickness of unconsolidated deposits is limited, limited storage capacity is the most likely explanation. The mid-basin portion of Bonaparte Creek has the potential to store large quantities of groundwater, given the thickness of unconsolidated deposits. In contrast to the Tunk Creek subbasin, however, there may be significant consumptive use of water in the Bonaparte Creek subbasin that leads to a decrease in streamflow.

Streamflow in Antoine Creek downstream of the mouth of a narrow canyon at about river mile (RM) 4.29 was lower than upstream of that point and also was lower than the streamflow per unit area at comparable locations on Tunk and Bonaparte Creeks. A possible explanation is that land use downstream of RM 5.11 appears to be intensively irrigated. Water for irrigation may be from wells or directly from Antoine Creek. In either case, streamflow in Antoine Creek would be affected.

Streamflows per unit area in Tonasket Creek were the smallest of the four subbasins. Data indicate that there is little groundwater recharge, even from winter/spring runoff, and generally little groundwater storage.

During June 2008, 10 of 17 reaches were identified as losing, and 11 of 21 measurement sites had negative hydraulic gradients. During September 2008, 9 of 17 reaches were identified as losing, and 18 of 21 measurement sites had negative hydraulic gradients. All four streams appeared to lose water to the groundwater system as they neared the Okanogan River, with Antoine Creek exhibiting the greatest losses. Streamflow losses probably occur as the streams flow across the relatively thick and permeable floodplain deposits of the Okanogan River.

In June, positive or neutral hydraulic gradients at upstream sites for all four streams indicated that either groundwater was discharging to these reaches or there was no net water movement into or out of the stream. All streams had negative hydraulic gradients near the mouths. In September, most sites had negative hydraulic gradients, except for a few upper-basin sites.

An evaluation of WDNR geologic maps indicates the extent of unconsolidated deposits in the four subbasins is greater than previously reported. However, an evaluation of drillers' logs with respect to location and lithology indicate general agreement with the previously reported extent map. The WDNR maps likely include significant areas of unsaturated or very thin unconsolidated deposits that may not have been classified as unconsolidated in the previously reported extent map.

Interpretation of drillers' logs to obtain depth-to-bedrock provided an estimate of the thickness of unconsolidated deposits. The Bonaparte Creek subbasin generally had the most and deepest wells, which is indicative of the subbasin having larger groundwater resources than the other subbasins. The Tonasket Creek subbasin had the fewest and shallowest wells, indicating more limited groundwater resources. Due to uncertainties in well locations listed on the drillers' logs and the inconsistent naming of geologic materials on the logs, the existence of deep, confined aquifers in the unconsolidated deposits could not be evaluated.

The presence of extensive and (or) thick layers of unconsolidated deposits is consistent with relatively constant streamflow in the creek, as in the Tunk Creek subbasin. Areas of less extensive or thinner layers of unconsolidated deposits may lead to decreases in streamflow, as in lower Antoine Creek subbasin.

Groundwater resources appear to be limited in most parts of the subbasins, which results in low summer streamflows, with a high potential to be affected by groundwater withdrawals from nearby, shallow wells. However, given the low precipitation, the limited groundwater storage capacity, and the permeable unconsolidated deposits underlying the stream channels, the creeks also would likely lose water to the groundwater system without any withdrawals. To better evaluate the specific effects of groundwater pumping on streamflow, additional studies would be helpful that are limited in areal extent and more focused on quantitative assessments of those effects.

To determine if deep, confined aquifers exist within unconsolidated deposits, an intensive effort, restricted to a limited geographic area would be required. Currently available data (drillers' logs) are not sufficient to confirm the presence of deep, confined aquifers.

Acknowledgments

Bob Clark, of the Okanogan Conservation District, and Rusty Post, of the Washington State Department of Ecology, provided valuable guidance on developing the scope of work and work plan for this investigation. Appreciation is expressed to landowners who gave permission to measure streamflow in creeks that crossed their properties and measure water levels in their wells.

References Cited

Drost, B.W., 2005, Quality-assurance plan for groundwater activities, U.S. Geological Survey, Washington Water Science Center: U.S. Geological Survey Open-File Report 2005-1126, 27 p. (Available on-line at http://pubs.usgs.gov/of/2005/1126)

Kahle, S.C., Longpré, C.I., Smith, R.R., Sumioka, S.S., Watkins, A.M., and Kresch, D.L., 2003, Water resources of the groundwater system in the unconsolidated deposits of the Colville River Watershed, Stevens County, Washington: U.S. Geological Survey Water-Resources Investigations Report 03-4128, 76 p. (Available on-line at http://pubs.usgs.gov/wri/wri034128/)

Kresch, D.L., and Tomlinson, S.A., 2004, Surface-water quality-assurance plan for the Washington District, U.S. Geological Survey, Water Resources Discipline: U.S. Geological Survey Open-File Report 03-490, 53 p. (Available on-line at (http://pubs.usgs.gov/of/2003/ofr03490)

Montgomery Water Group, Inc., Adolfson Associates, Inc., Hong West & Associates, Inc., RZ Resource Consultants, Inc., Marshall and Associates, Inc., and Washington State Department of Ecology, 1995, Initial watershed assessment, Water resources inventory area 49, Okanogan River watershed: Washington State Department of Ecology Open-File Report 95-14, 112 p.

Packard, F.A., Sumioka, S.S., and Whiteman, K.J., 1983, Ground water-surface water relationships in the Bonaparte Creek basin, Okanogan County, Washington: U.S. Geological Survey Open-File Report 82-172, 46 p. (available on-line at http://pubs.er.usgs.gov/usgspubs/ofr/ofr82172)

Rantz, S.E., and others, 1982, Measurement and computation of streamflow: Volume 1, Measurement of stage and discharge: U.S. Geological Survey Water-Supply Paper 2175, 283 p. (Available on-line at http://pubs.er.usgs.gov/usgspubs/wsp/wsp2175_vol1)

Walters, K.L., 1974, Water in the Okanogan River basin, Washington: State of Washington, Department of Ecology Water-Supply Bulletin 34, 136 p. (Available on-line at http://www.ecy.wa.gov/programs/eap/wsb/wsb_Hydrologic-Systems.html#p34)

Washington State Department of Natural Resources, 2005, Digital 1:100,000-scale Geology of Washington State: Division of Geology and Earth Resources Open File Report 2005-3, Version 1. (Available on-line at http://www.dnr.wa.gov/ResearchScience/Topics/GeologyPublicationsLibrary/Pages/pub_ofr05-3.aspx)

Publishing support provided by the U.S. Geological Survey
Publishing Network, Tacoma Publishing Service Center

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Sumioka and Dinicola—**Groundwater/Surface-Water Interactions in Four Subbasins, Okanogan River Basin, Washington, 2008**—Scientific Investigations Report 2009–5143