Prepared in cooperation with the Skagit County Public Works Department, Washington State Department of Ecology, and Skagit County Public Utility District No. 1

Hydrogeologic Framework, Groundwater Movement, and Water Budget in Tributary Subbasins and Vicinity, Lower Skagit River Basin, Skagit and Snohomish Counties, Washington

Scientific Investigations Report 2009–5270

U.S. Department of the Interior
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Cover: Lake Creek which connects Lake McMurray to Big Lake, lower Skagit River basin, Washington. Photograph taken May 9, 2006, courtesy of Skagit County Public Works.

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KEN SALAZAR, Secretary

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

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

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Suggested citation:
Savoca, M.E., Johnson, K.H., Sumioka, S.S., Olsen, T.D., Fasser, E.T., and Huffman, R.L., 2009, Hydrogeologic framework, groundwater movement, and water budget in tributary subbasins and vicinity, lower Skagit River basin, Skagit and Snohomish Counties, Washington: U.S. Geological Survey Scientific Investigations Report 2009–5270, 46 p.

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)
section (640 acres or 1 square mile)	259.0	square hectometer (hm^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

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

°F=(1.8×°C)+32.

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

°C=(°F-32)/1.8.

Datums

Vertical coordinate information was referenced to the North American Vertical Datum of 1988 (NAVD88), referred to in this report as “sea level.”

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD83).

Altitude, as used in this report, refers to distance above or below sea level.

Acronyms

ANUDEM	Australian National University Digital Elevation Model
DDMFZ	Darington-Devils Mountain Fault Zone
DEM	digital elevation model
DNR	Washington Department of Natural Resources
Ecology	Washington State Department of Ecology
GIS	Geographic Information System
GPS	Global Positioning System
LiDAR	Light Detection and Ranging
NWS	National Weather Service
NED	National Elevation Dataset
NLVD	National Land Cover Database
NWIS	USGS National Water Information System
PRISM	Parameter-elevation Regressions on Independent Slopes Model
PVC	polyvinyl chloride
USGS	U.S. Geological Survey

Well-Numbering System

Wells in Washington State are assigned a local well number that identifies each well based on its location within a township, range, section, and 40-acre tract. For example, local well number 33N/04E-02E01 indicates that the well is in township 33 north of the Willamette Base Line, and range 4 east of the Willamette Meridian. The numbers immediately following the hyphen indicate the section (02) within the township, and the letter following the section (E) gives the 40-acre tract of the section. The two-digit sequence number (01) following the letter is used to distinguish individual wells in the same 40-acre tract. A "D" following the sequence number indicates a well that has been deepened. In the plates of this report, wells are identified using only the section and 40-acre tract, such as 02E01; the township and range are shown on the map borders.

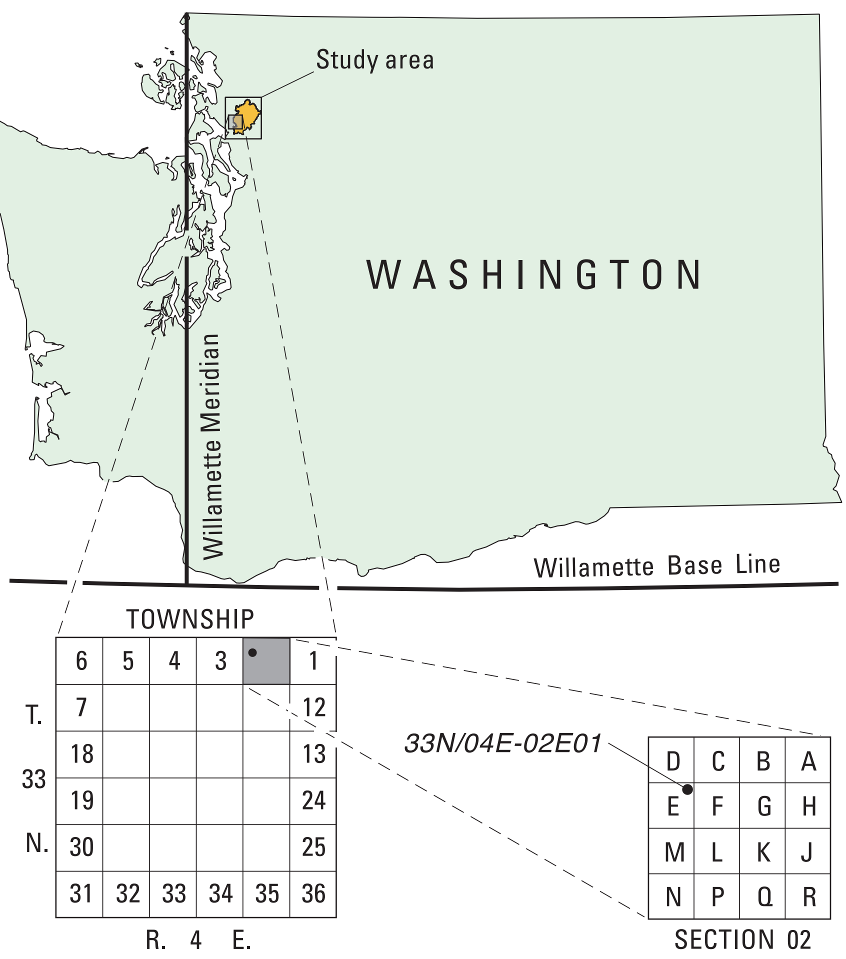

Diagram showing well numbering system used in Washington.

