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Hydrogeologic Framework and Groundwater/Surface-Water Interactions of the South Fork Nooksack River Basin, Northwestern Washington

Scientific Investigations Report 2014–5221

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

Cover: South Fork Nooksack River looking downstream of the bridge at Potter Road, Whatcom County, Washington. (Photograph taken by Rusty Sherman, U.S. Geological Survey, June 14, 2012.)

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SALLY JEWELL, Secretary

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

U.S. Geological Survey, Reston, Virginia: 2014

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Suggested citation:
Gendaszek, Andrew, 2014, Hydrogeologic framework and groundwater/surface-water interactions of the South Fork Nooksack River Basin, northwestern Washington: U.S. Geological Survey Scientific Investigations Report 2014–5221, 36 p., *http://dx.doi.org/10.3133/sir20145221.*

ISSN 2328-0328 (online)

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Conversion Factors

Inch/Pound to SI

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)
yard (yd)	0.9144	meter (m)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
	Area	
square kilometer (km^2)	247.1	acre
square kilometer (km^2)	0.3861	square mile (mi^2)

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

$$°F = (1.8 \times °C) + 32.$$

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

$$°C = (°F - 32) / 1.8.$$

Conversion Factors and Datums—Continued

Datums

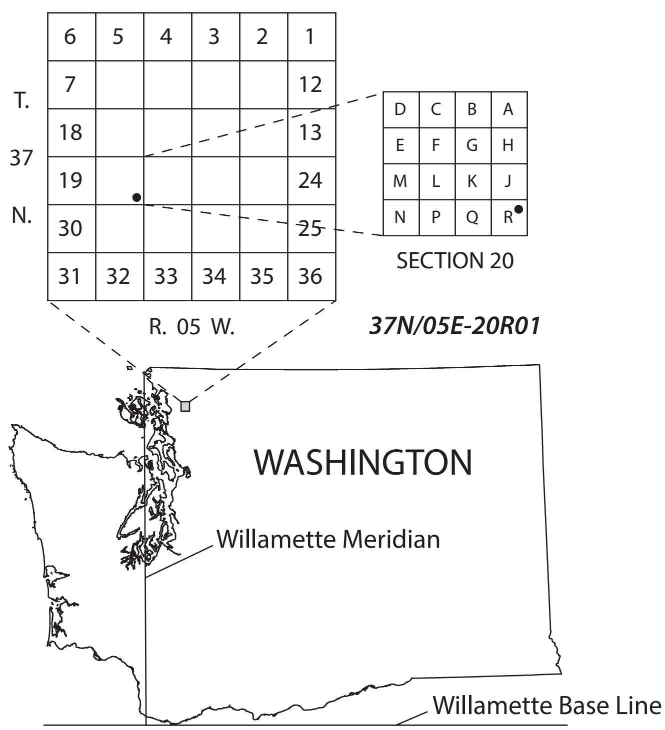
Vertical coordinate information is referenced to North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

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

Well Numbering System

In Washington State, wells are assigned numbers that identify their location within a township, range, section, and 40-acre tract. For example, number 37N/05E-20R01 indicates that the well is in township 37 north and range 05 east, north and east of the Willamette Base Line and Meridian, respectively. The numbers immediately following the hyphen indicate the section (20) within the township; the letter following the section gives the 40-acre tract of the section. The two-digit sequence number (01) following the letter indicates that the well was the first one inventoried by project personnel in that 40-acre tract. A "D" following the sequence number indicates that the well has been deepened. In the figures of this report, wells are identified individually by only the section and 40-acre tract, such as 20R01; township and range are shown on the map borders.



Well-numbering system used in Washington.

Hydrogeologic Framework and Groundwater/Surface-Water Interactions of the South Fork Nooksack River Basin, Northwestern Washington

By Andrew S. Gendaszek

Abstract

A hydrogeologic framework of the South Fork (SF) Nooksack River Basin in northwestern Washington was developed and hydrologic data were collected to characterize the groundwater-flow system and its interaction with surface-water features. In addition to domestic, agricultural, and commercial uses of groundwater within the SF Nooksack River Basin, groundwater has the potential to provide ecological benefits by maintaining late-summer streamflows and buffering stream temperatures. Cold-water refugia, created and maintained in part by groundwater, have been identified by water-resource managers as key elements to restore the health and viability of threatened salmonids in the SF Nooksack River. The SF Nooksack River drains a 183-square mile area of the North Cascades and the Puget Lowland underlain by unconsolidated glacial and alluvial sediments deposited over older sedimentary, metamorphic, and igneous bedrock. The primary aquifer that interacts with the SF Nooksack River was mapped within unconsolidated glacial outwash and alluvial sediment. The lower extent of this unit is bounded by bedrock and fine-grained, poorly sorted unconsolidated glaciomarine and glaciolacustrine sediments. In places, these deposits overlie and confine an aquifer within older glacial sediments. The extent and thickness of the hydrogeologic units were assembled from mapped geologic units and lithostratigraphic logs of field-inventoried wells. Generalized groundwater-flow directions within the surficial aquifer were interpreted from groundwater levels measured in August 2012; and groundwater seepage gains and losses to the SF Nooksack River were calculated from synoptic streamflow measurements made in the SF Nooksack River and its tributaries in September 2012. A subset of the field-inventoried wells was measured at a monthly interval to determine seasonal fluctuations in groundwater levels during water year 2013. Taken together, these data provide the foundation for a future groundwater-flow model of the SF Nooksack River Basin that may be used to investigate the potential effects of future climate change, land use, and groundwater pumping on water resources in the study area. Site-specific hydrologic data, including time series of longitudinal temperature profiles measured with a fiber-optic distributed temperature sensor and continuous monitoring of stream stage and water levels measured in wells in adjacent wetlands and aquifers, also were measured to characterize the interaction among the SF Nooksack River, surficial aquifers, and riparian wetlands.

Introduction

The South Fork (SF) Nooksack River heads in the Cascade Range of Whatcom County, northwestern Washington and flows into the Nooksack River near the town of Deming (fig. 1). Unlike the other forks of the Nooksack River that flow from the glaciers of Mount Baker, the SF Nooksack River does not receive meltwater from any extant glaciers, although small perennial snowfields occupy high-altitude, north-facing terrain in its headwaters (Post and others, 1971). After melting of winter snowpack, which largely occurs by June to July, late-summer streamflow of the SF Nooksack River is mostly sustained and its temperature buffered by groundwater, not glacial meltwater like other rivers in the North Cascades draining glaciated basins (Post and others, 1971; Fountain and Tangborn, 1985). Projected climatic changes in the Cascade Range during the 21st century, including smaller winter snowpack and earlier spring snowmelt, suggest changes in the timing and amount of summer runoff (Salathé and others, 2010). These changes in the hydrological regime may increase the importance of groundwater contributions to baseflow and the influence of groundwater on stream temperature and cold-water habitat during the summer. Concerns over the effect of increasing stream temperatures on cold-water fishes in the SF Nooksack River, including Endangered Species Act listed pacific salmon (*Oncorhynchus* spp.), have prompted the U.S. Environmental Protection Agency in cooperation with State, Tribal, and local agencies to assess the potential effects of climate change on instream temperatures in the development of temperature total maximum daily load (TMDL) guidelines for the SF Nooksack River (Klein and others, 2013).

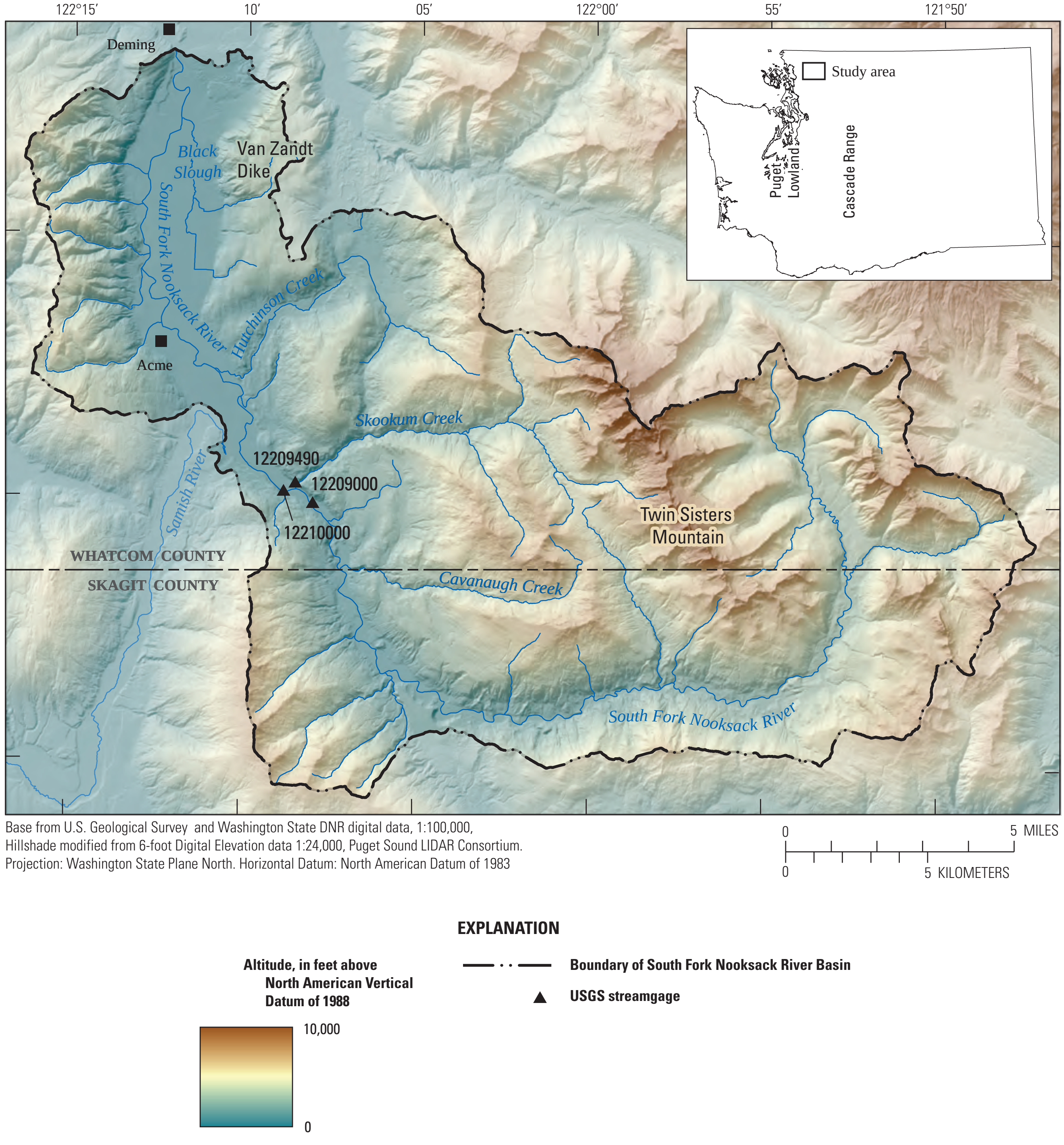


Figure 1. Location of the South Fork Nooksack River Basin, northwestern Washington.

Water temperature and adequate streamflow play a critical role in determining the quality and distribution of salmonid habitat in the Pacific Northwest (Poole and others, 2001) and have been identified as limiting factors for SF Nooksack River salmonid populations (Smith, 2002). Many physical, geochemical, and biological processes are regulated by water temperature including the solubility of gases like oxygen, nutrient cycling, and metabolism of ectothermic (cold-blooded) biota such as fish (Caissie, 2006). Salmonids and other cold-water fishes such as char (*Salvelinus* spp.) have lower temperature requirements than other fish such as bass and perch (*Centrarchids* spp.) or carp (*Cyprinids* spp.) making them particularly susceptible to warm water temperatures. Temperature of salmonid habitat ranges from 50 to 63 °F whereas lethal temperatures of 1-week exposure for adult and juvenile salmonids are greater than 70–72 °F and greater than 73–77 °F, respectively (Poole and others, 2001). Although lethal temperatures constrain an upper limit on the temperature regime of a salmonid-bearing river, sublethal temperatures may stress the ability of salmonids to survive and reproduce by impairing disease resistance, growth, and predator avoidance. In addition, although sublethal or greater temperatures may occur in a river, thermal refugia may exist; therefore, the temporal and spatial distribution, connectivity, and stability of thermal refugia may play a critical role in determining the health and viability of salmonid populations (Torgersen and others, 2012).

Several hydrologic and geomorphic features create and maintain thermal refugia within streams, including point sources of cool water such as cold-water tributaries or groundwater seeps and non-point sources such as gaining reaches (Torgersen and others, 2012). During the summer when stream temperatures reach their annual maximum, groundwater is typically cooler and more consistent in temperature than surface waters. During this time, groundwater cools surface waters and buffers them from diurnal temperature fluctuations. The location and magnitude of groundwater inflow into a stream depends largely on the distribution of hydrogeologic units, in-channel and floodplain geomorphic conditions, and the relation of the hydraulic gradients of the groundwater relative to the stream (Konrad, 2006). In addition to groundwater inflow, thermal stratification within pools also may create cold-water refugia; in the SF Nooksack River, many pools are related to log-jam structures, meander bends, and bedrock outcrops along the valley walls. In May 2012, the U.S. Geological Survey (USGS), in cooperation with the Nooksack Indian Tribe, began a project to characterize the groundwater-flow system within the SF Nooksack River Basin and its relation to the surface-water features, including the SF Nooksack River, its tributaries, and wetlands within its riparian corridor.

Purpose and Scope

The purpose of this report is to (1) describe the hydrogeology of the SF Nooksack River Basin and present hydrologic data that will provide the foundation for a future groundwater-flow model and (2) describe the relation between the groundwater-flow system and surface-water features including rivers and wetlands. The scope of this report includes a basin-wide hydrogeologic framework as well as a summary of the regional and local geologic history, the extent, thickness, and physical characteristics of substantial hydrogeologic units, and generalized groundwater-flow directions within the surficial aquifer. Groundwater/surface-water interactions were assessed at a basin scale and at site-specific locations with respect to temperature and streamflow. In addition, several investigations of groundwater/surface-water interactions at sites in the study area are presented with a focus on stream temperature within sub-mile scale reaches. The data presented in this report will provide components for a future groundwater-flow model to evaluate the effects of different management scenarios on the groundwater-flow system of the study area and its relation to the SF Nooksack River and its tributaries.

Description of Study Area

The study area includes the 183 mi^2 of the Cascade Range and its foothills in western Whatcom and Skagit Counties in northwestern Washington that drain into the SF Nooksack River (fig. 1). Altitudes of the study area range from 7,000 ft at the summit of Twin Sisters Mountain to 210 ft at the confluence of the SF Nooksack River with the mainstem Nooksack River. Upstream of its confluence with Skookum Creek, the SF Nooksack River is mostly confined by bedrock and its drainage basin is mostly forested with active timber-harvest operations on public and private timberlands. The SF Nooksack River enters a broad valley downstream of the confluence with Skookum Creek where agricultural and rural residential land uses are predominant. Within this valley, a subtle topographic divide delineates the drainage divide between the SF Nooksack River and the Samish River Basins to the south. Part of the headwaters of the Samish River also was included in the study area, to understand the occurrence and movement of groundwater beneath the topographic divide between the Samish River and SF Nooksack River Basins.

The uplands of the SF Nooksack River Basin are underlain by sedimentary, metamorphic, and igneous bedrock, which are mantled in places by unconsolidated sediments including modern alluvium, glacial outwash, glacial till, glaciomarine deposits, and glaciolacustrine deposits.

The broad, low-gradient valley of the lower SF Nooksack River downstream of its confluence with Skookum Creek is underlain by a thick sequence of unconsolidated sediments of alluvial and glacial origin, which comprise the primary groundwater supply for rural domestic and agricultural uses in the study area. Some domestic supply wells are developed within bedrock on adjacent uplands, but they have limited yield. Groundwater withdrawals from wells completed within glacial and alluvial sediments, together with a surface-water diversion from Skookum Creek, supply a salmon hatchery near the confluence of Skookum Creek and the SF Nooksack River (fig. 1).

The climate of the study area is characterized by cool, wet winters and warm, dry summers. Mean annual precipitation between 1981 and 2010 ranged from 52 in. at low altitudes to 200 in. at the highest altitudes within the basin (Daly and others, 2008; fig. 2). Historically, most precipitation falls between November and March as rain at low altitudes and snow at high altitudes. The annual hydrograph measured at the SF Nooksack River near Wickersham (USGS streamgage 12209000), which has the longest streamgage record in the study area, is characteristic of a mixed-rainfall/snowmelt-dominant watershed, with elevated streamflow in the autumn and winter from large rainfall events and a spring freshet in May from melt of the snowpack (fig. 3). A reduction in streamflow typically occurs during February and March between rainfall-driven and snowmelt-driven flows, whereas the lowest flows typically occur during August and late September following prolonged dry periods during the late summer. Stream temperatures and diurnal temperature fluctuations in the SF Nooksack River are typically lowest between December and January and are highest in July and August when streamflow is lowest (fig. 4).