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Abstract

A study to characterize the groundwater-flow system in four tributary subbasins and vicinity of the lower Skagit River basin was conducted by the U.S. Geological Survey to assist Skagit County and the Washington State Department of Ecology in evaluating the effects of potential groundwater withdrawals and consumptive use on tributary streamflows.

This report presents information used to characterize the groundwater and surface-water flow system in the subbasins, and includes descriptions of the geology and hydrogeologic framework of the subbasins; groundwater recharge and discharge; groundwater levels and flow directions; seasonal groundwater-level fluctuations; interactions between aquifers and the surface-water system; and a water budget for the subbasins.

The study area covers about 247 mi^2 along the Skagit River and its tributary subbasins (East Fork Nookachamps Creek, Nookachamps Creek, Carpenter Creek, and Fisher Creek) in southwestern Skagit County and northwestern Snohomish County, Washington. The geology of the area records a complex history of accretion along the continental margin, mountain building, deposition of terrestrial and marine sediments, igneous intrusion, and the repeated advance and retreat of continental glaciers. A simplified surficial geologic map was developed from previous mapping in the area, and geologic units were grouped into nine hydrogeologic units consisting of aquifers and confining units. A surficial hydrogeologic unit map was constructed and, with lithologic information from 296 drillers' logs, was used to produce unit extent and thickness maps and four hydrogeologic sections.

Groundwater in unconsolidated aquifers generally flows towards the northwest and west in the direction of the Skagit River and Puget Sound. This generalized flow pattern is likely complicated by the presence of low-permeability confining units that separate discontinuous bodies of aquifer material and act as local groundwater-flow barriers. Groundwater-flow directions in the sedimentary aquifer likely reflect local topographic relief (radial flow from bedrock highs) and more regional westward flow from the mountains to the Puget Sound. The largest groundwater-level fluctuations observed during the monitoring period (October 2006 through September 2008) occurred in wells completed in the sedimentary aquifer, and ranged from about 3 to 27 feet. Water levels in wells completed in unconsolidated hydrogeologic units exhibited seasonal variations ranging from less than 1 to about 10 feet.

Synoptic streamflow measurements made in August 2007 and June 2008 indicate a total groundwater discharge to creeks in the tributary subbasin area of about 13.15 and 129.6 cubic feet per second (9,520 and 93,830 acre-feet per year), respectively. Streamflow measurements illustrate a general pattern in which the upper reaches of creeks in the study area tended to gain flow from the groundwater system, and lower creek reaches tended to lose water. Large inflows from tributaries to major creeks in the study area suggest the presence of groundwater discharge from upland areas underlain by bedrock.

The groundwater system within the subbasins received an average (September 1, 2006 to August 31, 2008) of about 92,400 acre-feet or about 18 inches of recharge from precipitation a year. Most of this recharge (65 percent) discharges to creeks, and only about 3 percent is withdrawn from wells. The remaining groundwater recharge (32 percent) leaves the subbasin groundwater system as discharge to the Skagit River and Puget Sound.

Introduction

In Washington State, the availability of water for out-of-stream uses must be determined before water can be appropriated. This determination is most often made as part of an application for a water right; however, certain uses are exempted from the water rights permitting system. To prevent water withdrawals from impacting other out-of-stream and instream uses, Washington State may reserve a specific quantity of water in a stream basin for out-of-stream uses as part of the regulation establishing minimum instream flows (the Instream-Flow Rule). The reservation allows new groundwater withdrawals in basins where all available water is appropriated. Once the total of new withdrawals equals the quantity specified in the reservation, subsequent new uses would have to find an alternative source of water, obtain an existing water right, or provide compensating mitigation for streamflow impacts.

Recent population growth along the Interstate 5 corridor near Mount Vernon, Washington, has led to increased water use with many new domestic wells serving residents in the lower Skagit River basin in areas not served by a regional public water system. Planning for future development in the lower basin, including the reservation of water for new domestic wells, requires identification of areas where withdrawals from existing and new wells could adversely impact streamflow in the Skagit River or its tributaries. Skagit County, as the land-use authority for unincorporated areas requires a scientifically credible basis for implementing land-use restrictions to protect instream resources.

In June 2006, the USGS, in cooperation with Skagit County Public Works Department, the Washington State Department of Ecology (Ecology), and Skagit County Public Utility District No. 1, began a project to characterize the groundwater-flow system in the tributary subbasins and vicinity of the lower Skagit River basin. A second phase of this project will integrate this and other information into a numerical flow model to evaluate the effects of potential groundwater withdrawals and consumptive use on tributary streamflows.

Purpose and Scope

This report presents information used to characterize the groundwater-flow system in and around four subbasins tributary to the lower Skagit River: East Fork Nookachamps Creek, Nookachamps Creek, Carpenter Creek, and Fisher Creek. The report describes the hydrogeologic framework of the subbasins and vicinity; groundwater recharge and discharge; groundwater levels and flow directions; seasonal groundwater-level fluctuations; interactions between groundwater and the surface-water system; and a water budget for the subbasins.

Description of Study Area

The study area covers about 247 mi^2 along the Skagit River and its tributary subbasins in southwestern Skagit County and northwestern Snohomish County, Washington (fig. 1). The Skagit River occupies a large, relatively flat alluvial valley that extends across the northern and western margins of the study area, and is bounded to the south and east by upland and mountainous terrain. The alluvial valley primarily is underlain by fluvial sand and gravel deposits associated with the present and ancient Skagit River, and locally preserved lahar runout deposits originating from Glacier Peak, located about 55 mi east-southeast of the study area. Upland areas contain laterally discontinuous bodies of glacial and interglacial deposits that reflect both terrestrial and shallow marine depositional environments. Bedrock consisting of a complex assemblage of metamorphic rocks, sedimentary units, and igneous rocks underlies the alluvial valley and upland areas, and crops out throughout the mountainous terrain.

The southwest flowing Skagit River receives streamflow from four tributary subbasins that originate within the mountainous interior of the study area: East Fork Nookachamps Creek, Nookachamps Creek, Carpenter Creek, and Fisher Creek. These creeks drain areas of about 37, 28, 19, and 10 mi^2, respectively. The lower reaches of most creeks flow year-round, however, intermittent-flow conditions are common in middle and upper creek reaches during the summer months. Backwater conditions periodically occur near the confluence of creeks with the Skagit River. Springs are present throughout the study area, and contribute to late-summer baseflow to creeks. Major lakes in the study area include Big Lake, Clear Lake, Lake McMurray, Beaver Lake, Barney Lake, and Sixteen Lake (fig. 1).

The study area has a temperate marine climate with warm, dry summers, and cool, wet winters with snow and freezing temperatures common at high altitudes. Temperatures are moderated by the Pacific Ocean and Puget Sound, and these bodies of water provide an abundant supply of moisture for storms that typically approach the area from the west. Mean annual precipitation (average annual precipitation for the study period September 1, 2006, to August 31, 2008) varies across the study area according to distance from the Puget Sound and altitude, and ranges from about 30 in. near Puget Sound to greater than 120 in. in the mountains to the east. Land-surface altitude in the study area ranges from about 10 ft in the Skagit River valley to near 4,000 ft in the mountainous areas. Normal annual precipitation (average annual precipitation for 1971-2000) at Sedro-Woolley is 46.6 in., and at Mount Vernon is 32.7 in. (National Oceanic and Atmospheric Administration, 2007). The distribution of precipitation varies throughout the year. Summers (June-August) typically are dry with a normal summer precipitation (average “summer” precipitation for 1971–2000) of 6.4 in. at Sedro-Woolley and 4.5 in. at Mount Vernon. Winters (December–February) are wetter than summers with a normal winter precipitation (average “winter” precipitation for 1971–2000) of 16.4 in. at Sedro-Woolley and 11.0 in. at Mount Vernon. The normal monthly temperature (average temperature for selected months for 1971–2000) at these locations ranges from about 39 ºF in January to about 63 ºF in August (National Oceanic and Atmospheric Administration, 2007).

Figure 1. Location of tributary subbasins and vicinity, lower Skagit River basin, Washington.

Methods of Investigation

Methods used to compile and analyze information for the characterization of the groundwater and surface-water flow system in the study area are described in this section. Methods used to describe groundwater movement and water budget of the study area, are included with the respective sections later in this report.

Well Inventory and Water-Level Measurements

Characterization of the groundwater-flow system relied on the analysis of spatially distributed information about groundwater levels, and the physical and hydraulic properties of the geologic units encountered during well construction. This information was obtained through the measurement of water levels in wells, and the evaluation of hydrogeologic descriptions and well tests from well drillers' logs. Well records were compiled from USGS, Ecology, and Washington Department of Natural Resources (DNR) databases to identify potential wells to be used in this study. Candidate wells were selected for field inventory based on the location and depth of the well, and the availability of a driller's log. The goal of the inventory was to obtain an even distribution of wells throughout the study area. However, this was not possible for the entire study area because of a lack of wells in less populated areas. During the field inventory (August through October 2006), permission for access was obtained, and synoptic water levels were measured in 128 wells (pl. 1). Water levels were measured on a monthly basis from October 2006 through September 2008 in 62 of the inventoried wells and 9 new wells constructed for this study (pl. 1). Continuous water-level recorders were installed in four of the monthly monitoring wells (pl. 1).

Latitude and longitude locations were determined for each well using a Global Positioning System (GPS) receiver with a horizontal accuracy of one-tenth of a second (about 10 ft). Light Detection and Ranging (LiDAR) data were used to determine the altitude of land surface at each well, and for the computation of water-level altitudes. LiDAR data were collected and processed by a private vendor under contract with the USGS. Vertical accuracy (typically ±1 ft) was evaluated for internal consistency (repeatability), and conformance with independent ground-control points. Water level, reported as depth to water below land surface, was measured using a calibrated electric tape or graduated steel tape, both with accuracy to 0.01 ft. All water-level measurements were made by USGS personnel according to standardized techniques of the USGS (Drost, 2005). New wells were installed using direct-push technology and were constructed of 1.5 in. polyvinyl chloride (PVC) pipe, and 5 or 10 ft of 0.01- to 0.02-in. slotted PVC screen with integrated sand-filter pack. Sediment cores were continuously collected as the drive casing was advanced. Non-water bearing sediments were encountered at four locations; cores were collected, however, wells at these locations were not constructed (pl. 1).

The spatial distribution of hydrogeologic data from inventoried and newly constructed wells was insufficient to fully evaluate the high degree of spatial variability of hydrogeologic units in the study area. Therefore, an additional 168 wells with available drillers' logs were selected from USGS, Ecology, and DNR databases to help refine the hydrogeologic framework in areas where data from the original set of wells were limited (pl. 1). The approximate location of most of the additional wells had been previously established by DNR; these and the remaining well locations were established using the well address listed on the drillers' log and the Skagit County Assessors tax parcel database. Well information collected during the field inventory, monthly monitoring network, and construction of the hydrogeologic framework were entered into the USGS National Water Information System (NWIS) database and published in Fasser and Julich (2009).