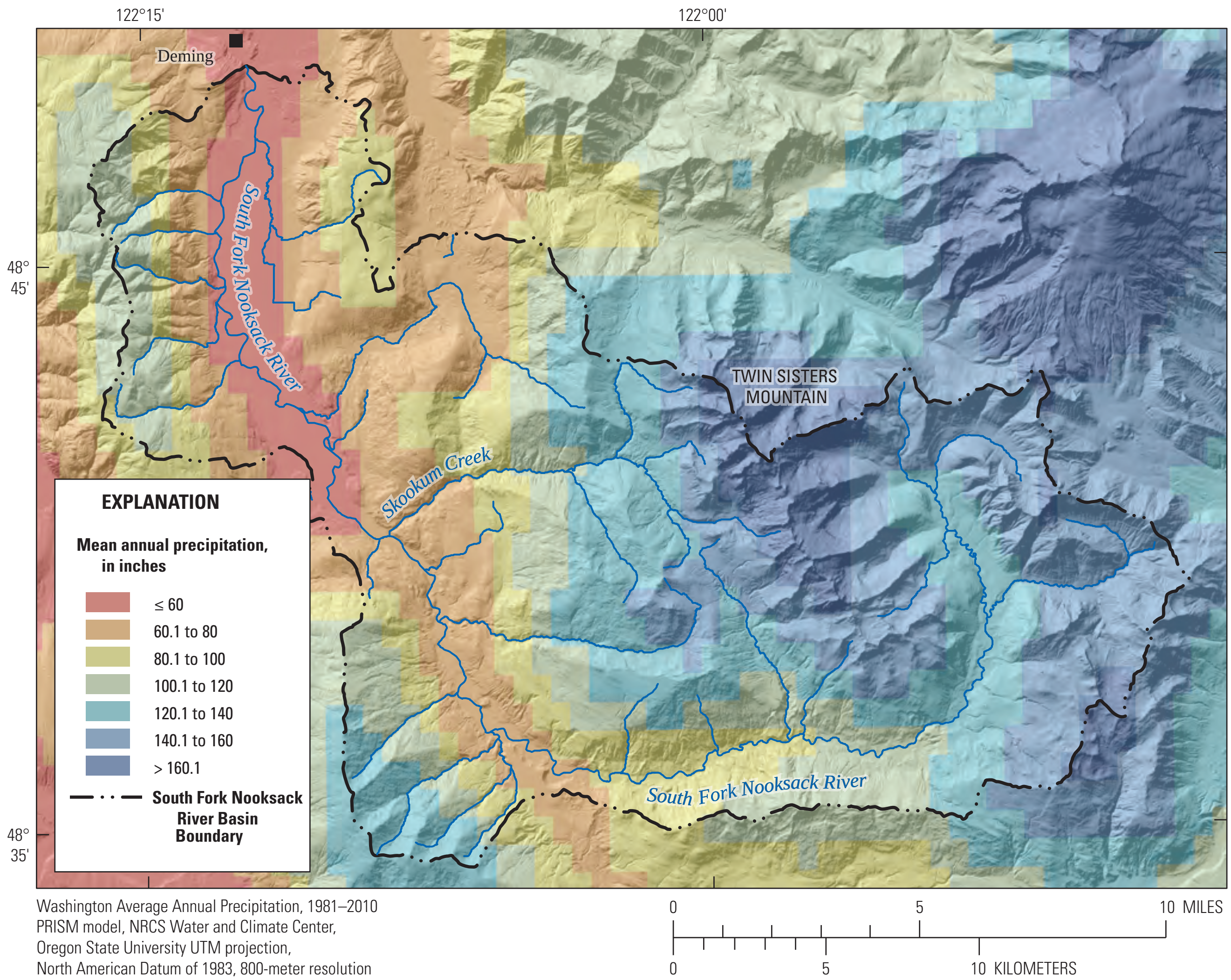


Figure 2. Mean annual precipitation in the South Fork Nooksack River Basin, northwestern Washington, 1981–2010.

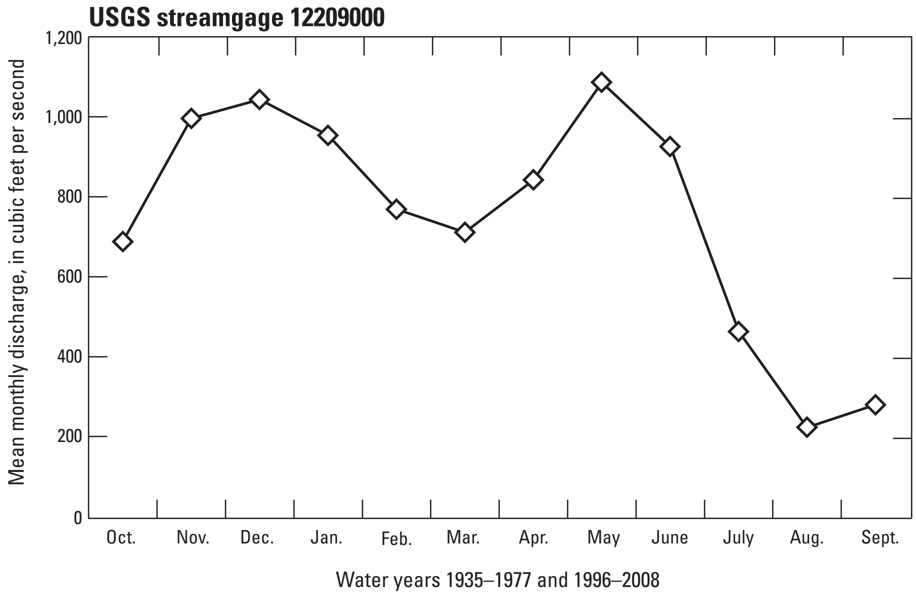


Figure 3. Mean monthly discharge for U.S. Geological Survey (USGS) streamgage (12209000) on the South Fork Nooksack River near Wickersham, northwestern Washington, water years 1935–77 and 1996–2008.

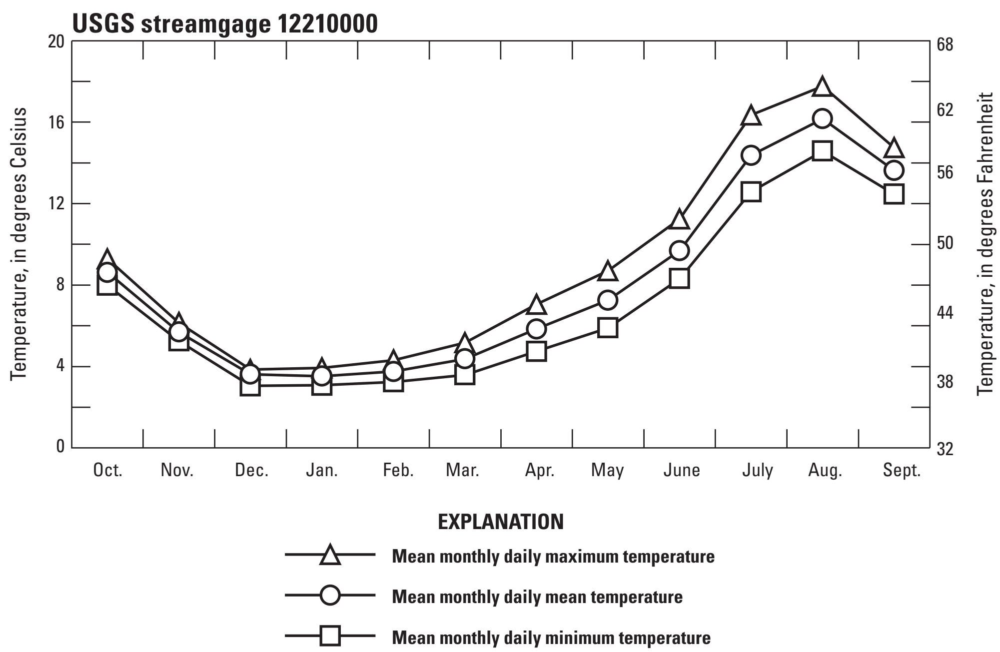


Figure 4. Mean monthly daily mean, minimum, and maximum stream temperatures measured at the U.S. Geological Survey (USGS) streamgage (12210000) on the South Fork Nooksack River at Saxon Bridge, northwestern Washington, water years 2009–2013.

Methods of Investigation

The hydrogeologic framework and groundwater/surface-water interactions of the SF Nooksack River Basin were characterized through a field inventory of wells, construction of hydrogeologic maps and sections, measurement of water levels in wells, and measurement of stream temperature.

Well Inventory and Water-Level Measurements

A field inventory of 51 wells was completed in August 2012 within the SF Nooksack River Basin and part of the adjacent Samish River Basin to acquire lithostratigraphic data and to measure the depth to water in wells. Inventoried wells were matched with drillers' logs obtained from USGS Washington Water Science Center and Washington State Department of Ecology databases. To the extent possible, inventoried wells were spatially distributed across the SF Nooksack River Basin and open within the major waterbearing units. Most wells in the study area were drilled for domestic or agricultural water use within the lower SF Nooksack River valley because only limited residential development exists in the uplands of the basin. In addition, study-area wells were mostly completed at shallow depths within unconsolidated sediment because of widespread availability of groundwater at shallow depths, thus limiting the number of wells completed in lower hydrogeologic units.

At each field-inventoried well, the location and details of the construction of the well were recorded. The geographic coordinates of each well were obtained using a Garmin® 60Csx Global Positioning System (GPS) unit with a horizontal accuracy of about 10 ft. The altitude of the land surface at each well location was determined from Light Detection and Ranging (lidar) topographic data and had a vertical accuracy of ±0.3 ft. At most field-inventoried wells, the depth to water was measured by USGS personnel following standard USGS techniques (Kozar and Kahle, 2013) for a calibrated electric tape or graduated steel tape, each accurate to ±0.01 ft. The locations of project wells and water levels measured during August 2012 are provided in table 1. The water level at 14 of the field-inventoried wells was measured at a monthly interval during the water year 2013 to characterize seasonal water-level fluctuations and are presented in appendix A. A water year is defined as the 12-month period from October 1 for any given year through September 30 of the following year. All water levels and well information collected during this study were entered into the USGS National Water Information System (NWIS). Fifteen additional wells with available drillers' logs were obtained from USGS and Washington State Department of Ecology databases where the distribution of the 51 field-inventoried wells was not sufficient to adequately define the hydrogeologic framework. The approximate locations of these wells were determined from the addresses and Whatcom County Assessor's tax parcel identification listed in the drillers' log.

Geology and Hydrogeology

Geologic units were simplified from previous geologic mapping at various scales by Dragovich and others (1997a, 1997b, 2000), Lapen (2000), and Tabor and others (2003). The digital geologic map database of the study area compiled by the Washington Division of Geology and Earth Resources (2005) included 1:100,000-scale surficial geologic mapping of the study area by Lapen (2000) of the Bellingham 30×60-minute quadrangle and Tabor and others (2003) of the Mount Baker 30×60-minute quadrangle. Geologic units were correlated across quadrangle boundaries and, in some cases, were modified based on field observations or stratigraphic evidence obtained during this investigation or through more detailed 1:24,000-scale geologic mapping by Dragovich and others (1997a, 1997b, 2000). Three hydrogeologic sections in the western part of the study area were constructed from surficial hydrogeologic mapping and lithostratigraphic information from drillers' logs.

Estimation of Horizontal Hydraulic Conductivity

Hydraulic conductivity is a measure of a material's capacity to transmit water. Horizontal hydraulic conductivity was estimated for the hydrogeologic units using the drawdown/discharge relation reported on drillers' logs that reported pump testing wells for more than 4 hours. Only data from those wells with a drillers' log containing discharge rate, duration of pumping, drawdown, static water level, well-construction, and lithologic data were used.

To estimate hydraulic conductivity, the modified Theis equation (Ferris and others, 1962) was used to estimate transmissivity of the pumped interval. Transmissivity is the product of the horizontal hydraulic conductivity and thickness of the hydrogeologic unit supplying water to the well.

The modified Theis equation is:

$$s = \frac{Q}{4\pi T} \ln \frac{2.25Tt}{r^2 S}, \qquad (1)$$

where

- s is drawdown in the well, in feet;
- Q is discharge, or pumping rate, of the well, in cubic feet per day;
- T is transmissivity of the hydrogeologic unit, in square feet per day;
- t is length of time the well was pumped, in days;
- r is the radius of the well, in feet; and
- S is storage coefficient, a dimensionless number; assumed to be 0.0001 for confined units and 0.1 for unconfined units.

Table 1. Selected physical and hydrologic data for the project wells in the South Fork Nooksack River Basin, northwestern Washington, August 2012.

[All altitudes are referenced to the North American Vertical Datum of 1988. **USGS well No.:** See Well Numbering System diagram for explanation of well-numbering system. **Latitude** and **Longitude:** Given in degrees, minutes, seconds. **Hydrogeologic unit of open interval:** Qa/go, alluvial and recessional outwash aquifer; Qvt/ls/gm_e, till and glacio-marine drift confining unit; Qga/pf, advance glacial outwash and older glacial drift aquifer; pTm, Igneous and metamorphic basal confining unit. **Status of water level:** R, recovering. **Abbreviations:** ft, foot; gal/min, gallons per minute; ft/d, foot per day; –, not available]

USGS site identifier	USGS well No.	Latitude	Longitude	Land-surface altitude (ft)	Well depth (ft)	Hydro-geologic unit of open interval	Driller reported yield (gal/min)	Well data: Estimated hydraulic conductivity	Well data: On cross section	Well data: Field inventoried August 2012	Well data: Monthly water level	Date of water-level measurement during August 2012 inventory	Water-level altitude (ft)	Water-level depth below land surface (ft)	Status of water level
484347122074801	37N/05E-02C01	48 43 47.4	122 07 47.8	659	97	Qa/go	15	X	X	X	–	08-20-12	580.8	78.2	–
484350122075601	37N/05E-02D01	48 43 50.2	122 07 55.9	619	46	Qa/go	–	X	–	X	–	–	–	–	–
484347122075701	37N/05E-02D02	48 43 46.7	122 07 57.2	622	58	Qa/go	–	X	X	X	X	08-20-12	576.7	45.3	–
484345122081501	37N/05E-03A01	48 43 44.8	122 08 15.4	613	50	Qa/go	–	–	X	X	–	08-20-12	576.43	36.57	–
484342122083401	37N/05E-03G01	48 43 42.1	122 08 34.3	595	57	Qa/go	–	–	X	X	X	08-21-12	568.7	26.3	–
484307122110701	37N/05E-05R01	48 43 06.8	122 11 06.9	309	28	Qa/go	16	X	–	X	–	08-22-12	299.75	9.25	–
484352122121401	37N/05E-06A01	48 43 51.9	122 12 14.2	284	28	Qa/go	–	–	–	X	–	–		–	–
484309122122401	37N/05E-06R01	48 43 09.0	122 12 23.7	301	33	Qa/go	–	–	X	X	X	08-24-12	288.72	12.28	–
484309122122301	37N/05E-06R02	48 43 09.0	122 12 23.0	299.6	98.5	Qga/pf	133	–	X	–	–	–	–	–	–
484230122123401	37N/05E-07K01	48 42 29.7	122 12 03.6	730	101	Qga/pf	–	–	–	X	–	–	–	–	–
484216122120601	37N/05E-08N01	48 42 16.0	122 12 06.1	445	40	pTm	0.5	–	–	X	–	08-21-12	436.48	8.52	–
484225122110001	37N/05E-08R01	48 42 24.9	122 11 00.0	313	4.5	Qa/go	–	–	–	–	–	–	–	–	–
484123122102601	37N/05E-16P01	48 41 22.7	122 10 25.9	344	38	Qa/go	30	–	X	X	–	08-23-12	333.6	10.4	–
484127122101001	37N/05E-16Q01	48 41 27.4	122 10 10.1	345	38	Qa/go	35	–	X	X	–	08-23-12	333.5	11.5	–
484214122111501	37N/05E-17B01	48 42 13.5	122 11 15.4	319	4.5	Qa/go	–	–	–	–	–	–	–	–	–
484211122113901	37N/05E-17C01	48 42 11.4	122 11 39.3	316	40	Qa/go	40	–	X	X	–	–	–	–	–
484143122114701	37N/05E-17L01D1	48 41 42.6	122 11 46.6	444	489.5	pTm	5	–	–	X	X	08-23-12	430.4	13.6	–
484138122113401	37N/05E-17L02	48 41 38.4	122 11 33.9	356	70	Qa/go	7	–	–	X	–	08-22-12	327.68	28.32	–
484124122120501	37N/05E-17N01	48 41 24.0	122 12 05.0	637	68	pTm	5	–	–	X	X	08-22-12	600.08	36.92	–
484119122110001	37N/05E-20A01	48 41 19.2	122 10 59.7	407	118	Qga/pf	30	–	X	X	X	08-24-12	323.28	83.72	–
484114122105601	37N/05E-20A02	48 41 14.0	122 10 56.4	412	282	Qvt/ls/gm_e	0.25	–	–	X	–	–	–	–	–
484118122114201	37N/05E-20C01	48 41 18.5	122 11 42.0	375	55	pTm	3	–	–	X	–	–	–	–	–
484102122113401	37N/05E-20H01	48 41 01.4	122 11 38.6	750	47.6	Qa/go	10	–	–	–	–	–	–	–	–
484102122110801	37N/05E-20H02	48 41 01.5	122 11 07.6	400	268	Qga/pf	12	–	X	X	–	08-22-12	317.38	82.62	R
484037122121101	37N/05E-20N01	48 40 36.7	122 12 11.3	330	49	Qa/go	5	–	–	X	–	08-23-12	303.62	26.38	–
484032122105901	37N/05E-20R01	48 40 32.2	122 10 59.4	383	441	Qga/pf	50	–	–	X	X	08-22-12	331.32	51.68	–
484034122110301	37N/05E-20R02	48 40 33.4	122 11 07.6	730	34	Qa/go	50	–	–	–	–	–	–	–	–
484037122105701	37N/05E-20R03	48 40 36.9	122 10 57.1	395	102	Qvt/ls/gm_e	0.25	–	–	X	X	08-22-12	345	50	–
484035122110101	37N/05E-20R04	48 40 34.7	122 11 01.1	392	380	Qga/pf	–	–	–	X	X	08-22-12	330.58	61.42	–
484052122093601	37N/05E-21J01	48 40 51.7	122 09 35.6	367	20	Qa/go	40	–	–	X	–	08-23-12	351.98	15.02	–
484054122095101	37N/05E-21J02	48 40 53.9	122 09 51.0	361	–	UNKNOWN	–	–	–	X	–	08-23-12	347.18	13.82	–
484053122094201	37N/05E-21J03	48 40 52.8	122 09 41.6	362	–	UNKNOWN	–	–	–	X	–	08-23-12	351.78	10.22	–
484053122101601	37N/05E-21K01	48 40 52.9	122 10 16.0	355.7	101	Qa/go	7	–	X	–	–	–	–	–	–
484041122093101	37N/05E-22N01	48 40 41.2	122 09 30.7	369	40	Qa/go	30	–	X	X	X	–	–	–	–
484036122090801	37N/05E-22P01	48 40 36.2	122 09 08.5	375	103	Qga/pf	25	–	X	X	X	08-21-12	363.61	11.39	–

Table 1. Selected physical and hydrologic data for the project wells in the South Fork Nooksack River Basin, northwestern Washington, August 2012.—Continued

[All altitudes are referenced to the North American Vertical Datum of 1988. **USGS well No.:** See Well Numbering System diagram for explanation of well-numbering system. **Latitude** and **Longitude:** Given in degrees, minutes, seconds. **Hydrogeologic unit of open interval:** Qa/go, alluvial and recessional outwash aquifer; Qvt/ls/gm_e, till and glacio-marine drift confining unit; Qga/pf, advance glacial outwash and older glacial drift aquifer; pTm, Igneous and metamorphic basal confining unit. **Status of water level:** R, recovering. **Abbreviations:** ft, foot; gal/min, gallons per minute; ft/d, foot per day; –, not available]