Hydrogeology

The surficial geology for the tributary subbasins was compiled from previous mapping by Schuster (2000; 1:100,000), Dragovich and others (2002; 1:24,000), and Dragovich and DeOme (2006; 1:24,000). No attempt was made to reconcile matching of surficial geologic units across map boundaries; however, in some areas, modifications were made to unit designations from previous maps based on stratigraphic evidence obtained during this investigation, primarily drillers' logs for field located wells. Differences in geologic unit nomenclature and map scales were addressed through the use of simplified stratigraphy and consistent nomenclature that is based on the work of Dragovich and others (2002). When possible, geologic units were grouped under a single new unit designation based on similarities in lithology and stratigraphic position to allow for a simplified and consistent representation of geology across the study area. This process resulted in the grouping of 62 geologic units from previous mapping into 18 geologic units, and the production of a simplified surficial geologic map for this study (pl. 1). These geologic units were grouped into nine hydrogeologic units, consisting of aquifers and confining units, on the basis of lithologic (depositional facies, grain size, and sorting) and hydrologic (hydraulic conductivity and unit geometry) characteristics. A map of the surficial distribution of these hydrogeologic units was constructed for this study (pl. 2). The hydrogeologic units identified in this report do not in all cases correspond to geologic time-stratigraphic deposits.

Hydrogeologic sections and unit extent and thickness maps of the tributary subbasin groundwater system were constructed based on: (1) the simplified surficial geology, (2) geologic and hydrogeologic interpretations, maps, and sections from previous investigations, and (3) geologic unit delineations made by this and previous investigations using information collected from 296 wells. Hydrogeologic unit top and extent information was used to create digital elevation model (DEM) surfaces in a Geographic Information System (GIS) database at a 30 ft cell size. The interpolation method for creating each hydrogeologic unit surface in GIS was based on the Australian National University Digital Elevation Model (ANUDEM) procedure developed by Hutchinson (1989), using well unit picks and extent maps. Each hydrogeologic unit surface was constrained to the National Elevation Dataset (NED) 30 ft DEM for land surface where the unit cropped out.

Thickness maps were constructed for each hydrogeologic unit using GIS to calculate the difference between the altitude of the interpolated top of the unit and the altitude of the interpolated top of units underlying it. If part of a hydrogeologic unit was interpolated to extend above the top of an overlying hydrogeologic unit, then minimum thickness values for the overlying unit were used in the calculations to adjust the altitude of the top of the underlying unit where needed. Unconsolidated hydrogeologic unit thicknesses were constrained by bedrock-surface data in areas with limited subsurface information. Average minimum thicknesses were used to represent occurrences of unconsolidated hydrogeologic units overlying bedrock in areas of limited subsurface data.

In developing the hydrogeologic framework, the original data interpretations were honored as much as possible. The resulting interpolated hydrogeologic unit surfaces, and calculated unit thickness, were compared to the original map, section, and well interpretations, and adjusted to more accurately reflect the original interpretations when necessary. The areas where the calculated units are less accurate are in areas of (1) data gaps, (2) where the surficial geology changes abruptly, and (3) where the well locations are less accurate.

Streamflow

Characterization of the surface-water flow system in the tributary subbasins was facilitated by the installation of three USGS streamflow-gaging stations to measure streamflow on Nookachamps, Carpenter, and Fisher Creeks; streamflow on East Fork Nookachamps Creek was already being measured at an Ecology streamflow-gaging station (pl. 1). Two sets of synoptic streamflow measurements were made in August 2007 and June 2008 at 27 sites along the four major creeks and their tributaries (pl. 1) to quantify surface water leaving the tributary subbasins during low-flow conditions, and to identify gaining and losing creek reaches. Streamflow measurements at USGS gaging stations and synoptic sites were made by USGS personnel, assisted by Skagit County Public Works staff, using Price pygmy or AA current velocity meters according to standardized techniques of the USGS (Rantz, 1982). Streamflow data from the Ecology gaging station on East Fork Nookachamps Creek were obtained from the Washington State Department of Ecology (2009). The USGS rates the accuracy of discharge measurements based on the equipment, character of the measurement section, number of observations, stability of stage, wind, and the accuracy of depth and velocity measurements (Rantz, 1982, p. 179). Accuracy ratings of “good” indicate that the measurements are within 5 percent of actual values, ratings of “fair” indicate the measurements are within 8 percent of actual values, and ratings of “poor” indicate the measurements are not within 8 percent of actual values (assumed to be within 11 percent of actual values for this study).

Hydrogeologic Framework

This section describes the geology and hydrogeologic framework, which define the physical, lithologic, and hydrologic characteristics of the hydrogeologic units that compose the groundwater system in the tributary subbasins. An understanding of these characteristics is important in determining the occurrence, movement, and availability of groundwater within the aquifer system, and the exchange of water between the aquifer system and surface-water features.