USGS site identifier	USGS well No.	Latitude	Longitude	Land-surface altitude (ft)	Well depth (ft)	Hydro-geologic unit of open interval	Driller reported yield (gal/min)	Well data: Estimated hydraulic conductivity	Well data: On cross section	Well data: Field inventoried August 2012	Well data: Monthly water level	Date of water-level measurement during August 2012 inventory	Water-level altitude (ft)	Water-level depth below land surface (ft)	Status of water level
484025122082001	37N/05E-27A01	48 40 14.5	122 08 47.9	386.7	68	Qa/go	500	X	–	X	–	08-28-12	370.46	16.24	–
484016122084801	37N/05E-27B01	48 40 16.2	122 08 48.3	384.6	30	pTm	0	–	–	X	–	–	–	–	–
484019122083801	37N/05E-27B02	48 40 18.8	122 08 38.0	393.6	–	UNKNOWN	–	–	–	X	–	08-28-12	377.49	16.11	–
4840122084301	37N/05E-27B03	48 40 19.9	122 08 42.7	386.2	100	Qga/pf	300	–	X	X	–	08-28-12	375.11	11.09	–
484014122084601	37N/05E-27G01	48 40 14.2	122 08 46.3	384.7	101	Qga/pf	312	–	X	X	–	08-28-12	369.82	14.88	–
484011122084701	37N/05E-27G02	48 40 11.8	122 08 47.2	382.6	–	UNKNOWN	–	–	–	X	–	08-28-12	370.99	11.61	–
484012122084701	37N/05E-27G03	48 40 12.2	122 08 47.0	382.3	–	UNKNOWN	–	–	–	X	–	08-28-12	370.24	12.06	–
484018122105801	37N/05E-29A01	48 40 18.4	122 10 58.5	327	68	Qga/pf	–	–	–	X	–	–	–	–	–
484000122113701	37N/05E-29L01	48 40 00.4	122 11 36.7	370	83	Qa/go	15	X	X	X	–	08-24-12	304.67	65.33	–
484625122132101	38N/04E-24A01	48 46 25.0	122 13 21.0	310	58	Qa/go	10	X	X	–	–	–	–	–	–
484559122132901	38N/04E-24J02	48 45 59.2	122 13 29.3	323	82.25	Qa/go	5	X	–	X	–	08-23-12	311.25	11.75	–
484736122122801	38N/05E-07K01	48 47 36.4	122 12 28.0	292	110	Qa/go	30	–	–	X	–	–	–	–	–
484801122111101	38N/05E-08B01	48 48 01.4	122 11 10.9	283.7	78	Qa/go	15	X	–	X	X	08-22-12	233.83	49.87	–
484746122111901	38N/05E-08K01	48 47 45.9	122 11 18.9	239.5	28	Qa/go	20	X	X	X	–	08-22-12	229.44	10.06	–
484731122112701	38N/05E-08P01	48 47 31.4	122 11 27.2	233.9	179	Qga/pf	30	–	X	–	–	–	–	–	–
484731122104301	38N/05E-09N01	48 47 31.1	122 10 43.2	315.4	79	Qga/pf	18	X	–	X	–	–	–	–	–
484708122104201	38N/05E-16D01	48 47 07.5	122 10 42.5	342.9	130	Qga/pf	–	–	X	–	–	–	–	–	–
484716122112401	38N/05E-17B01	48 47 15.9	122 11 23.5	252.2	33	Qa/go	–	–	–	X	–	08-23-12	237.42	14.78	–
484716122113301	38N/05E-17C01	48 47 16.4	122 11 32.6	247.2	38	Qa/go	30	–	X	X	X	08-23-12	229.9	17.3	–
484713122112801	38N/05E-17C02	48 47 13.3	122 11 28.4	249.5	38	Qa/go	17	–	X	X	–	08-23-12	232.2	17.3	–
484704122105001	38N/05E-17H01	48 47 03.4	122 10 54.6	300	59	Qa/go	17	–	–	–	–	–	–	–	–
484712122120501	38N/05E-18A01	48 47 11.4	122 12 09.6	240	12	Qa/go	–	–	–	–	–	–	–	–	–
484701122123001	38N/05E-18G01	48 47 0.4	122 12 34.6	250	405	Qvt/ls/gm_e	–	–	–	–	–	–	–	–	–
484609122113001	38N/05E-20F01	48 46 09.1	122 11 30.4	247.1	39	Qa/go	20	–	–	X	X	08-21-12	242.9	4.2	–
484615122110801	38N/05E-20H01	48 46 15.2	122 11 07.5	268	256	Qga/pf	0.75	X	X	–	–	–	–	–	–
484546122114701	38N/05E-20P01	48 45 45.9	122 11 47.0	250.9	40	Qa/go	15	–	X	X	–	08-23-12	247.54	3.36	–
484547122110301	38N/05E-20R01	48 45 46.6	122 11 03.1	260.5	40	Qa/go	15	–	–	X	–	–	–	–	–
484507122071001	38N/05E-26K01	48 45 06.4	122 07 14.6	700	47	Qa/go	33	–	–	–	–	–	–	–	–
484535122115301	38N/05E-29D01	48 45 34.4	122 11 57.6	300	16	Qa/go	200	–	–	–	–	–	–	–	–
484510122114401	38N/05E-29L02	48 45 09.7	122 11 44.4	259.4	78	Qa/go	30	–	X	X	–	–	–	–	–
484535122120801	38N/05E-30A01	48 45 35.2	122 12 07.7	257	33	Qa/go	18	X	–	X	–	–	–	–	–

Simplifying assumptions used in the derivation of equation 1 are that aquifers are homogeneous, isotropic, and infinite in extent; wells are fully penetrating; flow to the well is horizontal; and water is instantaneously released from storage. Additionally, for unconfined aquifers, drawdown is assumed to be small in relation to the saturated thickness of the aquifer. Aquifers and wells never fully meet these assumptions, and as such, the derived aquifer property values represent only approximate values, the magnitudes of which are useful for a regional-scale analysis.

A computer program was used to solve equation 1 for transmissivity (T) using Newton's iterative method (Carnahan and others, 1969). The calculated transmissivity values were not sensitive to assumed storage coefficient values; the difference in computed transmissivity, between using 0.1 and 0.0001 as the storage coefficient, is a factor of about 2. Equation 2 was used to calculate horizontal hydraulic conductivity from the calculated transmissivity

$$K_h = \frac{t}{b}, \qquad (2)$$

where

K_h is horizontal hydraulic conductivity of the geologic material near the well opening in feet per day; and

b is thickness, in feet, approximated using the length of the open interval as reported in the driller's report.

Using the length of an open interval of a well for b, overestimates values of K_h because the equations assume that the water flows horizontally within a layer of this thickness. Although some of the flow will be outside this interval, the amount likely will be negligible because, in most aquifers, vertical flow is inhibited by geologic heterogeneity.

Streamflow Gains and Losses

In September 2012, a seepage run (a set of synoptic streamflow measurements) was made along the SF Nooksack River to identify gaining, losing, and near-neutral reaches. Twenty-three streamflow measurements were made along 10 seepage measurement reaches between RM 1.9 and 14.8. These seepage reaches correspond approximately with the downstream reaches of a more spatially extensive seepage run made by the USGS in August and September 1998 that included 20 reaches of the SF Nooksack River between RM 0 and 37.4 and three tributaries, including Cavanaugh, Skookum, and Hutchinson Creeks (Wiggins and others, 1999). The net gain or loss of streamflow was calculated for each seepage reach as the increase or decrease of streamflow that was not accounted for by tributary inflows.

Discharge was measured using the velocity-area method following standard USGS streamgaging techniques with a Price AA current meter (Rantz, 1982) or an acoustic Doppler current profiler (ADCP; Oberg and others, 2005). Each discharge measurement was assigned an accuracy rating of "good," indicating measurements are within 5 percent margin of error; "fair," indicating measurements are within 8 percent margin of error; or "poor," indicating that measurements have an error of 8 percent or more (Sauer and Meyer, 1992). The measurement error, associated with the upstream, downstream, tributary, and diversion streamflow measurements used to calculate a single seepage gain or loss, was propagated using the following formula for each seepage reach (Wheeler and Eddy-Miller, 2005):

$$s = \sqrt{(\pm a)^2 + (\pm b)^2 + ...(\pm n)^2}, \qquad (3)$$

where

s is the propagated error of the individual discharge measurements (a, b,…, n) associated with seepage gain or loss calculation.

Seepage reaches with gains or losses less than the propagated error of the individual discharge measurements were classified as "near neutral" with respect to seepage gains and losses.

Fiber-Optic Distributed Temperature Sensing

The fiber-optic distributed temperature sensor (FO-DTS) was installed on the streambed of two reaches of the SF Nooksack River during two 1-week deployments to characterize the extent and distribution of groundwater-discharge and cold-water refugia. A FO-DTS uses a fiber-optic cable to emit a pulse of laser light that returns to the sensor as Raman-backscattered light at a higher (Stokes) and lower (anti-Stokes) wavelength relative to the incident light wavelength (Selker and others, 2006). Unlike the Stokes wavelength intensity, the anti-Stokes wavelength intensity is strongly affected by temperature; the temperature at a given section of the fiber-optic cable may be determined by measuring the ratio of the Stokes and anti-Stokes intensities together with the time-of-travel information of the laser pulse propagation.

The FO-DTS used during the study, an Oryx DTS® manufactured by Sensornet®, was initially calibrated for temperature by placing the ends of the fiber-optic cable in a constant-temperature ice bath (32.0 °F) verified with a National Institute of Standards and Technology (NIST) certified thermistor with an accuracy of ±0.2 °F. The FO-DTS was programmed to average stream temperatures over 3-ft sections of cable during 1-minute periods every 30 minutes. During the survey, data-logging thermistors were placed in the streambed adjacent to calibration points on the fiber-optic cable. These data were used to solve a set of linear equations at each time step of the FO-DTS, which maintained a fully dynamic calibration (Hausner and others, 2011).

The fiber-optic cable was mostly submerged in the streambed, but low, dispersed streamflow and large logs in several locations precluded complete submergence of the fiber-optic cable. Locations of individual meter marks on the fiber-optic cable were surveyed with a real-time kinematic global positioning system (RTK-GPS); the position of meter marks between surveyed points was linearly interpolated. The FO-DTS was deployed in a 950-ft side channel of the SF Nooksack River at river mile (RM) 11.2, August 8–16, 2012; and in a 650-ft reach of the main channel of the SF Nooksack River downstream of its confluence with Hutchinson Creek at RM 10.0, August 13–19, 2013.

Hydrogeologic Framework

The hydrogeologic framework of the study area, including the physical, lithologic, and hydraulic characteristics of aquifers and confining units, and a simplified geologic history of the study area was compiled for this study. Mapped geologic units (pl. 1) were grouped into five hydrogeologic units based on their lithologic and hydrologic characteristics and stratigraphic distribution (pl. 2). These hydrogeologic units include two aquifers (Qa/go and Qga/pf) and a confining unit (Qvt/ls/gm$_e$) within unconsolidated glacial and alluvial sediments and two bedrock units (Ec$_{cb}$ and pTm). These hydrogeologic units are based, in part, on previous hydrogeologic studies of the western SF Nooksack River Basin (Dragovich and others, 1997a) and the adjacent Skagit River Basin (Savoca and others, 2009). The surficial extent of hydrogeologic units across the study area was mapped using the extent of previously mapped geologic units and the lithology and stratigraphic position of hydrogeologic units recorded in drillers' logs was used to construct three hydrogeologic sections in the study area.

Geology and Geologic Setting

Three groups of geologic units underlie the study area including unconsolidated Quaternary sediments, Eocene sedimentary rocks, and pre-Tertiary metamorphic and igneous rocks. These geologic units have been described and mapped at various scales, most recently by Dragovich and others (1997a, 1997b, 2000), Lapen (2000), and Tabor and others (2003). Significant geologic events recorded by the rocks and sediments of the SF Nooksack River Basin include the accretion of tectonic terranes (fragments of tectonic plates with unique paleogeographic origins and structural and metamorphic histories), the uplift of the Cascade Range, and Pleistocene glaciation.

The pre-Tertiary metamorphic and igneous rocks that crop out in the study area record the emplacement and deformation of four distinct tectonic terranes that accreted onto the western margin of North America by the mid-Cretaceous (Tabor and Haugerud, 1999; Haugerud and Tabor, 2009). These terranes include, structurally from youngest to oldest (Tabor and Haugerud, 1999): (1) the Easton terrane, comprised of well-metamorphosed deep-marine sediments and basaltic ocean floor formed during the Jurassic, (2) the Bell Pass Mélange, a heterogeneous mixture of metamorphosed oceanic crust, continental crust, and mantle formed between the Precambrian and Triassic, (3) the Chilliwack River terrane, comprised of metamorphosed sedimentary and volcanic rocks of a volcanic arc formed between the Devonian and Triassic, and (4) the Nooksack terrane, a metamorphosed submarine fan flanking a volcanic arc deposited during the Jurassic and early Cretaceous. The rocks contained within these terranes greatly vary depending on protolith and metamorphic history and, in the study area, prominently include the Twin Sisters Dunite (Ragan, 1963) of the Bell Pass Mélange, a mantle-origin ultramafic rock comprised mostly of olivine, and the Darrington Phyllite, which originated as metamorphosed deep-marine sediments within the Easton terrane.

After assemblage of the North Cascades terranes, thrusting continued to thicken the crust from the Mid to Late Cretaceous followed by Eocene pluton emplacement, strike-slip faulting, and extensional faulting, which exhumed some of the deeply buried metamorphic rocks of the North Cascades. Uplift of metamorphic rocks in the North Cascades during Eocene time supplied arkosic sediments that were deposited unconformably over pre-Tertiary rocks in subsiding basins. These sediments lithified into rocks including the Chuckanut Formation, an arkosic sandstone and mudstone with layers of coal (Johnson, 1984). The Chuckanut Formation, which crops out in the western part of the study area, contains plant fossils indicative of a subtropical climate during the Eocene.

The area that is currently the SF Nooksack River Basin and much of the Puget Lowland was glaciated at least six times during the Pleistocene by the Puget lobe of the Cordilleran ice sheet, most recently during the Fraser glaciation 30–10 thousand years ago (Kya; Booth and others, 2004). The major valleys of the Puget Lowland were excavated by subglacial meltwater processes (Booth and Hallet, 1993). Pre-Fraser glacial deposits do not presently crop out in the study area but are inferred to underlie Fraser glacier deposits in major valleys such as the SF Nooksack River valley (Dragovich and others, 1997a). In the Puget Lowland, the Fraser glaciation was comprised of three distinct glacial advances, termed stades, including the Coquitlam Stade (30–25Kya), the Vashon Stade (18–13 Kya), and the Sumas Stade (11.5–10 Kya; Booth and others, 2004).

The Puget lobe terminated to the north of the SF Nooksack River Basin in the Fraser Lowland of British Columbia, Canada, during the Coquitlam Stade (Ward and Thomson, 2004). In western Washington, alpine glaciers originating in the Cascade Range advanced during Coquitlam time, which is termed the Evans Creek Stade. Deposits from the Evans Creek Stade are found throughout the major drainages of the Cascade Range, including the valley of the SF Nooksack River, where glacial till consisting of locally derived ultramafic and metamorphic rocks was deposited (Dragovich and others, 2000).

The next advance of the Puget lobe, during the Vashon Stade, was much more extensive than the advance during the Coquitlam Stade. During the Vashon Stade, the Puget lobe advanced over the SF Nooksack River Basin leaving only peaks greater than approximately 6,900 ft exposed as nunataks within the northern Cascade Range (Ragan, 1963). Advance outwash comprised of gravel and sand transported from the north was deposited in advance of the Puget lobe. As the advance of the Puget lobe during the Vashon Stade progressed southward, the ice sheet blocked major drainages of the Cascade Range, including the SF Nooksack River, forming a glacially dammed lake in the SF Nooksack River valley in which glaciolacustrine sediments were deposited (Dragovich and others, 2000). Basal till was deposited beneath the Puget lobe as the ice sheet thickened and overrode the SF Nooksack River Basin. In the major river valleys, subglacial meltwater streams eroded the major Puget Lowland valleys (Booth, 1987) precluding widespread deposition of till in the valleys (Dragovich and others, 1997a). The Puget lobe began to abruptly retreat about 14 Kya and by about 13 Kya it had thinned sufficiently to allow incursion of marine water into the isostatically depressed Puget Lowland resulting in the deposition of glaciomarine drift in the SF Nooksack River valley lower than 400 ft above present sea level (Dethier and others, 1995). A complex assemblage of marine, estuarine, deltaic, and fluvial sediments were deposited within the major fluvial valleys, including the SF Nooksack River valley, during the Everson Interstade.

The Puget lobe’s latest advance into the northern Puget Lowland occurred during the Sumas Stade about 10 Kya (Easterbrook and Kovanen, 2001). The Puget lobe terminated in the Columbia Valley about 10 mi north of the confluence of the outlet of the SF Nooksack River during the Sumas Stade. Easterbrook (1992) proposed that the Puget lobe drained through the SF Nooksack River and Samish River valleys depositing outwash before terminating at a delta in the Skagit River valley. However, more recently, Kovanen and Easterbrook (2001) have proposed an advancement of an alpine glacier through the SF Nooksack River valley after the ice occupying the South Fork Nooksack River valley became detached from the Puget lobe at the end of the Vashon Stade and its accumulation zone changed to the high topography of the Cascade Range. They propose that this ice split into three distinct lobes including a lobe that flowed northward through the present SF Nooksack River valley, eastward towards Lake Whatcom, and southward through the present Samish River valley. The occurrence of locally derived sediment within Sumas glacial outwash in the SF Nooksack River and Samish River valleys is consistent with the advancement of alpine glaciers in the SF Nooksack River Basin, but does not preclude the transport of sediment from the Puget lobe to the north (Dragovich, 2000).

Geologic Units

Major geologic units were generalized from units previously mapped at a 1:100,000 scale across the study area (Lapen, 2000; Tabor and others, 2003) and parts of the Deming and Lyman quadrangles mapped at a 1:24,000 scale (Dragovich and others, 1997a, 2000). The spatial extent of the generalized geologic units is presented in plate 1. In addition to the scale and extent of geologic mapping, there are differences in the resolution and naming conventions within the bedrock and unconsolidated sediment units within these maps, which are unified in this report.

Quaternary (Holocene to latest Pleistocene) deposits include:

Alluvium (Qa).—Alluvium was deposited over older bedrock and unconsolidated sediments by the SF Nooksack River and its tributaries after the establishment of the present drainage pattern following deglaciation and relative sea-level fall between the late-Pleistocene and Holocene. Several distinct types of alluvium occur in the study area including channel, overbank, and alluvial fan deposits. Channel deposits are typically comprised of uncompacted, moderate to well-sorted cobbles, gravel, and sand; and occur within the present channel of the SF Nooksack River and in abandoned channels across its floodplain. Overbank deposits typically are comprised of fine-grained, well-stratified sand, silt, and clay; and primarily occur in the wide valley of the SF Nooksack River downstream of its confluence with Skookum Creek. Alluvial fan deposits occur throughout the study area where tributaries to the SF Nooksack River flow from high-gradient uplands to the lower-gradient SF Nooksack River valley. Alluvial-fan deposits typically are poorly sorted, massive to weakly stratified boulders to clay of debris-flow origin. The thickness of Qa ranges from a thin veneer over bedrock and older unconsolidated sediments to a maximum thickness of about 90 ft (Dragovich and others, 1997a).