Geologic Setting

A brief summary of major geologic events in the study area is given below, and is based on the work of Hansen and Mackin (1949), Easterbrook (1969), Marcus (1981), Johnson (1982), Booth (1994), Tabor (1994), Dragovich, and Grisamer (1998), Dragovich and others (2002), and Dragovich and DeOme (2006). The geology of the study area records a complex history of accretion along the continental margin, mountain building, deposition of terrestrial and marine sediments, igneous intrusion, and the repeated advance and retreat of continental glaciers. Bedrock in the study area consists of: (1) complex assemblages of faulted and folded low-grade metamorphic rocks formed during Late Jurassic or Early Cretaceous continental margin subduction; (2) sedimentary units deposited in alluvial fan, braided stream, and near shore shallow marine settings; and (3) igneous intrusive and extrusive rocks that occur as dikes, sills, domes, and flows (pyroclastic and lava). Metamorphic rocks were likely brought to the surface by Mid-Cretaceous thrust faulting and Tertiary displacement along the Darington-Devils Mountain Fault Zone (DDMFZ; extends from northwest to southeast across the central part of the study area). Tertiary vertical or oblique offset along the DDMFZ likely provided the topographic relief necessary to produce the alluvial fan and braided stream deposits in the sedimentary units. The presence of igneous rocks within fault-bounded blocks of the DDMFZ suggests that emplacement of these rocks was strongly controlled by pre-existing strands of the DDMFZ. Evidence of Quaternary displacement along the DDMFZ and other faults in the study area has not been widely documented. Dragovich and DeOme (2006) offer evidence of Holocene offset along a mile-long portion of the main strand of the DDMFZ located north of Lake McMurray. Surficial and subsurface interpretations suggest a lack of Quaternary displacement along faults else where in the study area (Dragovich and others, 2002; Dragovich and DeOme, 2006).

Continental glaciers advanced into Skagit County several times during the Pleistocene Epoch. This ice, part of the Cordilleran ice sheet, is known as the Puget Lobe. The most recent period of glaciation, the Vashon Stade of Fraser glaciation, began about 17,000 years ago when the continental ice sheet in Canada expanded, and the Puget Lobe advanced southward into western Skagit County, eventually covering the entire Puget Sound basin before halting and retreating. During the Everson Interstade, beginning about 13,500 years ago, the climate warmed and the lobe wasted back allowing marine waters to enter the Puget Sound basin, which had been depressed due to glacial isostatic loading. Marine inundation buoyed the retreating ice and produced marine and estuarine conditions in the study area. Postglacial filling of the Skagit River valley, which had been excavated by subglacial melt water, was accomplished through Holocene fluvial, estuarine, and deltaic deposition, and volcanic lahar deposits originating from Glacier Peak.

Unconsolidated deposits of glacial and interglacial origin are present throughout the study area. A typical glacial sequence progresses from advance outwash, to till, to recessional outwash. Fluvial, lacustrine, bog and marsh depositional environments were common during interglacial periods. Beneath these unconsolidated deposits of varying thickness are bedrock units that are exposed in large parts of the glacial upland and within the mountains along the eastern margin of the study area. Descriptions of the unconsolidated and bedrock units present in the study area are given below.

Geologic Units

The simplified geologic representation of the tributary subbasins developed for this study consists of 18 geologic units (table 1) that are described below and are shown on the surficial geologic map (pl. 1) constructed for this investigation. Quaternary (Holocene to latest Pleistocene) nonglacial deposits include:

Alluvium (Qa).—Alluvium consisting of active or abandoned channel and overbank deposits associated with the present and ancient Skagit River. Channel deposits typically are coarse grained and consist of loose sand and gravel. Overbank deposits consist mostly of soft to stiff, stratified sand, silt, and clay and minor amounts of peat. Floodplain splay deposits are composed of sand and gravel and form subtle to distinct levees adjacent to or near the present Skagit River channels. Alluvial-fan deposits are composed of poorly sorted, massive to weakly stratified, soft to stiff, gravel, silt, and sand that are mostly of debris-flow or debris-torrent origin. Beach deposits consist of loose, moderately to well-sorted sand and gravel along modern shorelines that locally include wave-worn shell fragments. Nearshore deposits in estuarine or tidal flat environments are composed of loose or soft, sand, silt, and clay with various admixtures of organic material.

Peat (Qp).—Soft fibrous to woody peat, muck, and organic silt accumulated in bogs and swamps of abandoned channels, kettles, and shallow oxbow lakes or other depressions; commonly poorly stratified to unstratified.

Landslide deposits (Qls).—Landslide deposits consisting of mostly poorly sorted, unstratified, soft to cohesive diamicton composed of boulders, cobbles, and gravel in a soft sand, silt, or clay matrix. Mode of origin includes slump-earth flows, debris slumps or flows, and rock avalanches (talus) and also includes a few alluvial fan and thick colluvial deposits.

Lahar runout deposits (Qvl)—Lahar runout deposits consisting of loose, well-sorted, massive to normally graded, medium to fine grained, volcanic sand. These deposits are interpreted by Dragovich and others (2000) as hyperconcentrated flood or lahar runout deposits, originating from a Glacier Peak eruptive event(s), that followed an ancestral channel of the Skagit River, and are preserved in the lower Skagit River Valley within the study area.

Quaternary (Pleistocene) glacial and non-glacial deposits include:

Everson glaciomarine drift ($Qgdm_e$).—Glaciomarine drift deposits consisting of soft (when wet) to stiff (when dry) diamicton locally containing vertical jointing or desiccation cracks, and lenses or layers of loose outwash sand and gravel. Dragovich and others (2002) identified two distinct facies: (1) a clast-rich diamicton that is massive or crudely stratified and composed of clay, gravel, sand and silt, with abundant dropstones, and (2) a silt- and clay-rich deposit that is massive or, less commonly, occurs as varved or laminated rhythmites and is composed of moderately to well-sorted silt, clay, and sand that lacks or contains only rare gravel, cobble, or boulder dropstones.

Everson recessional outwash (Qgo_e).—Terrestrial to marine recessional and deltaic outwash deposits consisting of loose sand, gravel, with local concentrations of cobbles, boulders, and lenses of silt. Recessional outwash deposits vary from non-bedded to subhorizontal beds a few feet thick that are crudely defined by variations in cobble, gravel, and sand content, and contain sedimentary structures indicative of a fluvial braided-channel environment. Deltaic outwash deposits are moderately to well-sorted, and beds typically are inches to several feet thick. Dragovich and others (2002) identified high-amplitude planar foreset beds, indicative of deltaic deposition in the study area.

Everson glaciomarine outwash ($Qgom_e$).—Glaciomarine outwash deposits consisting of loose gravel, sand, and silt, and occasional silt beds and laminated to varved silt-sand couplets. Average grain size is smaller in this unit than in terrestrial or deltaic outwash (Qgo_e). Interlayering with glaciomarine drift indicates submarine deposition for most areas mapped as unit $Qgom_e$, although it may locally

Table 1. Simplified geologic units defined in this study and correlation with previous investigations.

[Definitions of simplified geologic units defined in this study are shown on plate 1]

Period	Epoch	Simplified geologic units defined in this study	Geologic units in Schuster (2000) 1:100,000	Geologic units in Dragovich and others (2002) 1:24,000	Geologic units in Dragovich and DeOme (2006) 1:24,000
Quaternary	Holocene to latest Pleistocene	Qa	Qa Qa_c Qa_s Qaf Qb Qf Qoa Qoa_s	af Qb Qn Qa_s Qa_{sl} Qaf	Qa Qoa
		Qp	Qp	Qm Qp	Qp
		Qls	Qls Qta	Qls	Qls
		Qvl	Qvl_k	Qvl	
	Pleistocene	$Qgdm_e$	$Qgdm_e$ Qgoc	$Qgdm_e$ $Qgdm_{ec}$ $Qgdm_{ed}$	$Qgdm_e$ Qgl_e
		Qgo_e	Qgo Qgog Qgos	Qgo_e $Qgod_e$	$Qgog_e$ $Qgik_e$ $Qgod_e$ $Qgos_e$
		$Qgom_e$	Qgom $Qgom_e$	$Qgom_e$ $Qgom_{ee}$	
		Qgt_v	Qgt	Qgt_v	Qgt_v
		Qga_v	Qga Qgas	Qga_v	Qga_v
		Qgl_v	Qga_t	Qgl_v	Qgl_v
		Qc_o	Qc_o	Qc_o	Qc_o
		ot		ot	ot
		oo		oo	oo
		Qc_w	Qc_w	Qc_w	
Tertiary	Oligocene to Eocene	OEc_b	OEc_b OEn_b	OEc_{bs} OEc_{bcg}	OEc_{bs} OEc_{bcg}
		Evr	Evr	Evr	Evr Eib
		Ec_{bc}	Ec_c	Ec_b	Ec_c
Jurassic and Pennsylvanian		JTP	Jph_d Jmv_h Jsh_s $JTRmt_e$ $JMmt_t$ MZu_h $MZmm_h$ $Pigbd_t$	Jmv_h Ju_h Ju_{hl} $Jhmc_h$	Jmv_h Ju_h JT_Rmc_t JT_Rmv_t Pzi

include terrestrial outwash deposits (Dragovich and others, 2002). Beach deposits of loose sand and gravel are included in this unit and are locally associated with topographic benches or subtle wave-cut terraces that reflect temporary beach reworking of the substrate during isostatic emergence.

Vashon Till (Qgt_v).—Till composed of non-stratified, unsorted, dense to very dense diamicton consisting of clay, silt, sand, and gravel in various proportions, with scattered cobbles and boulders and rare to locally common layers and lenses of sand and/or gravel. Vashon till commonly underlies glaciomarine drift in the western part of the study area, and unconformably overlies bedrock, advance outwash, and less commonly, older glacial and non-glacial units.

Vashon advance outwash (Qga_v).—Advance outwash deposits of moderately to very dense, medium to coarse sand and gravel, with local silt and clay interbeds. Advance outwash deposits are moderately stratified to stratified, moderately to well sorted, thinly to very thickly bedded (subhorizontal or cross-stratification), and contain sedimentary structures indicative of fluvial deposition. Advance outwash commonly is overlain by till along a sharp contact, and conformably overlies or is complexly interlayered with older glacial and nonglacial units where present.

Glaciolacustrine and distal outwash deposits (Qgl_v).—Glaciolacustrine and distal outwash deposits of glacial and (or) nonglacial origin, composed of moderately dense to dense, well sorted, clay and silt that are very thinly to very thickly bedded, and contain varying amounts of sand and gravel, and locally contains thick beds of massive, clast-rich diamicton, and scattered dropstones. Clay and silt deposits represent low-energy lacustrine and distal fluvial facies; diamicton and dropstones likely resulted from iceberg melt-out.

Olympia nonglacial deposits (Qc_o).—Olympia nonglacial deposits composed of dense to very dense, well sorted, sand, gravelly sand, silt, clay, and peat that are very thinly to thickly bedded, with minor gravel and cobble gravel, and rare diamicton of probable mass-flow origin (Dragovich and others, 2002). Organic material (logs or wood fragments) is common and differentiates the Olympia from the overlying glaciolacustrine and distal outwash deposits. Olympia deposits contain sedimentary structures indicative of a meandering river environment.

Older till (ot).—Older till consisting of dense to very dense diamicton composed of clay, silt, sand, and gravel in various proportions, with scattered cobbles and boulders; may locally include glaciomarine drift. Dragovich and others (2002) do not assign a formal geologic symbol to this unit, which indicates the tentative nature of the correlation with deposits of the Possession Glaciation (60,000–80,000 yr B.P.).