Landslide deposits (Qls).—Landslide deposits consisting of poorly sorted, unstratified diamicton occur throughout the study area as a result of shallow debris flows, deep-seated earth flows, as well as rock avalanches (talus). Landslide deposits vary greatly in thickness and originate in sedimentary, metamorphic, and igneous bedrock as well as unconsolidated glacial sediment throughout the study area. Notable landslide deposits are associated with deep-seated earth flows that originated within the Twin Sisters Dunite of which several have reached the SF Nooksack River valley. In addition, a large (about 5 km^2) landslide deposit near the outlet of the SF Nooksack River originated on the flanks of Van Zandt Dike within the Chuckanut Sandstone.

Glacial outwash, Sumas Stade and Everson Interstade (Qgo_s/Qgo_e).—Glacial outwash deposited in the study area during the Sumas Stade and Everson Interstade consists of loose, moderately to well-sorted sand, gravel, and cobbles.

Sumas glacial outwash deposits are typically stratified and locally contain silt interbeds. Sumas glacial outwash typically overlies Everson glaciomarine drift and Everson outwash and is preserved in isolated terraces at the margins of the SF Nooksack River valley owing to post-glacial incision and reworking by the SF Nooksack River. The thickness of Sumas glacial outwash varies from a few feet to about 100 ft within terraces of the SF Nooksack River valley (Dragovich and others, 1997a).

Glaciomarine drift, Everson Interstade (Qgm_e).— Everson glaciomarine drift was deposited over older glacial sediments in the study area below the glaciomarine limit and typically consists of a poorly to moderately sorted, poorly compacted, massive diamicton deposited in glaciomarine environment (Dragovich and others, 1997a). Isostatic uplift during the Everson Interstade resulted in fluvial incision and erosion of Qgm_e prior to subsequent deposition of overlying glacial outwash and alluvium. This unit does not crop out in the study area, but is inferred to underlie younger unconsolidated sediments including Qgo_s, Qgo_e, and Qa in the major valleys (Dragovich and others, 1997a).

Till, Vashon Stade (Qvt).—Vashon till consists of a dense to very dense unstratified diamicton of poorly sorted clay, silt, sand, and gravel, and varies in thickness from a few feet on bedrock uplands to 50 ft or more within localized depressions (Dragovich and others, 1997a). Locally, cobbles and boulders occur within the Vashon till. In the lower SF Nooksack River valley, Vashon till is preserved along valley walls but was mostly removed by subglacial meltwater processes prior to the deposition of Everson glaciomarine drift below the glaciomarine limit during the Everson Interstade. Locally, the Vashon till underlies Everson glaciomarine drift below the Everson glaciomarine limit (Dragovich, 1997a).

Advance outwash, Vashon Stade (Qga).—Advance outwash deposits consist of moderately to well-sorted and dense sand and gravel with discontinuous clay and silt interbeds. Advance outwash was deposited throughout the study area and is commonly overlain by till or glaciomarine sediment.

Glacial drift, pre-Fraser Glaciation (Qpf).—Older glacial deposits deposited before the Fraser Glaciation may be locally preserved in the SF Nooksack River valley where they were not subsequently eroded by fluvial or glacial processes (Dragovich and others, 1997a). This unit was not mapped at the surface of the study areas, but may occur locally as small, unmapped outcrops or at depth below younger glacial sediments and alluvium. Pre-Fraser glacial deposits likely include both well-sorted glacial outwash deposits and poorly-sorted diamictons such as glacial tills.

Chuckanut Formation, Bellingham Bay Member (Ec_{cb}).—The Chuckanut Formation consists of alternating interbeds of coarse-grained sediments including arkosic sandstones and conglomerates with fine-grained mudstones, siltstones, and minor coal layers deposited during the Eocene. Sedimentary structures suggest a meandering and adjacent floodplain depositional environment for the Bellingham Bay Member of the Chuckanut Formation.

Metasedimentary rocks, pre-Tertiary (pTms).— Metasedimentary rocks include a diverse suite of rocks from several different tectonic terranes including well-metamorphosed deep-marine sediments including the Darrington Phyllite of the Easton terrane, metamorphosed sedimentary rocks of the Chilliwack River and Nooksack terranes.

Metaigneous rocks, pre-Tertiary (pTmi).— Metaigneous rocks including the Twin Sisters Dunite of the Bell Pass Mélange and metamorphosed volcanic sediments primarily occur in the eastern part of the study area.

Hydrogeologic Units

Five hydrogeologic units in the SF Nooksack River Basin consisting of aquifers and confining units were identified from surficial geologic mapping, lithostratigraphic information, and field observations (pl. 2). These units were differentiated from each other on the basis of their lithologic and hydraulic characteristics, stratigraphic position, and the occurrence of groundwater under unconfined and confined conditions. Saturated hydrogeologic units that were sufficiently permeable to yield water in significant quantities to a well or a spring were classified as aquifers, whereas hydrogeologic units with low permeability that restricts the movement of groundwater were classified as confining units. Groundwater occurs under unconfined or water-table conditions where the upper surface of the saturated zone of aquifers is in contact with the atmosphere and the groundwater level freely rises and declines in response to changes in recharge and discharge. Confined or artesian conditions occur when a low-permeability confining unit overlies an aquifer and keeps groundwater under a pressure greater than atmospheric pressure. In a tightly cased well open to a confined aquifer, water levels rise to a height corresponding with the hydraulic head of the confined aquifer at that location, which is termed the potentiometric surface. A well completed in a confined aquifer that has a potentiometric surface above land surface is called a flowing artesian well.

Complex depositional environments of Quaternary alluvium and glacial sediment create local variability of the thickness of hydrogeologic units and their stratigraphic relation to one another. In addition, alluvial and glacial deposits are heterogeneous; thus an aquifer, generally composed of coarse-grained, well-sorted sediments that readily transmit groundwater, also may contain discontinuous fine-grained or poorly sorted sediments that inhibit groundwater flow and act as confining units. Although this heterogeneity may affect the occurrence and flow of groundwater at a local scale, it does not occur at a large enough scale to be adequately represented within the basin-scale hydrogeologic framework presented in this report.

Three hydrogeologic units consist of unconsolidated sediment of Holocene and Pleistocene age: Qa/go (alluvial and recessional outwash aquifer), $Qvt/ls/gm_e$ (till and glaciomarine drift confining unit), and Qga/pf (advance glacial outwash and older glacial drift aquifer). Hydrogeologic units within Tertiary and older bedrock include the Ec_{cb} sedimentary bedrock unit and the pTm metamorphic bedrock unit. These hydrogeologic units broadly correspond to those described in the western part of the study area by Dragovich and others (1997a) and in the adjoining Skagit River Basin to the south of the study area by Savoca and others (2009). In general, groundwater flows through interstitial spaces within unconsolidated hydrogeologic units, but largely occurs in fractures and other sources of secondary porosity in bedrock hydrogeologic units.

Alluvial and recessional (post-Vashon glacial) outwash aquifer (Qa/go).—The alluvial and recessional outwash aquifer is present throughout the SF Nooksack River valley and exists discontinuously in upland areas including the headwaters of Hutchinson Creek. This aquifer consists of a heterogeneous mixture of sand, gravel, and cobbles deposited by the modern SF Nooksack River, its tributaries, and meltwater streams originating from the Puget lobe and alpine glaciers during the latest Pleistocene and Holocene. Groundwater generally occurs under unconfined conditions within Qa/go where saturated, but discontinuous lenses of silt and clay may locally create confined conditions. The thickness of these units varies considerably owing to local topography and is greatest within the lower SF Nooksack River valley where it reaches a maximum thickness within terraces at the margins of the valley. The thickness of Qa/go ranged from 15 to 79 ft with a median thickness of 47 ft in the 28 study wells that fully penetrated the unit. The hydraulic conductivity of nine wells completed within this unit was computed and ranged from 15 to 945 ft/d with a median hydraulic conductivity of 162 ft/d.

Till and glacio-marine drift confining unit ($Qvt/ls/gm_e$).—The till and glaciomarine drift confining unit consists of diamictons within the landslide deposits (Qls), Vashon till (Qvt), and Everson glaciomarine drift (Qgm_e). The poorly sorted clay, sand, gravel, cobbles, and boulders within this hydrogeologic unit have low permeability and confine groundwater within the advance glacial outwash and older glacial drift aquifer (Qga/pf), which underlies the $Qvt/ls/gm_e$ confining unit where present. This unit mantles parts of the bedrock uplands in the study area as a thin, discontinuous veneer and also occurs at depth in the SF Nooksack River valley and other tributary valleys beneath the Qa/go aquifer. The thickness of $Qvt/ls/gm_e$ ranged from 22 to 363 ft with a median thickness of 57 ft in the 13 study wells that fully penetrated the unit. Pump test data were not available for wells completed in this unit precluding estimates the hydraulic conductivity of this unit.

Advance glacial outwash and older glacial drift aquifer (Qga/pf).—The advance glacial outwash and older glacial drift aquifer occurs within the main SF Nooksack River valley and the adjacent Samish River valley and is typically bounded by the overlying $Qvt/ls/gm_e$ confining unit and underlying bedrock. Groundwater occurs under confined conditions and under artesian pressure at several locations in the study area. In addition, low-permeability units may locally exist within the unit. Few wells penetrate the entire thickness of this unit precluding complete characterization of its extent and thickness. The thickness of Qa/pf ranged from 32 to 40 ft in the two study wells that fully penetrated the unit. Hydraulic conductivity was estimated for two wells completed within this unit with pump test data, and ranged from 520 to 991 ft/d.

Sedimentary aquifer (Ec_{cb}).—The sedimentary aquifer largely crops out in the western part of the study area and occurs below unconsolidated glacial sediments in the western part of the SF Nooksack River valley. Groundwater primarily occurs in coarse-grained, permeable sandstone and conglomerate units that alternate with less permeable mudstone and sandstone layers. Groundwater in this aquifer may be locally unconfined where this unit crops out, but generally occurs under confined conditions where it is fully saturated and overlain by the till and glaciomarine drift confining unit. Pump test data were not available for wells completed in this unit, precluding estimates the hydraulic conductivity of this unit.

Igneous and metamorphic bedrock basal confining unit (pTm).—Igneous and metamorphic rocks crop out in large parts of the uplands of the study area and include phyllites, schists, dunites, and volcanic rocks. Permeability within these rocks is typically low and the relatively small amount of groundwater present occurs and flows through fractures, joints, and other sources of higher permeability. Some domestic wells are open within water-bearing fractures within phyllites in the western part of the study area, but yields for these wells are typically low according to drillers' logs. Pump test data were not available for wells completed in this unit, precluding estimates the hydraulic conductivity of this unit.

Groundwater

Groundwater flows in the direction of decreasing water-level altitudes and perpendicular to water-level altitude contours, which generally follow topographic contours in the study area. In general, groundwater moves from high-altitude areas of recharge to low-altitude areas of discharge including springs, wells, and surface-water features, such as rivers and wetlands. Groundwater in the study area is derived from precipitation, including rainfall and snowmelt, which does not run off over the surface or evapotranspire, but percolates below the root zone from the surface into unconsolidated sediments and rocks.

Groundwater levels were measured synoptically throughout the study area in domestic wells during the well inventory in August 2012 and were measured at 14 wells at a monthly interval from October 2012 through September 2013.

The movement of groundwater through the study area is determined by the characteristics of the hydrogeologic units and their relation to each other as described in section, "Hydrogeologic Framework." The presence or absence of low-permeability confining units results in the occurrence of groundwater under both confined or unconfined (water-table) conditions in aquifers in the study area.

Groundwater Occurrence and Movement

In the valleys of the SF Nooksack River and its tributaries, groundwater primarily occurs in the permeable, unconsolidated sediments of the Qa/go and Qga/pf aquifers. In addition, groundwater locally occurs in permeable interbeds within the Qvt/ls/gm_e confining unit, but is not significant at a regional scale. Groundwater also occurs within the bedrock hydrogeologic units including Ec_{cb} and pTm that underlie the uplands of the study area, but its occurrence and movement within these units is restricted by low hydraulic conductivity and generally restricted to fractures, bedding planes, and other sources of secondary porosity.

Unconfined or water-table conditions prevail in the Qa/go aquifer except where it is locally overlain by poorly sorted landslide deposits within the Qvt/ls/gm_e confining unit or confined by low-permeability interbeds within the Qa/go aquifer. Horizontal groundwater-flow directions within the Qa/go aquifer were inferred from water-table contours of the Qa/go aquifer constructed from groundwater-level altitudes measured in August 2012 (fig. 5). Water-table gradients within the Qa/go aquifer followed the slope of the land surface with the steepest gradients mapped in the tributary valleys to the main SF Nooksack River valley. Groundwater gradients in the main SF Nooksack River valley were considerably less (about 35 ft/mi) than the tributary valleys and became progressively flat downstream, approaching 15 ft/mi in the lower SF Nooksack River valley. A shallow groundwater drainage divide between the SF Nooksack River and the Samish River Basins exists within the Qa/go aquifer near the low topographic divide between the basins. Mapped water-table contours (fig. 5) suggest that the Samish River Basin receives some groundwater flow from the SF Nooksack River Basin, however, the seasonal stability of this groundwater divide is not well known because of limited distribution of wells and water-level measurements within the Qa/go aquifer near the divide.

The Qvt/ls/gm_e confining unit is present throughout the SF Nooksack River valley and also occurs as part of a thin veneer over the bedrock uplands. This unit, which consists of poorly sorted and compacted unconsolidated sediments, generally acts as a confining unit, but groundwater occurs locally in high-permeability lenses within it. Groundwater within the Qga/pf aquifer is typically bounded by the overlying Qvt/ls/gm_e confining unit and underlying bedrock. In parts of the study area, the potentiometric surface within the Qga/pf aquifer is above land surface resulting in flowing (artesian) wells including wells 37N/05E-06R02 and 37N/05E-07K01 (pl. 2).

Few of the inventoried wells were completed within the Ec_{cb} or the pTm hydrogeologic units (table 1) precluding a complete characterization of these hydrogeologic units. In Skagit County, to the south of the study area, Savoca and others (2009) report the occurrence of groundwater in coarse-grained strata within a correlative hydrogeologic unit of the Ec_{cb} aquifer, which has a relatively low hydraulic conductivity (median: 0.27 ft/d). Groundwater primarily occurs in coarse-grained sandstone and conglomerate layers within this unit, which are separated by fine-grained siltstone intervals that locally produce confined conditions (Savoca and others, 2009). The limited extent of this hydrogeologic unit within the SF Nooksack River Basin coupled with its low hydraulic conductivity and the availability of water within the unconsolidated sediments of the Qa/go aquifer at shallower depths in the main river valley, preclude the Ec_{cb} aquifer from becoming an important water-bearing unit in the study area.

Seasonal Groundwater Fluctuations

Groundwater levels in the aquifers of the study area fluctuate because of changes in the rates of recharge to and discharge from the aquifers. When recharge exceeds discharge, groundwater levels rise and groundwater storage increases; conversely, when discharge exceeds recharge, groundwater levels decline and groundwater storage decreases. Precipitation infiltrates the land surface and percolates through the unsaturated zone to the water table and recharges the aquifers. Precipitation is not evenly distributed throughout the year; most rainfall occurs between November and March, whereas snowmelt is greatest during April and May resulting in seasonal variability in recharge to aquifers in the study area. Surface-water features such as streams also provide recharge to underlying aquifers when surface-water stages exceed groundwater levels. Streamflow and stage of the SF Nooksack River is greatest as a result of storms during the autumn and early winter (November through January) and following the melting of the snowpack during the spring freshet in May (fig. 3). Streamflow and stage reach an annual minimum during August and September during the dry season and following the melting of the snowpack.

In the seven wells completed within the Qa/go aquifer, where groundwater levels were monitored monthly during water year 2013, water-level fluctuations ranged from 13.8 to 2.6 ft with a median fluctuation of 6.1 ft. Seasonal changes in water-level altitudes measured during water year 2013 in well 37N/05E-22N01 are typical of other completed wells in the Qa/go aquifer. The hydrograph of well 37N/05E-22N01 is characterized by increasing water-level altitudes between October and December during storm-driven high flows in late autumn and early winter, and snowmelt-driven high-flows during early spring between March and April (fig. 6). After the spring freshet, water-level altitudes in this well decrease throughout the summer corresponding with low precipitation and increased water use for domestic and agricultural irrigation.

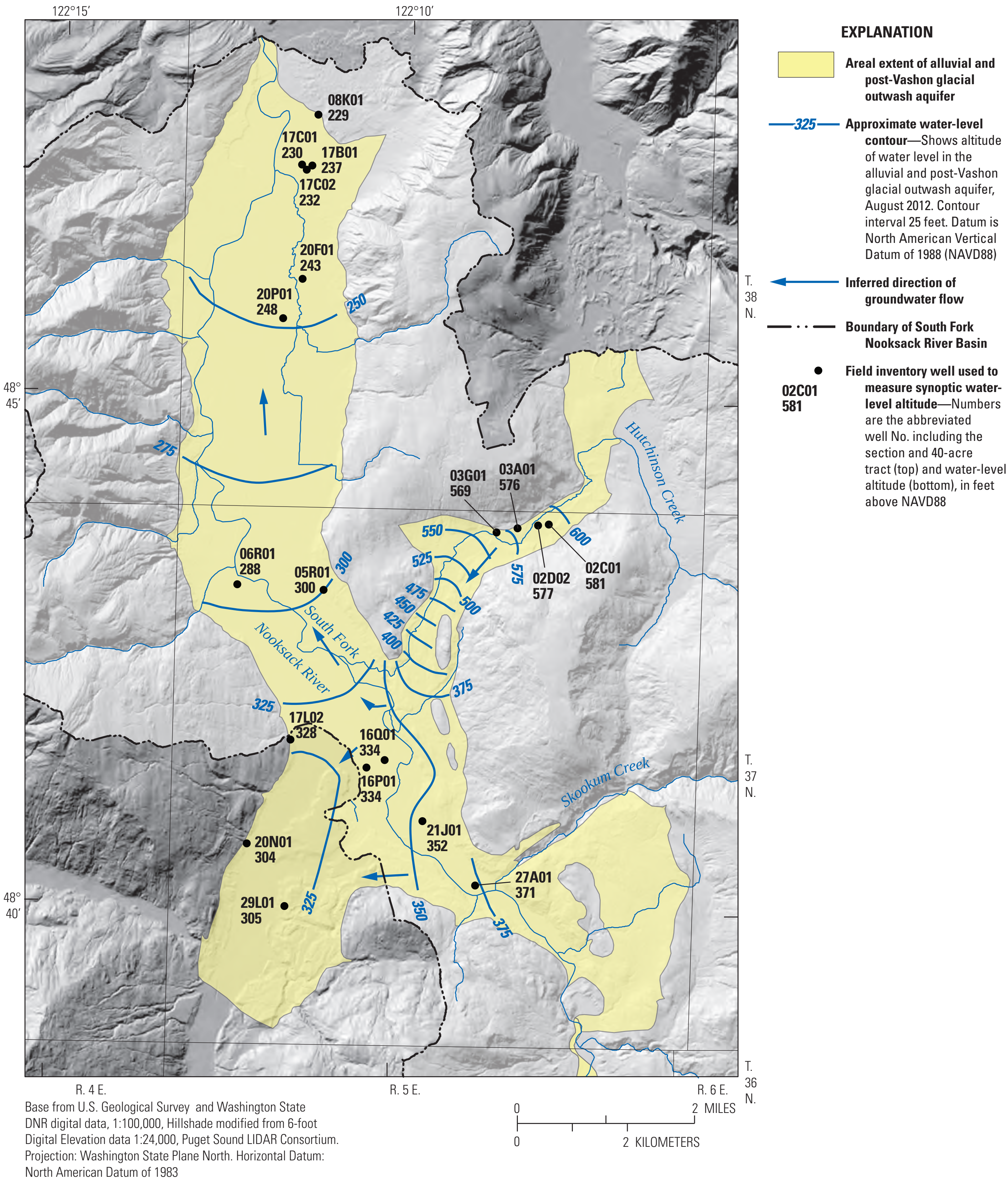


Figure 5. Water-level altitudes and groundwater flow directions in the alluvial and recessional (post-Vashon glacial) outwash aquifer (Qa/go) in the South Fork Nooksack River Basin, northwestern Washington, August 2012.

Seasonal changes in water-level altitudes in wells completed within the Qga/pf aquifer were largely similar to those measured in wells completed within the Qa/go aquifer for water year 2013. Water-level altitudes in well 37N/05E-22P01, for example, increased during the late autumn and early winter and again during spring before decreasing throughout the summer (fig. 7). The distribution of wells precluded determination of vertical gradients, but the close correspondence of seasonal water-level fluctuations in wells within the Qa/go and Qga/pf aquifers suggests hydraulic connections between them. Water levels measured in one well (37N/05E-20R04), which was completed in a low-permeability layer in the Qga/pf aquifer were not consistent with the seasonal water-level fluctuations measured in either the Qga/pf or Qa/go aquifer elsewhere in the study area (fig. 8). Water-level altitude measured in this well (37N/05E-20R04) increased from November to May, but did not decrease between December and February like well 37N/05E-22N01 (fig. 6) or well 37N/05E-22P01 (fig. 7). These data suggest heterogeneity within the Qga/pf aquifer and differences in its hydrologic connection to adjacent hydrogeologic units and surface-water features.

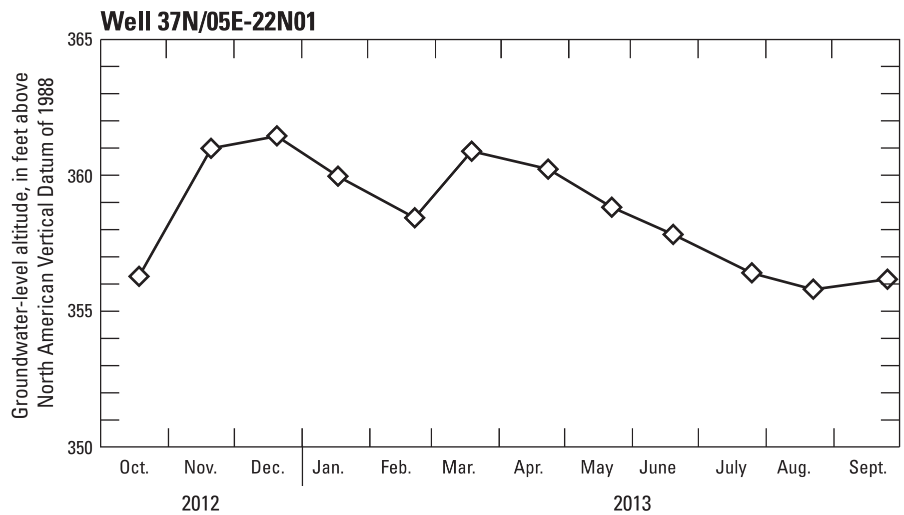


Figure 6. Water-level altitudes for well 37N/05E-22N01, South Fork Nooksack River Basin, northwestern Washington, October 2012–September 2013.

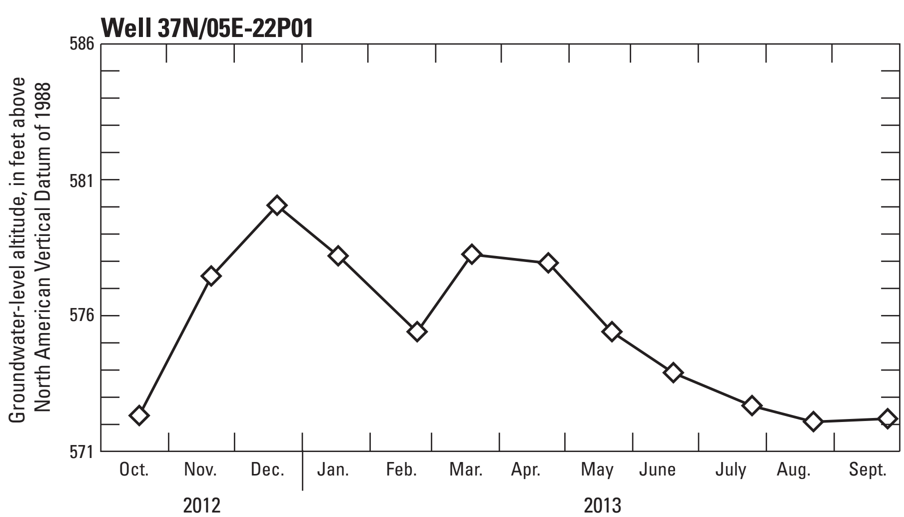


Figure 7. Water-level altitudes for well 37N/05E-22P01, South Fork Nooksack River Basin, northwestern Washington, October 2012–September 2013.

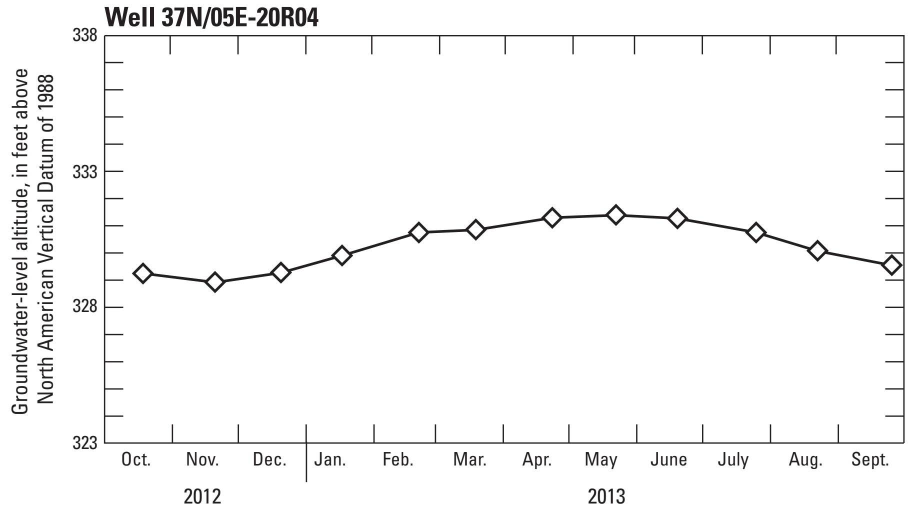


Figure 8. Water-level altitudes for well 37N/05E-20R04, South Fork Nooksack River Basin, northwestern Washington, October 2012–September 2013.

Groundwater/Surface-Water Interactions

Groundwater/surface-water interactions were characterized by synoptic streamflow measurements, FO-DTS, and continuous monitoring of water levels in the SF Nooksack River, the surficial Qa/go aquifer, and wetlands. The Qa/go aquifer is the principal hydrogeologic unit that interacts with surface-water features in the study area including rivers, streams, and wetlands. Groundwater/surface-water interactions are spatially and temporally variable in the study area. Depending on hydrologic conditions within the Qa/go aquifer and surface-water features, the Qa/go aquifer discharges to and receives recharge from surface-water features. Discharge to surface-water features may vary over spatial scales as long as mile-scale reaches and over the scales of discrete seeps and springs. Recharge of the Qa/go aquifer occurs when the stage of the SF Nooksack River is higher than the Qa/go aquifer, which occurs during late autumn and winter precipitation, and spring snowmelt. Conversely, the Qa/go aquifer generally discharges to the SF Nooksack River during the late summer when surface runoff is minimal and most streamflow originated as groundwater inflow to the SF Nooksack River.

Diurnal and seasonal variability in surface water temperature is not present in the temperature of shallow groundwater, which generally approximates the mean annual air temperature. Consequently, groundwater moderates surface-water temperatures and helps to maintain ecological function of fluvial systems (Brunke and Gonser, 1997). Groundwater is one of several atmospheric, geomorphic, and hydrogeologic factors that influence stream temperature across different spatial and temporal scales (Caissie, 2006). The water temperature measured at a point in a stream reflects the energy balance within the upstream drainage network. Solar (shortwave) radiation plays a dominant role in the thermal budget of many streams (Sinokrot and Stefan, 1993; Webb and Zhang, 1997), but other factors including long wave radiation, sensible and latent heat transfer, friction, bed conduction, and advective of heat through groundwater input, also play important roles (Kelleher and others, 2012). Diurnal and seasonal temperature variability resulting from changes in the solar radiation are apparent in thermographs measured on the SF Nooksack River at USGS streamgage 12210000 (fig. 4). The coldest stream temperatures occurred in the winter, coincident with the annual minimum in solar radiation, whereas the warmest stream temperatures occur in the summer, coincident with the annual maximum in solar radiation. In addition, daily variability in stream temperature occurs as the result of the diurnal cycle of solar radiative forcing, but is most pronounced during summer relative to winter because the contrast in solar radiation from night to day is greatest during the summer.

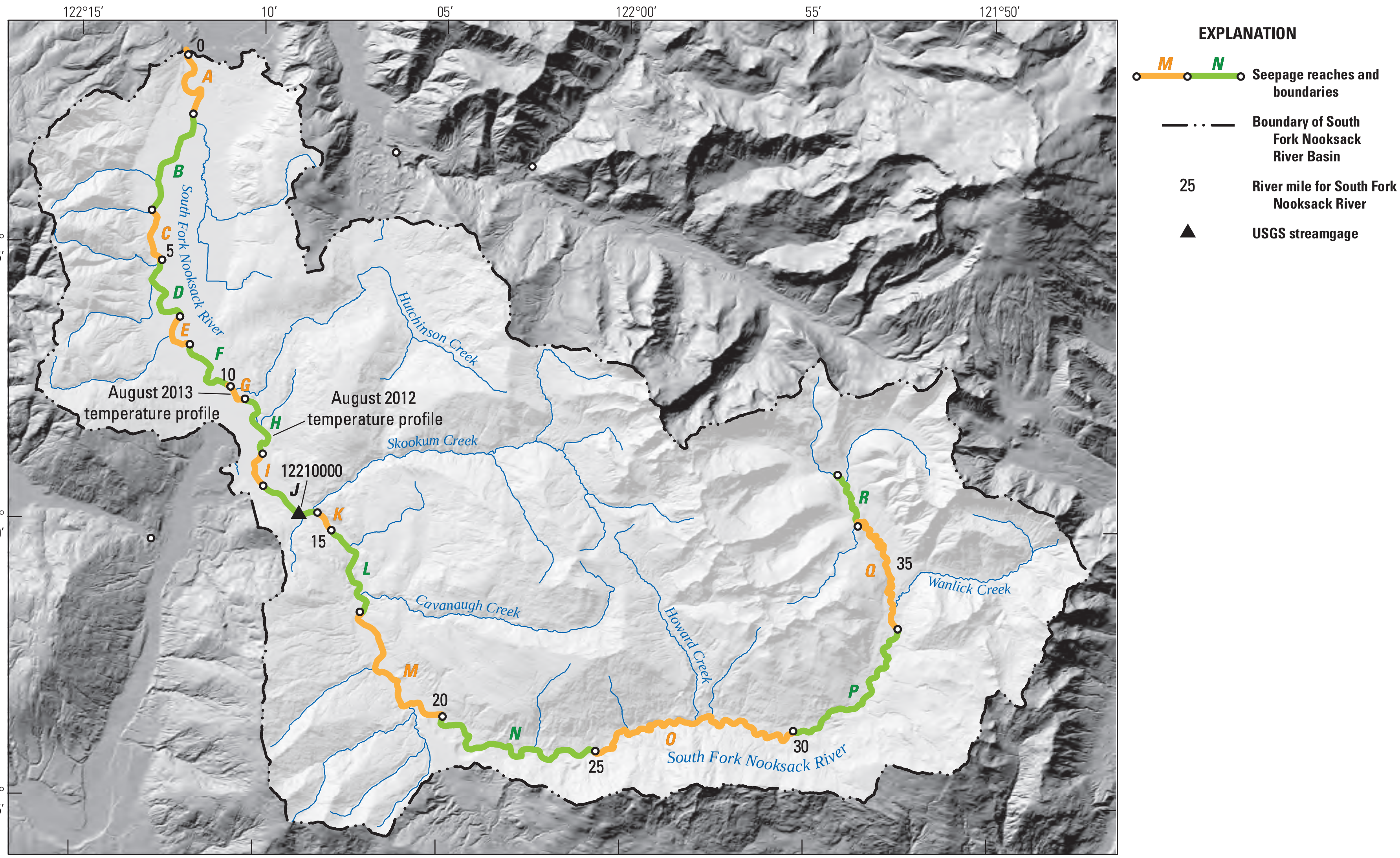
The exchange of groundwater and surface water has the potential to buffer stream temperatures and to create thermal refugia that plays a critical role in promoting the health and viability of salmonid populations (Torgersen and others, 2012). Groundwater inflow may occur as discrete seeps into a river or more broadly along several miles of stream length. The influence of discharging groundwater on stream temperature reflects the difference in temperature between groundwater and surface water, the magnitude of groundwater inflow relative to streamflow, and the length of reach over which the exchange occurs. Several types of geomorphic conditions create and maintain cold-water habitat including lateral seeps where the active channel intercepts groundwater flow through the floodplain, an alluvial fan, or hillslope; subsurface flow through meander bends and former channels; upwelling of hyporheic flow and shallow groundwater into the upstream sides of pools within channels; and thermal stratification within pools (Torgersen and others, 2012).

Seepage Investigation

The bulk exchange of water between the SF Nooksack River and the shallow groundwater system was characterized through seepage run data collected in August 1998, September 1998, and September 2012. Collectively, the three seepage runs show spatial variability of seepage gains and losses in the SF Nooksack River and provide insight into their temporal variability over a range of baseflows. Seepage data were collected in August and September 1998 by Wiggens and others (1999) between RM 0.05 and 37.4 at 18 seepage reaches (A–R; fig. 9). The seepage runs during August and September 1998 indicate that the SF Nooksack River was primarily gaining streamflow from groundwater in seepage reaches L–R upstream of the confluence of the SF Nooksack River with Skookum Creek, but gains, loses, and remains near neutral downstream of this location in reaches A–K (figs. 10*A* and 10*B*). Downstream of its confluence with Skookum Creek, the SF Nooksack River meanders across a broad 1–2-mi wide floodplain consisting of alluvium and glacial outwash (pl. 2). Unconsolidated sediments consisting of alluvium and glacial drift are much thinner and the depth to bedrock is shallower in the upper SF Nooksack River compared to downstream reaches. Although the primary porosity of the pTm hydrogeologic unit, which underlies the upper SF Nooksack River, is poor, flow from fractures within this unit may contribute to streamflow gains within the SF Nooksack River.

The seepage runs in August and September 1998 were augmented by a seepage run conducted during September 2012 between RM 1.9 and 14.8 (seepage reaches B–K; fig. 9). Streamflow was measured over a 2-day period at 23 locations including 12 sites on the SF Nooksack River and 11 sites on tributaries, and streamflow gains and losses were calculated for 10 seepage reaches (B–K) along the SF Nooksack River (fig. 9). The seepage run in September 2012 included reaches in the broad lower valley of the SF Nooksack River downstream of RM 14.8, whereas the seepage runs in August and September 1998 also included reaches in the confined upper SF Nooksack River valley. Based on streamflow measurements at USGS streamgage 12209000 (RM 14.8) during each of the seepage runs, streamflow was about 28 and 47 percent higher during the September 2012 seepage run than during the August 1998 and September 1998 seepage runs, respectively. The same streamflow gains and losses measured during the September 2012 seepage run (fig. 10*C*) were not measured during the August and September 1998 seepage runs (figs. 10*A* and 10*B*) suggesting temporal variability in groundwater/surface-water interactions throughout much of the SF Nooksack River. In the upper SF Nooksack River in seepage reaches N, O, P, and R, streamflow gains were measured during the seepage runs in August and September 1998.

Seepage gains and losses calculated for the SF Nooksack River during September 2012 are presented in table 2. Seven of the ten seepage reaches measured in 2012 were categorized as “near-neutral” with calculated seepage gains and losses less than the propagated streamflow-measurement errors. The greater occurrence of near-neutral seepage measurements in the downstream reaches of the SF Nooksack River may reflect the small magnitude of seepage gains and losses relative to streamflow. Because streamflow measurement errors are directly proportional to the magnitude of streamflow, the streamflow gains or losses must be commensurately larger in magnitude to be detectable. In the near-neutral seepage reaches, net streamflow gains and losses were measured, but collectively they were smaller in magnitude than the propagated streamflow-measurement errors. Gains or losses greater than measurement error for a given reach during a seepage run were determined to be significant. Two of the 10 reaches between F and H, show significant streamflow gains of 13.0 and 20.6 ft^3/s (fig. 10*C*). There was one significant streamflow loss of 20.0 ft^3/s measured in seepage reach G during the seepage run in September 2012 (fig. 10*C*).



Base from U.S. Geological Survey and Washington State DNR digital data, 1:100,000,
Hillshade modified from 6-foot Digital Elevation data 1:24,000, Puget Sound LIDAR Consortium.
Washington State Plane North. Horizontal Datum: North American Datum of 1983.

Figure 9. Seepage reaches (A–R) during seepage runs in August and September 1998 and September 2012, South Fork Nooksack River Basin, northwestern Washington.