Older outwash (oo).—Older outwash consisting of glacial or nonglacial deposits composed of sand and gravel with varying amounts of silt and clay. Dragovich and others (2002) do not assign a formal geologic symbol to this unit, which indicates the tentative nature of the correlation with deposits of the Possession Glaciation (60,000–80,000 yr B.P.).

Whidbey nonglacial deposits (Qc_w).—Whidbey nonglacial deposits of sand with interbeds of silt, clay, and local gravel lenses; peat and wood are common. Hansen and Mackin (1949) interpreted the depositional environment as slowly aggrading meandering streams and adjacent flood plains.

Tertiary (Oligocene to Eocene) sedimentary and igneous rocks include:

Rocks of Bulson Creek (OEc_b).—The rocks of Bulson Creek consist of a conglomerate and sandstone facies. The conglomerate facies is composed of poorly to rarely well indurated pebble and cobble conglomerate, and contains lesser interbeds of pebbly sandstone, siltstone, and minor diamictite (debris flows), and coal. The sandstone facies is composed of sandstone with interbeds of pebbly sandstone, siltstone, conglomerate, coal, and shale. Marcus (1981) concluded that the conglomerate facies was deposited in an alluvial fan to braided river environment. Dragovich and others (2002) suggest the sandstone facies was deposited in a nearshore or shallow marine environment.

Volcanic rocks (Evr).—Rhyolite, andesite, and basalt occur as pyroclastic ash flow tuffs, lava flows, domes, dikes, sills, and breccias. Lahar deposits (sandstones, siltstones, and conglomerates) are locally interbedded with rhyolitic tuffs, breccias, and very thin coal beds. Age and field relations indicate that andesites are contemporaneous with deposition of the Bulson Creek sandstone facies (Dragovich and DeOme, 2006).

Chuckanut Formation (Ec_{bc}).—The Chuckanut Formation consists of alternating intervals of coarse-grained (sandstone and minor conglomerate) and fine-grained (mudstone, fine-grained sandstone, and siltstone) deposits. These upward-fining cycles have been interpreted to represent a river and adjacent flood-plain depositional environment (Johnson, 1982).

Jurassic to Pennsylvanian low-grade metamorphic rocks:

Metamorphic rocks (JTP).—Rocks of the Helena-Haystack melange and Trafton sequence are composed of complex assemblages of faulted and folded low-grade metasediments, metavolcanics, and meta-intrusives, formed as a result of continental margin subduction during the Late Jurassic or Early Cretaceous. The exhumation of these rocks from the subduction zone was likely accomplished by mid-Cretaceous thrust faulting; followed by Tertiary displacement along the DDMFZ (Tabor, 1994; Dragovich and others, 2002; Dragovich and DeOme, 2006).

Hydrogeologic Units

The geologic units defined for this study were grouped into hydrogeologic units, consisting of aquifers and confining units (table 2) on the basis of lithologic (depositional facies, grain size, and sorting) and hydrologic (hydraulic conductivity and unit geometry) characteristics. The hydrogeologic units defined in this study are similar to those defined and used by other investigations in areas adjacent to this study (Thomas and others, 1997; Dragovich and Grisamer, 1998; GeoEngineers, 2003).

An aquifer is saturated geologic material that is sufficiently permeable to yield water in significant quantities to a well or spring, whereas a confining unit has low permeability that restricts the movement of groundwater and limits the usefulness of the unit as a water source. Unconfined and confined aquifer conditions are present in the tributary subbasins groundwater system. Unconfined or “water-table” conditions occur when the upper surface of the saturated zone is at atmospheric pressure and is free to rise and decline in response to changes in groundwater recharge and discharge. The position of the water table is represented by water levels in shallow wells. Confined or “artesian” conditions occur when an aquifer is overlain by a less permeable confining unit and the groundwater is under pressure greater than atmospheric pressure. Water in a tightly cased well drilled into a confined aquifer will rise to a height corresponding to the hydraulic head (the potentiometric surface) of the confined groundwater at that location. If the hydraulic head is sufficient to raise the water above land surface, the well will flow and is called a flowing artesian well. The potentiometric surface in a confined aquifer is analogous to the water table in an unconfined aquifer. It fluctuates in response to changes in recharge and discharge, however, unlike the water table, the potentiometric surface is higher in altitude than the top of the confined aquifer.

Glacial deposits generally are heterogeneous, and although a glacial aquifer may be composed primarily of sand or gravel, it may locally contain varying amounts of clay or silt. Conversely, a confining layer composed predominantly of silt or clay, may contain local lenses of coarse material. These small-scale variations in lithology may influence the occurrence and movement of groundwater at a scale that is likely too small to be adequately represented by the hydrogeologic framework constructed for this

Table 2. Hydrogeologic units defined in this study and correlation with geologic units defined in this study and previous investigations.

[Definitions for hydrogeologic units defined in this study are shown on plate 2]