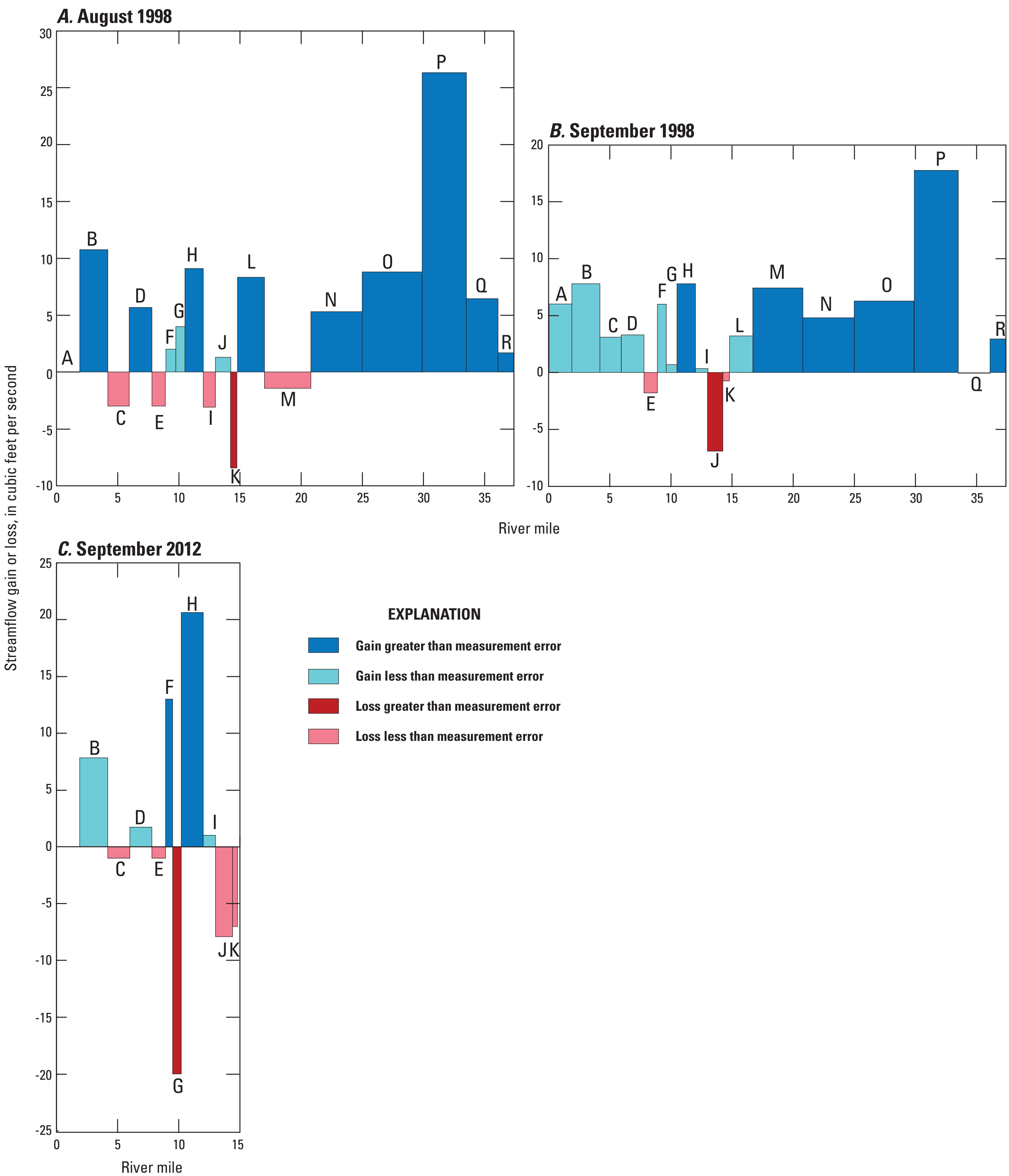


Figure 10. Seepage gains and losses measured during the seepage runs in August 1998 (*A*), September 1998 (*B*), and September 2012 (*C*), South Fork Nooksack River Basin, northwestern Washington.

Table 2. Evaluation of gains and losses for seepage investigation, South Fork Nooksack River Basin, northwestern Washington, September 2012.

[Associated measurement error for net gain or loss was calculated using the propogation of error formula (Wheeler and Eddy–Miller, 2005) where *s* is the error propogated from all estimated individual errors and *a*, *b*, …, *n* are estimated errors for the discharge measurement at each site: $s = \sqrt{(\pm a)^2 + (\pm b)^2 + ...(\pm n)^2}$. Seepage reach delineated in figure 9. **Remarks:** Near neutral; difference in measured discharge is less than associated measurement error. **Abbreviations:** ft^3/s, cubic feet per second; mi, mile; SF, South Fork; USGS, U.S. Geological Survey; –, no data]

Measurement sites and USGS station No.	Measured streamflow (ft^3/s)		Assumed measurement error (percent)	Date	Net seepage gain or loss of mainstem (ft^3/s)	Associated measurement ± error (ft^3/s)	SF Nooksack River river mile (mi)	Remarks
	Mainstem	Tributary						
SF Nooksack River (12209000)	113	–	8	09-12-12	–	–	14.8	–
SF Nooksack River (12209010)	106	–	8	09-12-12	-7	12.4	14.4	Near neutral
Skookum Creek (12209494)	–	18.8	8	09-12-12	–	–	–	–
Hatchery Ouflow (12209498)	–	15.1	5	09-12-12	–	–	–	–
SF Nooksack River (12210000)	132	–	5	09-12-12	-7.9	10.8	13	Near neutral
SF Nooksack River (12210140)	133	–	5	09-12-12	1	9.4	12	Near neutral
Hutchinson Creek (12210205)	–	3.42	11	09-12-12	–	–	–	–
SF Nooksack River (12210160)	157	–	5	09-12-12	20.6	10.3	10.2	Gaining
SF Nooksack River (12210210)	137	–	5	09-12-12	-20	10.4	9.5	Losing
SF Nooksack River (12210215)	150	–	5	09-12-12	13	10.2	8.9	Gaining
SF Nooksack River (12210215)	143	–	5	09-13-12	–	–	8.9	–
Jones Creek (12210220)	–	0.01	11	09-13-12	–	–	–	–
Unnamed Tributary (12210273)	–	1.12	8	09-13-12	–	–	–	–
SF Nooksack River (12210275)	143	–	5	09-13-12	-1.13	10.1	7.8	Near neutral
McCarty Creek (12210285)	–	0.19	11	09-13-12	–	–	–	–
Standard Creek (12210290)	–	0.08	11	09-13-12	–	–	–	–
SF Nooksack River (1210300)	145	–	5	09-13-12	1.73	10.2	6	Near neutral
Hardscrabble Gulch (12210315)	–	0	0	09-13-12	–	–	–	–
SF Nooksack River (12210340)	144	0	5	09-13-12		10.2	4.2	Near neutral
Sygitowicz Creek (12210340)	–	0.04	11	09-13-12	–	–	–	–
Todd Creek (12210360)	–	0.14	11	09-13-12	–	–	–	–
Black Slough (12210380)	–	0	0	09-13-12	–	–	–	–
SF Nooksack River (12210485)	152	–	5	09-13-12	7.82	10.5	1.9	Near neutral

Influence of Groundwater on Surface-Water Temperature in the South Fork Nooksack River

Near-streambed temperatures were monitored at 30-minute intervals at two reaches of the SF Nooksack River using a FO-DTS in August 2012 and August 2013. During August, stream temperatures typically reach their annual maximum in the SF Nooksack River and the difference between stream temperature and shallow groundwater temperature is most pronounced. From August 8–16, 2012, the FO-DTS was deployed along a 950-ft reach of a side channel at RM 11.2 of the SF Nooksack River (fig. 11). This side channel flows through an active gravel bar at the edge of a floodplain terrace of the SF Nooksack River, which is confined on the other side by a bedrock hillslope. Groundwater seeps were observed at several locations along the edge of the floodplain terrace. From August 13 to 19, 2013, the FO-DTS was deployed in a 650-ft reach of the main channel of the SF Nooksack River at RM 10.0 (fig. 12). This deployment was immediately downstream of the confluence of the SF Nooksack River with Hutchinson Creek, and adjacent to the wetland where water levels were monitored continuously from December 2012 to July 2013. During August 2012, engineered log jams were constructed in this reach and the FO-DTS was placed within three pools associated with these log jams during the August 2013 deployment. These pools provide cover and other structural habitat requirements for anadromous salmonids at several key life history stages including rearing of juvenile (for example, Pess and others, 2012) and adult salmonids in the Pacific Northwest (Peters and others, 1998) and these data suggest that they also have the potential to help meet the thermal requirements of salmonids.

Fiber-Optic Distributed Temperature Sensor Deployment at River Mile 11.2 (August 2012)

Near-streambed temperature data measured during the August 2012 deployment of the FO-DTS in a side channel at RM 11.2 are shown in figure 13. Throughout much of the reach, temperature was measured between approximately 50 and 70 °F during the 7-day deployment. The diurnal temperature variability was muted at several locations including near 80, 510, 840, and 920 ft (fig. 13) and near-streambed temperatures generally were between 50 and 54 °F, which is much lower than adjacent reaches of the side channel. Active stream bank seeps were observed during the deployment at 510 and 840 ft and additional groundwater was inferred to be upwelling into the side-channel streambed at these locations. At 80 and 920 ft where the other cold-water anomalies were observed, active bank seeps were not observed. The magnitude of cold groundwater input relative to surface water flowing into the upstream was high at these locations allowing cool temperature anomalies associated with their input to be detected. The spatial distribution of these cool temperature anomalies also suggests that groundwater input into the reach occurs at short, discrete locations and are not spatially extensive such that they cool the entire reach. In the main channel of the SF Nooksack River, upstream input of streamflow is much greater than the potential input of similar bank seeps, suggesting that cool temperature anomalies may be more limited in the main channel.

Fiber-Optic Distributed Temperature Sensor Deployment at River Mile 10.0 (August 2013)

During August 2013, the FO-DTS was deployed in a loop along both margins of the SF Nooksack River channel and across two riffles at RM 10.0 (fig. 12). Near-streambed temperature data measured during this deployment are shown in figure 14. Temperatures had a diurnal range between approximately 55 and 70 °F during the 7-day deployment. At a distance of 1,080 ft, a cool temperature anomaly was recorded in the pool of one of the engineered log jams. During the nighttime, this temperature anomaly did not persist and was similar to the temperature of the surrounding area, suggesting that the cold-water anomaly observed during the daytime may have resulted, at least partly, from thermal stratification and could not entirely be attributed to groundwater inflow at this location.

Wetland/Groundwater/River Interactions

Several permanently and seasonally flooded wetlands presently occupy the study area. More extensive wetlands in the SF Nooksack River valley were ditched and drained for conversion to agricultural land beginning in the late 19th century like wetlands in other river valleys throughout the Puget Lowland (Collins and others, 2003). Wetlands in the study area occur as a result of several hydrologic and geomorphic conditions, and consequently have different relations to the groundwater-flow system. For example, some perennial wetlands at the margins of the SF Nooksack River valley result from the intersection of the steep-gradient water table in upland areas with the flat river valley bottom. Other riparian wetlands, however, occur where groundwater is perched on fine-grained, low-permeability sediments on the floodplain and receive recharge predominantly from direct precipitation. Finally, some wetlands in the study area occur in depressions, including former channels of the SF Nooksack River floodplain below the water-table of the Qa/go aquifer, and are hydrologically connected to the Qa/go aquifer and the SF Nooksack River itself. Brinson (1993) discusses in detail the geomorphic and hydrogeologic occurrence of these different types of wetlands and their ecological context.

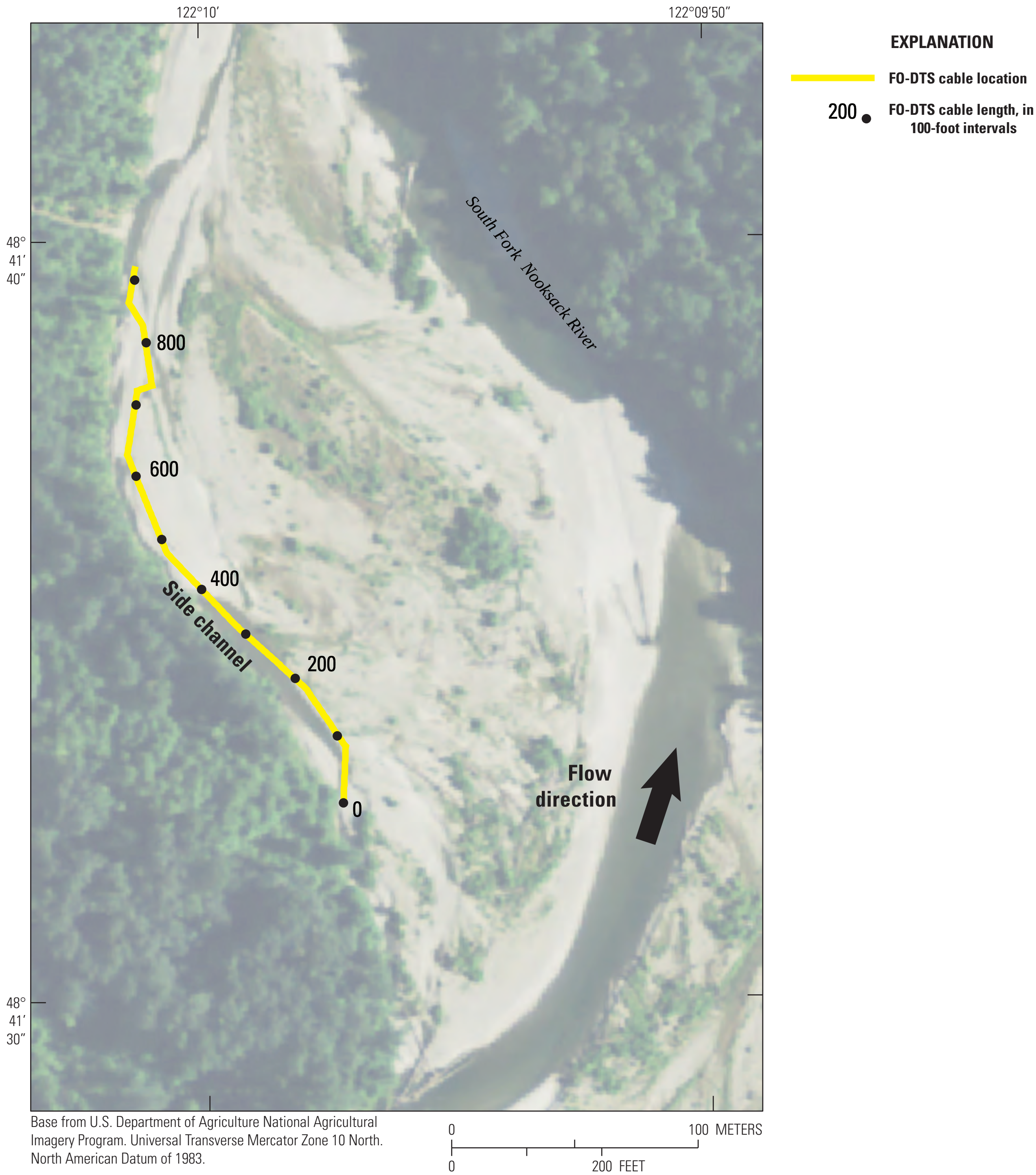


Figure 11. Location of near-streambed temperature monitoring using a fiber-optic distributed temperature sensing (FO-DTS) at river mile 11.2, South Fork Nooksack River, northwestern Washington, August 2012.

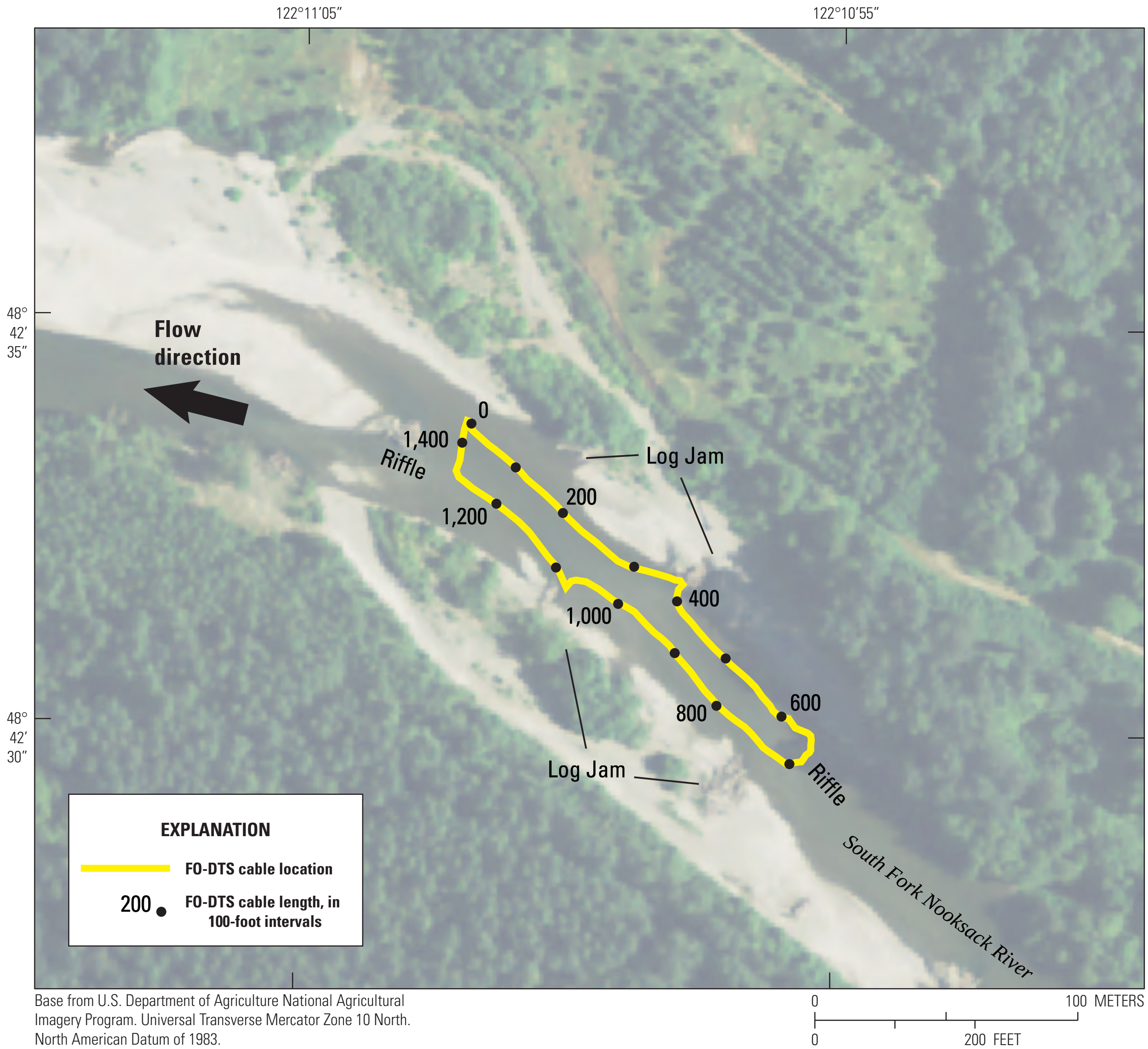


Figure 12. Location of near-streambed temperature monitoring using a fiber-optic distributed temperature sensing (FO-DTS) at river mile 10.0, South Fork Nooksack River, northwestern Washington, August 2013.

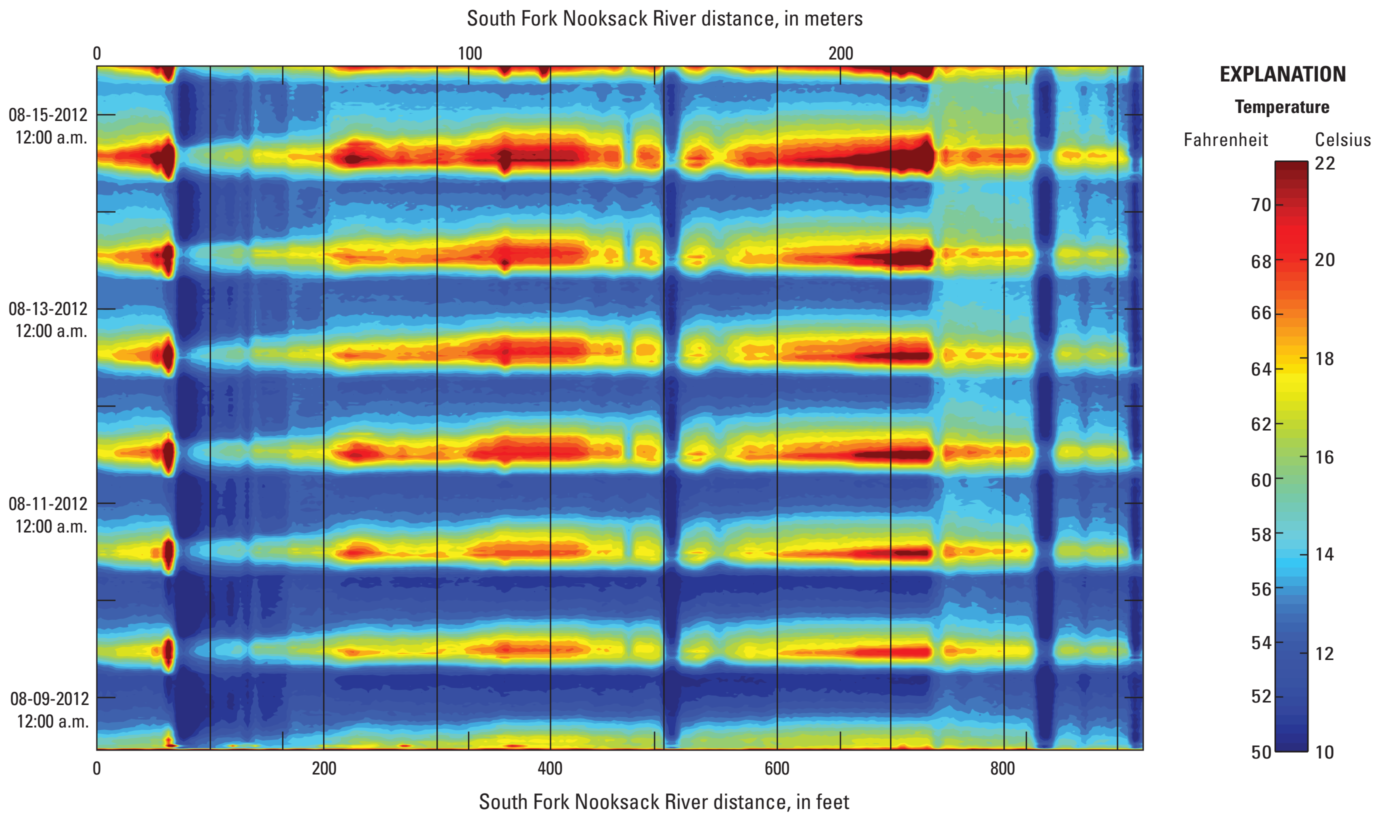


Figure 13. Longitudinal thermal profile of a 950-foot-long reach in a side channel at river mile 11.2 measured by fiber-optic distributed temperature sensor, South Fork Nooksack River, northwestern Washington, August 2012.

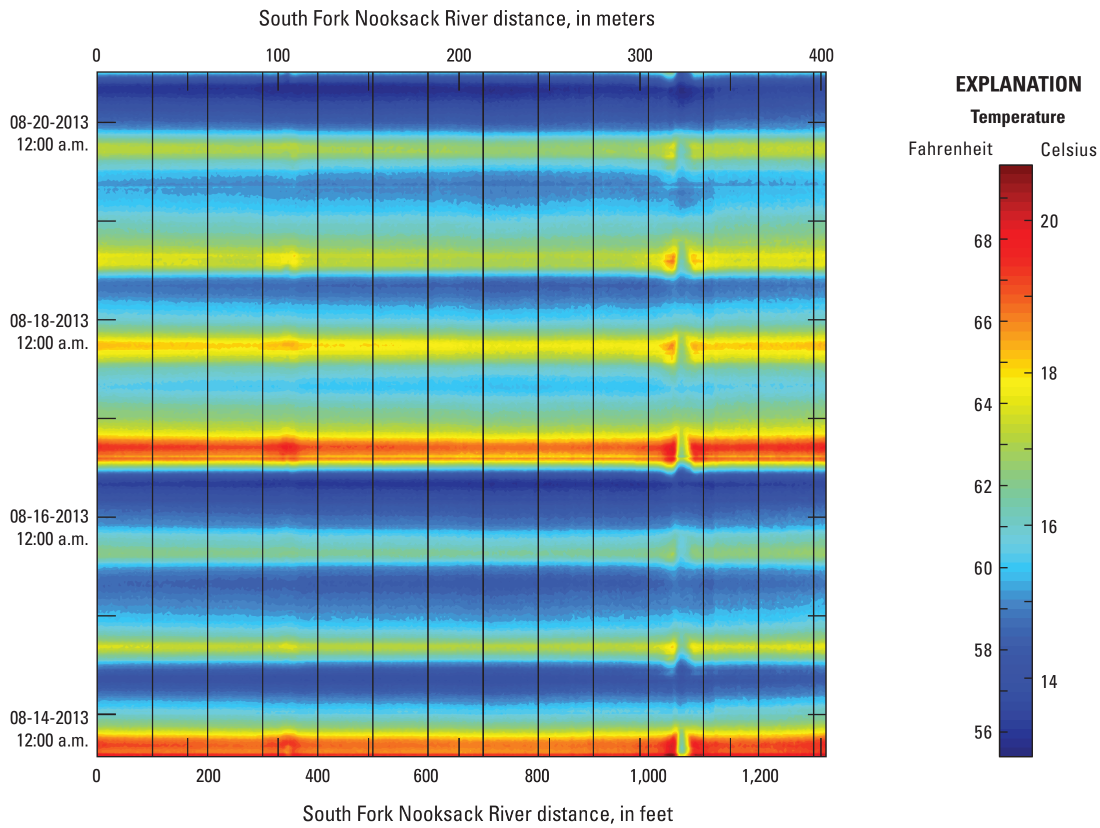


Figure 14. Longitudinal thermal profile of a 650-foot-long reach at river mile 10.0 measured by fiber-optic distributed temperature sensor, South Fork Nooksack River, northwestern Washington, August 2013.

The hydrology of a wetland complex consisting of multiple wetlands in the SF Nooksack River valley was evaluated to qualitatively determine the influence of precipitation, surface-water flow, and groundwater flow with respect to the SF Nooksack River and adjacent surficial aquifer (fig. 15). A mixed conifer-hardwood forest predominates in this wetland, although a portion of the wetland was cleared of trees and is currently managed for hay production. Surficial drainage to the wetland is connected to a slough that reconnects with the SF Nooksack River downstream of the wetland area. Water levels were continuously recorded at 15-minute intervals from December 2012 to July 2013 at three locations along a transect from the SF Nooksack River to the wetland (fig. 15). These water levels include the stage of the SF Nooksack River (USGS streamgage 12210208) and two shallow wells screened within the Qa/go hydrogeologic unit (37N/05E-08R01 and 37N/05E-17B01). Well 37N/05E-08R01 was driven 4.5 ft through coarse, unconsolidated sediment likely deposited as bedload within the former channel of the SF Nooksack River, whereas well 37N/05E-17B01 was driven 4.5 ft through fine clay to sand-sized sediment likely deposited as overbank alluvium or fine-grained glacial outwash, glacio-lacustrine, or glacio-marine sediment.

Water levels in well 37N/05E-08R01 corresponded closely with the stage of the SF Nooksack River, but the water level of well 37N/05E-17B01 remained relatively consistent and at a higher altitude than the water level measured in the adjacent riparian well (fig. 16). The consistent maximum water level recorded in the wetland well (approximately 318 ft) likely resulted from the altitude of the surface-runoff control leading to the slough to the north. During dry periods (for example, May 1–11, 2013) water-level altitudes measured at well 37N/05E-17B01 gradually decreased, but increased to the maximum measured water level (approximately 318 ft) following precipitation events, such as the event on May 12, 2013, when 0.57 in. of rain was recorded at a nearby National Oceanic and Atmospheric Administration (NOAA) weather station at Bellingham International Airport (NOAA Station ID: 450574; altitude 148 ft). During the dry period between May 1 and May 11, 2013, the snowpack within the high-altitude

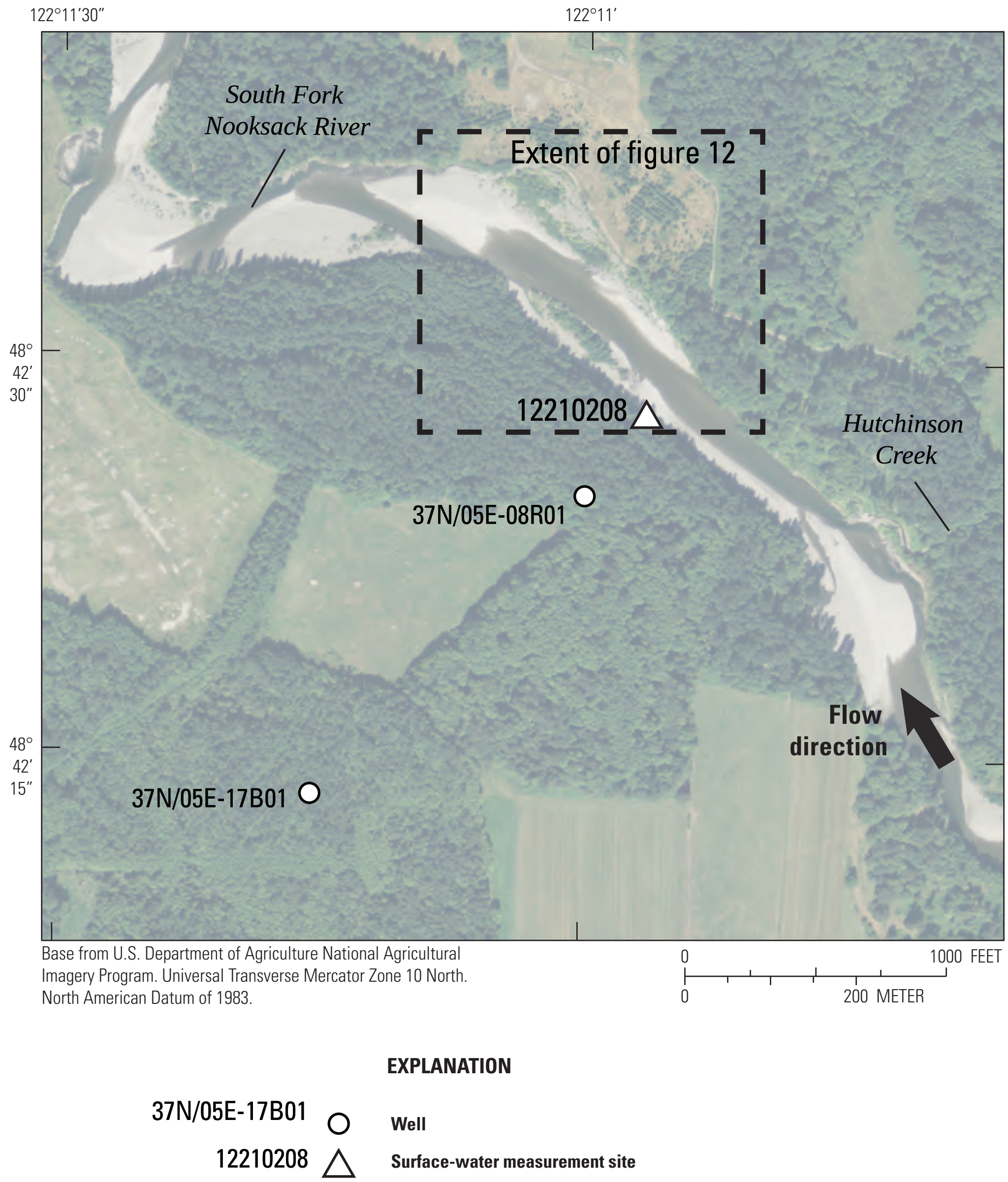


Figure 15. Location of South Fork Nooksack River at river mile 10.0 near Acme, Washington, (USGS streamgage 12210208) and wells 37N/05E-08R01 and 37N/05E-17B01, northwestern Washington.

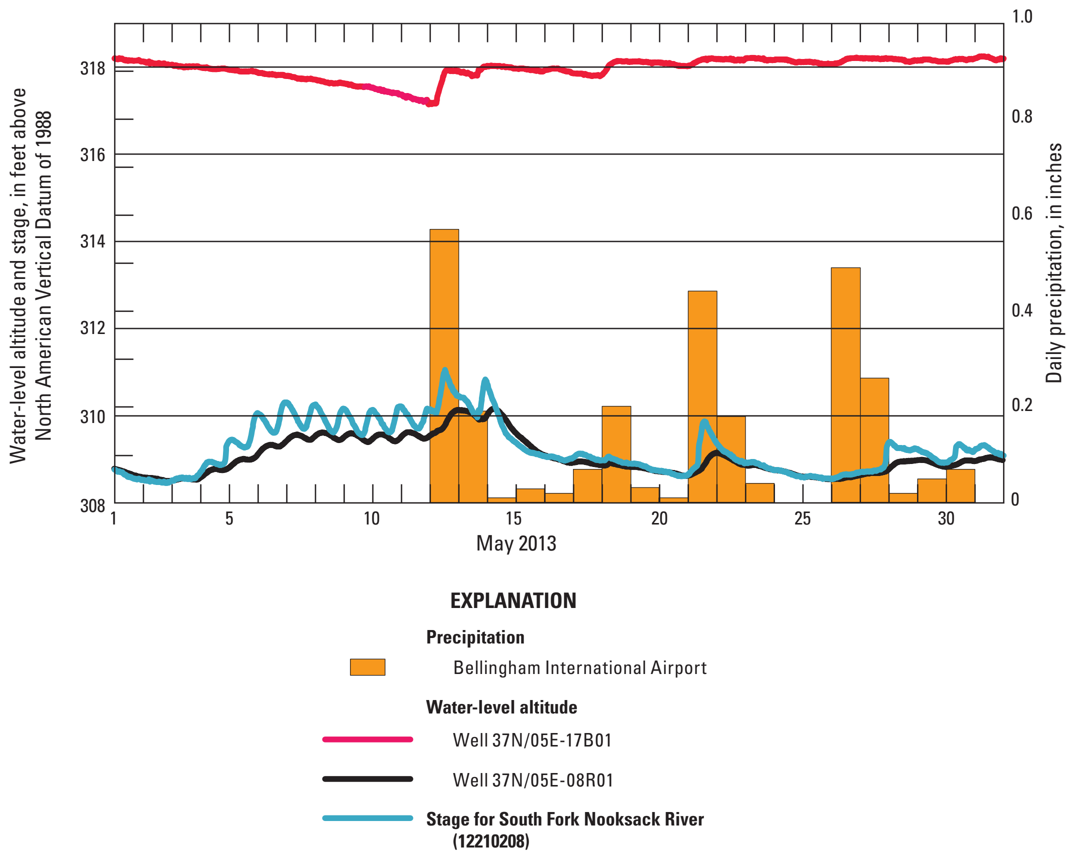


Figure 16. Daily precipitation measured at Bellingham International Airport (National Oceanic and Atmospheric Administration station ID: 450574; altitude 148 feet); stage of the South Fork Nooksack River (U.S. Geological Survey streamgage 12210208); and water-level altitudes measured at wells 37N/05E-17B01 and 37N/05E-08R01 within a wetland complex near the confluence of the South Fork Nooksack River with Hutchinson Creek, northwestern Washington.

headwaters of the SF Nooksack River melted at an accelerated rate causing a spring freshet marked by increased streamflow and diurnal fluctuation of the hydrograph. Despite the increase in stream stage during this period, water-level altitudes measured at well 37N/05E-17B01 decreased, suggesting that the wetland associated with this well is disconnected hydrologically from the SF Nooksack River. Instead, the wetland is likely perched on low-hydraulic conductivity sediment and recharged through direct precipitation. The water-level altitude of well 37N/05E-08R01, however, increased between May 1 and May 11, 2013, and recorded small-amplitude diurnal fluctuations that were delayed by about 10 hours, suggesting a direct connection between the SF Nooksack River and adjacent aquifer. These data suggest that the relation of wetlands to other surface-water features, including the SF Nooksack River, varies; whereas some wetlands directly exchange water with the SF Nooksack River, other wetlands are hydrologically isolated from it.

Future Groundwater-Flow Model Development

Water-resource management concerns in the study area include ensuring future supplies of water for domestic and agricultural users while maintaining streamflows and water quality for aquatic biota in the SF Nooksack River and its tributaries, most saliently the recovery of endangered and threatened salmonids. Potential changes to the SF Nooksack River Basin and climate introduce uncertainty into the future of groundwater and surface-water availability. To plan for future management of groundwater and surface-water resources in the study area, managers need tools to simulate the effect of projected changes in climate including air temperature and precipitation, land-use changes, and changes in groundwater pumping on the groundwater and surface-water hydrology of the SF Nooksack River Basin.

Questions for water resource managers include understanding the effect of projected decreases in snowpack and changes in the timing of snowmelt runoff and winter storms on streamflow and groundwater recharge. In addition, water-resource managers need to understand the potential effects of land-use changes on groundwater and surface-water hydrology in the study area including the restoration of riparian wetlands, residential development in the SF Nooksack River floodplain, and changes in forestry practices in the uplands of the study area.

A groundwater-flow model coupled with a watershed model may be used to investigate groundwater/surface-water interactions, develop water budgets, and simulate the effects of current and potential land use, climate, and groundwater pumping in the study area. The USGS has used a coupled groundwater and surface-water flow model (GSFLOW; Markstrom and others, 2008) based on the integration of the Precipitation-Runoff Modeling System (PRMS) and the Modular Groundwater-Water Flow Model (MODFLOW-2005), to develop simulations of groundwater and surface-water resources in other areas of Washington, including the Chamokane Creek Basin in northeastern Washington (Ely and Kahle, 2012). The hydrogeologic and hydrologic data presented in this report; including the surficial extent and thickness of hydrogeologic units along three cross sections, water-level altitudes measured in August 2012, and at monthly intervals during water year 2013, provide components needed to construct and calibrate a groundwater-flow model.

Summary and Conclusions

The SF Nooksack River drains a 183-square mile area of the Cascade Range and the Puget Lowland in northwestern Washington. After the spring freshet, which typically occurs during May and June, groundwater discharge forms the primary component of summer streamflow in the SF Nooksack River and its tributaries. The extent of groundwater discharge to the SF Nooksack River and the ability of groundwater to buffer warm stream temperatures and create cold-water refugia have been identified as important elements for the recovery of threatened salmonids within the SF Nooksack River Basin. This study characterized the groundwater-flow system of the SF Nooksack River Basin and its relation to rivers, streams, and other surface-water features to evaluate the role of groundwater in the hydrologic and thermal regime of the SF Nooksack River.

The eastern uplands of the study area are underlain by a diverse suite of metamorphic and igneous bedrock whereas sedimentary bedrock underlies the western part of the study area. Pleistocene glacial sediment and alluvium were deposited in the main river valleys and form the main hydrogeologic units that supply groundwater for domestic and agricultural users and exchange water with surface-water features including the SF Nooksack River and its tributaries. Five hydrogeologic units in the study area were defined. Three of these hydrogeologic units occur within unconsolidated sediments: an unconfined aquifer within glacial outwash and alluvium (Qa/go), an unconsolidated confining unit within poorly sorted and fine-grained glacial and landslide deposits (Qvt/ls/gm$_e$), which confined older glacial sediments of the Qga/pf aquifer. The other two hydrogeologic units occur within bedrock and include the sedimentary bedrock unit (Ec$_{cb}$) and the metamorphic bedrock unit (pTm). The bedrock units also are used as aquifers for domestic supply in the study area, but their yield is typically limited relative to the Qa/go and Qga/pf aquifers within unconsolidated sediments. The areal and vertical extent of these hydrogeologic units are presented in plan view and three hydrogeologic sections. Groundwater-level altitudes increased during wet periods in the late autumn and again during early spring when the melting of the winter snowpack in the uplands of the study area occurred. Groundwater-level altitudes typically decreased during the warm, dry summer months. These data will be used to support a future groundwater-flow model coupled with a watershed model that may be used to investigate groundwater/surface-water interactions, develop water budgets, and simulate the effects of current and potential land-use, climate, and groundwater pumping in the study area.

Seepage runs on several reaches in the study area completed in August 1998, September 1998, and September 2012 suggest spatial variability in the exchange of groundwater with surface water in the SF Nooksack River and its tributaries. In the confined upper SF Nooksack River valley, the SF Nooksack River consistently gained streamflow during seepage runs in August 1998 and September 1998; downstream of the confluence of the SF Nooksack River with Skookum Creek, however, gains and losses of streamflow were measured and are not necessarily consistent between the three seepage runs. Stream temperatures typically were warmest and had the largest diurnal fluctuations during the summer months. The longitudinal distribution of stream temperatures were characterized at two locations—in a side channel of the SF Nooksack River at river mile 11.2 in August 2012 and in the main channel of the SF Nooksack River at river mile 10.0 in August 2013. Discrete cold-water anomalies with low diurnal temperature variability were recorded at both locations. These cold-water anomalies were associated with both bank and streambed seepage of groundwater as well as thermal stratification within pools associated with log jams. Continuously monitored groundwater-level altitudes in riparian wetlands and water-surface stage of the SF Nooksack River suggest that some wetlands are dynamically linked to the SF Nooksack River whereas other wetlands are perched on low-permeability floodplain sediments and receive their recharge from direct precipitation.

Acknowledgments

The author would like to thank the many people who contributed their time and knowledge to help complete this study. Jean Snyder, Tom Cline, and Rich Auguston of the Nooksack Indian Tribe Natural Resources Department are gratefully acknowledged for their assistance deploying the fiber-optic distributed temperature sensor during this study. In addition, the author would like to thank the following USGS employees for collecting the groundwater and surface-water data presented in this report: Karen Payne, Chad Opatz, Joe Miles, Rusty Sherman, Eric Porter, and Curtis Chabot. The author also would like to thank the Whatcom Land Trust and the many private landowners throughout the study area that graciously provided access to their wells for groundwater-level measurements.

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Appendix A. Monthly Measured Water Levels in the South Fork Nooksack River Basin, Northwestern Washington, October 2012–September 2013

[All altitudes are in feet and referenced to the North American Vertical Datum of 1988]

Station name	Well depth (feet)	Altitude of well	Date of measurement	Water level depth, in feet below land surface	Water-level altitude	Status of water level
37N/05E-22N01	40	369	10-18-12	12.72	356.28	–
37N/05E-22N01	40	369	11-20-12	8.01	360.99	–
37N/05E-22N01	40	369	12-20-12	7.56	361.44	–
37N/05E-22N01	40	369	1-17-13	9.04	359.96	–
37N/05E-22N01	40	369	2-21-13	10.57	358.43	–
37N/05E-22N01	40	369	3-19-13	8.12	360.88	–
37N/05E-22N01	40	369	4-23-13	8.78	360.22	–
37N/05E-22N01	40	369	5-22-13	10.18	358.82	–
37N/05E-22N01	40	369	6-19-13	11.18	357.82	–
37N/05E-22N01	40	369	7-25-13	12.6	356.4	–
37N/05E-22N01	40	369	8-22-13	13.2	355.8	–
37N/05E-22N01	40	369	9-25-13	12.83	356.17	–
37N/05E-22P01	103	375	8-21-12	11.39	363.61	–
37N/05E-22P01	103	375	10-18-12	11.68	363.32	–
37N/05E-22P01	103	375	11-20-12	6.55	368.45	–
37N/05E-22P01	103	375	12-20-12	3.95	371.05	–
37N/05E-22P01	103	375	1-17-13	5.81	369.19	–
37N/05E-22P01	103	375	2-22-13	8.6	366.4	–
37N/05E-22P01	103	375	3-19-13	5.75	369.25	–
37N/05E-22P01	103	375	4-23-13	6.07	368.93	–
37N/05E-22P01	103	375	5-22-13	8.6	366.4	–
37N/05E-22P01	103	375	6-19-13	10.11	364.89	–
37N/05E-22P01	103	375	7-25-13	11.32	363.68	–
37N/05E-22P01	103	375	8-22-13	11.91	363.09	–
37N/05E-22P01	103	375	9-25-13	11.8	363.2	–
37N/05E-20R01	441	383	8-22-12	51.68	331.32	–
37N/05E-20R01	441	383	10-18-12	52.85	330.15	–
37N/05E-20R01	441	383	11-20-12	50.99	332.01	-
37N/05E-20R01	441	383	12-20-12	48.65	334.35	–
37N/05E-20R01	441	383	1-17-13	48	335	–
37N/05E-20R01	441	383	2-21-13	48.6	334.4	–
37N/05E-20R01	441	383	3-19-13	47.85	335.15	–
37N/05E-20R01	441	383	4-23-13	47.94	335.06	–
37N/05E-20R01	441	383	5-22-13	47.93	335.07	–
37N/05E-20R01	441	383	6-19-13	49.86	333.14	–
37N/05E-20R01	441	383	7-25-13	51.64	331.36	–
37N/05E-20R01	441	383	8-22-13	52.6	330.4	–
37N/05E-20R01	441	383	9-25-13	52.93	330.07	–
37N/05E-20R03	102	395	8-22-12	50	345	–
37N/05E-20R03	102	395	10-18-12	45.4	349.6	–
37N/05E-20R03	102	395	11-20-12	47.47	347.53	–
37N/05E-20R03	102	395	12-20-12	42.94	352.06	–
37N/05E-20R03	102	395	1-17-13	42.36	352.64	–
37N/05E-20R03	102	395	2-21-13	37.85	357.15	–
37N/05E-20R03	102	395	3-19-13	36.95	358.05	–
37N/05E-20R03	102	395	4-23-13	56.15	338.85	R

Appendix A. Monthly Measured Water Levels in the South Fork Nooksack River Basin, Northwestern Washington, October 2012–September 2013.—Continued

[All altitudes are in feet and referenced to the North American Vertical Datum of 1988]

Station name	Well depth (feet)	Altitude of well	Date of measurement	Water level depth, in feet below land surface	Water-level altitude	Status of water level
37N/05E-20R03	102	395	5-22-13	40.39	354.61	–
37N/05E-20R03	102	395	6-19-13	59.58	335.42	R
37N/05E-20R03	102	395	7-25-13	80.68	314.32	P
37N/05E-20R03	102	395	8-22-13	77.65	317.35	–
37N/05E-20R03	102	395	9-25-13	44.92	350.08	–
37N/05E-20R04	380	392	8-22-12	61.42	330.58	–
37N/05E-20R04	380	392	10-18-12	62.76	329.24	–
37N/05E-20R04	380	392	11-20-12	63.08	328.92	–
37N/05E-20R04	380	392	12-20-12	62.73	329.27	–
37N/05E-20R04	380	392	1-17-13	62.1	329.9	–
37N/05E-20R04	380	392	2-21-13	61.25	330.75	–
37N/05E-20R04	380	392	3-19-13	61.15	330.85	–
37N/05E-20R04	380	392	4-23-13	60.71	331.29	–
37N/05E-20R04	380	392	5-22-13	60.61	331.39	–
37N/05E-20R04	380	392	6-19-13	60.73	331.27	–
37N/05E-20R04	380	392	7-25-13	61.25	330.75	–
37N/05E-20R04	380	392	8-22-13	61.93	330.07	–
37N/05E-20R04	380	392	9-25-13	62.46	329.54	–
37N/05E-20A01	118	407	8-24-12	83.72	323.28	–
37N/05E-20A01	118	407	10-17-12	84.18	322.82	–
37N/05E-20A01	118	407	11-20-12	80.76	326.24	–
37N/05E-20A01	118	407	12-20-12	80.28	326.72	–
37N/05E-20A01	118	407	1-17-13	81	326	–
37N/05E-20A01	118	407	2-21-13	81.18	325.82	–
37N/05E-20A01	118	407	3-19-13	80.2	326.8	–
37N/05E-20A01	118	407	4-23-13	80.55	326.45	–
37N/05E-20A01	118	407	5-22-13	81.21	325.79	–
37N/05E-20A01	118	407	6-19-13	82.22	324.78	–
37N/05E-20A01	118	407	7-25-13	83.68	323.32	–
37N/05E-20A01	118	407	8-22-13	84.46	322.54	–
37N/05E-20A01	118	407	9-25-13	84.1	322.9	–
37N/05E-17N01	68	637	8-22-12	36.92	600.08	–
37N/05E-17N01	68	637	10-17-12	40.76	596.24	R
37N/05E-17N01	68	637	11-20-12	35.82	601.18	–
37N/05E-17N01	68	637	12-20-12	32.65	604.35	–
37N/05E-17N01	68	637	1-17-13	32.87	604.13	–
37N/05E-17N01	68	637	2-21-13	34.3	602.7	–
37N/05E-17N01	68	637	3-19-13	31.65	605.35	–
37N/05E-17N01	68	637	4-23-13	33.46	603.54	–
37N/05E-17N01	68	637	5-22-13	35.68	601.32	–
37N/05E-17N01	68	637	6-19-13	36.65	600.35	–
37N/05E-17N01	68	637	7-25-13	46.9	590.1	R
37N/05E-17N01	68	637	8-22-13	39.35	597.65	–
37N/05E-17N01	68	637	9-25-13	39.38	597.62	–

Appendix A. Monthly Measured Water Levels in the South Fork Nooksack River Basin, Northwestern Washington, October 2012–September 2013.—Continued

[All altitudes are in feet and referenced to the North American Vertical Datum of 1988]

Station name	Well depth (feet)	Altitude of well	Date of measurement	Water level depth, in feet below land surface	Water-level altitude	Status of water level
37N/05E-17L01D1	489.5	444	8-23-12	13.6	430.4	–
37N/05E-17L01D1	489.5	444	10-17-12	14.85	429.15	–
37N/05E-17L01D1	489.5	444	11-20-12	7.33	436.67	–
37N/05E-17L01D1	489.5	444	12-20-12	7.94	436.06	–
37N/05E-17L01D1	489.5	444	1-18-13	13.4	430.6	–
37N/05E-17L01D1	489.5	444	2-21-13	7.43	436.57	–
37N/05E-17L01D1	489.5	444	3-19-13	6.08	437.92	–
37N/05E-17L01D1	489.5	444	4-23-13	6.32	437.68	–
37N/05E-17L01D1	489.5	444	5-22-13	6.6	437.4	–
37N/05E-17L01D1	489.5	444	6-19-13	10.28	433.72	–
37N/05E-17L01D1	489.5	444	7-25-13	12.52	431.48	–
37N/05E-17L01D1	489.5	444	8-22-13	13.87	430.13	–
37N/05E-17L01D1	489.5	444	9-25-13	11.65	432.35	–
37N/05E-06R01	33	301	8-24-12	12.28	288.72	–
37N/05E-06R01	33	301	10-17-12	13	288	–
37N/05E-06R01	33	301	11-20-12	6.5	294.5	–
37N/05E-06R01	33	301	12-20-12	5.54	295.46	–
37N/05E-06R01	33	301	1-17-13	5	296	–
37N/05E-06R01	33	301	2-21-13	7.1	293.9	–
37N/05E-06R01	33	301	3-19-13	5.09	295.91	–
37N/05E-06R01	33	301	4-23-13	6	295	–
37N/05E-06R01	33	301	5-22-13	7.98	293.02	–
37N/05E-06R01	33	301	6-19-13	9.81	291.19	–
37N/05E-06R01	33	301	7-25-13	12.92	288.08	–
37N/05E-06R01	33	301	8-22-13	13.74	287.26	–
37N/05E-06R01	33	301	9-25-13	13.08	287.92	–
37N/05E-03G01	57	595	8-21-12	26.3	568.7	–
37N/05E-03G01	57	595	10-18-12	28.25	566.75	–
37N/05E-03G01	57	595	11-20-12	24.27	570.73	–
37N/05E-03G01	57	595	12-20-12	22.28	572.72	–
37N/05E-03G01	57	595	1-17-13	22.92	572.08	–
37N/05E-03G01	57	595	2-21-13	24.03	570.97	–
37N/05E-03G01	57	595	3-19-13	22.36	572.64	–
37N/05E-03G01	57	595	4-23-13	23.15	571.85	–
37N/05E-03G01	57	595	5-22-13	24.45	570.55	–
37N/05E-03G01	57	595	6-19-13	25.12	569.88	–
37N/05E-03G01	57	595	7-25-13	26.65	568.35	–
37N/05E-03G01	57	595	8-22-13	27.77	567.23	–
37N/05E-03G01	57	595	9-25-13	28.35	566.65	–
37N/05E-02D02	58	622	8-20-12	45.3	576.7	–
37N/05E-02D02	58	622	10-18-12	49.9	572.1	–
37N/05E-02D02	58	622	11-20-12	43.9	578.1	–
37N/05E-02D02	58	622	12-20-12	36.5	585.5	–
37N/05E-02D02	58	622	1-17-13	37.13	584.87	–

Appendix A. Monthly Measured Water Levels in the South Fork Nooksack River Basin, Northwestern Washington, October 2012–September 2013.—Continued

[All altitudes are in feet and referenced to the North American Vertical Datum of 1988]

Station name	Well depth (feet)	Altitude of well	Date of measurement	Water level depth, in feet below land surface	Water-level altitude	Status of water level
37N/05E-02D02	58	622	2-21-13	40.06	581.94	–
37N/05E-02D02	58	622	3-19-13	36.5	585.5	–
37N/05E-02D02	58	622	4-23-13	38.12	583.88	–
37N/05E-02D02	58	622	5-22-13	41.45	580.55	–
37N/05E-02D02	58	622	6-19-13	42.95	579.05	–
37N/05E-02D02	58	622	7-25-13	46.4	575.6	–
37N/05E-02D02	58	622	8-22-13	48.76	573.24	–
37N/05E-02D02	58	622	9-25-13	50.33	571.67	–
38N/05E-20F01	39	247.1	8-21-12	4.2	242.9	–
38N/05E-20F01	39	247.1	10-17-12	4.25	242.85	–
38N/05E-20F01	39	247.1	11-20-12	2.47	244.63	–
38N/05E-20F01	39	247.1	12-20-12	2.35	244.75	–
38N/05E-20F01	39	247.1	1-17-13	2.86	244.24	–
38N/05E-20F01	39	247.1	2-21-13	2.93	244.17	–
38N/05E-20F01	39	247.1	3-19-13	2.11	244.99	–
38N/05E-20F01	39	247.1	4-23-13	2.65	244.45	–
38N/05E-20F01	39	247.1	5-22-13	2.83	244.27	–
38N/05E-20F01	39	247.1	6-19-13	3.51	243.59	–
38N/05E-20F01	39	247.1	7-25-13	4.21	242.89	–
38N/05E-20F01	39	247.1	8-22-13	4.71	242.39	–
38N/05E-20F01	39	247.1	9-25-13	4.08	243.02	–
38N/05E-17C01	38	247.2	8-23-12	17.3	229.9	–
38N/05E-17C01	38	247.2	10-17-12	16.59	230.61	–
38N/05E-17C01	38	247.2	11-20-12	13.64	233.56	–
38N/05E-17C01	38	247.2	12-20-12	14.88	232.32	–
38N/05E-17C01	38	247.2	1-17-13	15.93	231.27	–
38N/05E-17C01	38	247.2	2-21-13	16.12	231.08	–
38N/05E-17C01	38	247.2	3-19-13	14.65	232.55	–
38N/05E-17C01	38	247.2	4-23-13	15.16	232.04	–
38N/05E-17C01	38	247.2	5-22-13	15.12	232.08	–
38N/05E-17C01	38	247.2	6-19-13	16.25	230.95	–
38N/05E-17C01	38	247.2	7-25-13	17.15	230.05	–
38N/05E-17C01	38	247.2	8-22-13	17.48	229.72	–
38N/05E-17C01	38	247.2	9-25-13	16.68	230.52	–
38N/05E-08B01	78	283.7	8-22-12	49.87	233.83	–
38N/05E-08B01	78	283.7	10-17-12	50.45	233.25	–
38N/05E-08B01	78	283.7	11-20-12	49.13	234.57	–
38N/05E-08B01	78	283.7	12-20-12	48.58	235.12	–
38N/05E-08B01	78	283.7	1-17-13	48.42	235.28	–
38N/05E-08B01	78	283.7	2-21-13	49.2	234.5	–
38N/05E-08B01	78	283.7	3-19-13	47.76	235.94	–
38N/05E-08B01	78	283.7	4-23-13	48.38	235.32	–
38N/05E-08B01	78	283.7	5-22-13	48.38	235.32	–
38N/05E-08B01	78	283.7	6-19-13	48.99	234.71	–
38N/05E-08B01	78	283.7	7-25-13	49.58	234.12	–
38N/05E-08B01	78	283.7	8-22-13	50.08	233.62	–
38N/05E-08B01	78	283.7	9-25-13	50.22	233.48	–

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

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Gendaszek—**Groundwater/Surface-Water Interactions of the South Fork Nooksack River Basin, Washington**—Scientific Investigations Report 2014–5221

ISSN 2328-0328 (online)
http://dx.doi.org/10.3133/sir20145221