Period	Epoch	Hydrogeologic units defined in this study	Simplified geologic units defined in this study	Geologic units in Schuster (2000)	Geologic units in Dragovich and others (2002)	Geologic units in Dragovich and DeOme (2006)
Quaternary	Holocene to Pleistocene	Qago Alluvial and recessional outwash aquifer	Qa Qvl Qgom$_e$ Qgo$_e$	Qa Qa$_c$ Qa$_s$ Qaf Qb Qf Qoa Qoa$_s$ Qvl$_k$ Qgom Qgom$_e$ Qgo Qgog Qgos	af Qb Qn Qa$_s$ Qa$_{sl}$ Qaf Qvl Qgom$_e$ Qgom$_{ee}$ Qgo$_e$ Qgod$_e$	Qa Qoa Qgog$_e$ Qgik$_e$ Qgod$_e$ Qgos$_e$
	Pleistocene	Qgt Till confining unit	Qls Qgdm$_e$ Qgt$_v$	Qp Qls Qta Qgdm$_e$ Qgoc Qgt	Qm Qp Qls Qgdm$_e$ Qgdm$_{ec}$ Qgdm$_{ed}$ Qgt$_v$	Qp Qls Qgdm$_e$ Qgl$_e$ Qgt$_v$
		Qga Advance outwash aquifer	Qga$_v$	Qga Qgas	Qga$_v$	Qga$_v$
		Qgl Glaciolacustrine and distal outwash confining unit	Qgl$_v$	Qga$_t$	Qgl$_v$	Qgl$_v$
		Qco Inter-glacial alluvial aquifer	Qc$_o$	Qc$_o$	Qc$_o$	Qc$_o$
		Qot Older till confining unit	ot		ot	ot
		Qooa Older outwash and alluvial aquifer	oo Qc$_w$	Qcw	oo Qc$_w$	oo
Tertiary	Oligocene to Eocene	OEc Sedimentary aquifer	OEc$_b$ Ec$_{bc}$	OEc$_b$ OEn$_b$ Ec$_c$	OEc$_{bs}$ OEc$_{bcg}$ Ec$_b$	OEc$_{bs}$ OEc$_{bcg}$ Ec$_c$
Tertiary to Pennsylvanian		EJTP Igneous and metamorphic bedrock unit	Evr JTP	Jph$_d$ Jmv$_h$ Jsh$_s$ JTRmt$_e$ JMmt$_t$ MZu$_h$ MZmm$_h$ Pigbd$_t$	Evr Jmv$_h$ Ju$_h$ Ju$_{hl}$ Jhmc$_h$	Evr Eib Jmv$_h$ Ju$_h$ JT$_R$mc$_t$ JT$_R$mv$_t$ Pzi

study. Local-scale variability in the distribution of glacial depositional facies often results in the formation of spatially discontinuous units of varying thickness. Therefore, most units are not aerially contiguous throughout the study area, and unit thickness may vary considerably over short distances. Glacial and older non-glacial deposits are interpreted as largely absent within the Skagit River valley to a depth of about 300 ft below sea level, likely due to removal by southward flowing subglacial melt water, prior to subaerial exposure of the glacier bed during ice recession (Booth, 1994; Dragovich and others, 1994). This interpretation is supported by the absence of glacial and older non-glacial deposits in wells located along the Skagit River valley, and similar interpretations from previous investigations (Dragovich and Grisamer, 1998; GeoEngineers, 2003). Infilling of the Skagit River valley was accomplished through the accumulation of Holocene fluvial, estuarine, and deltaic deposits, and volcanic lahar deposits originating from Glacier Peak.

Bog and marsh deposits (Qp) typically are thin (less than 10 ft), discontinuous, and have a small areal extent in the study area. These deposits likely have little influence on the regional hydrologic system and are not designated as a hydrogeologic unit in this study. Nine hydrogeologic units are recognized in the study area (table 2 and pl. 2) and their lithologic and hydrologic characteristics are described below.

Alluvial and recessional outwash aquifer (Qago).—The alluvial and recessional outwash aquifer is present throughout the Skagit River valley (Qa and Qvl, pl. 1) and in discontinuous or isolated bodies in glacial upland areas (Qgo_e and $Qgom_e$, pl. 1) (fig. 2). The aquifer consists of sand, gravel, and cobbles with minor lenses of silt and clay. Thicknesses of Qago typically range from 10 to 50 ft in upland areas, and from 200 to 450 ft in the Skagit River valley. Groundwater in this aquifer is unconfined where it is not fully saturated or exposed at land surface, however, confined conditions are likely where it is fully saturated and overlain by the till confining unit (Qgt).

Till confining unit (Qgt).—The till confining unit is present at land surface throughout the glacial upland area and as thin, discontinuous bodies in the mountains along the eastern margin of the study area (fig. 3). This low-permeability unit is composed of marine and terrestrial glacial diamicton ($Qgdm_e$, and Qgt_v) and poorly sorted landslide deposits (Qls). The till confining unit consists of various proportions of clay, silt, sand, gravel, cobbles, and boulders, with locally occurring sand and gravel lenses capable of providing water for domestic use. Thicknesses of Qgt vary widely, but generally range from 10 to 100 ft, and exceed 300 ft in places (fig. 3).

Advance Outwash Aquifer (Qga).—The advance outwash aquifer is present in the subsurface throughout large parts of the glacial upland (fig. 4). Surface exposures of the unit are limited to a few steep slopes and along the walls of deeply incised stream valleys. The unit consists mostly of sand and gravel with minor amounts of silt, and scattered layers of pebble-cobble gravel and local silt and clay interbeds. The thickness of Qga typically ranges from 10 to 100 ft, but exceeds 200 ft in places. In most of the study area, groundwater in this aquifer is confined by the overlying till confining unit (Qgt), however, unconfined conditions may occur locally where it is not fully saturated or is exposed at land surface.

Glaciolacustrine and distal outwash confining unit (Qgl).—The glaciolacustrine and distal outwash confining unit is present in the subsurface throughout much of the glacial upland in the northern part of the study area, and in discontinuous or isolated bodies in upland areas to the south (fig. 5). Surface exposures of the unit are limited to a few steep slopes and along the walls of deeply incised stream valleys. This low-permeability unit consists of layers of clay and silt that contain varying amounts of sand and gravel with occasional diamicton and dropstones. The unit commonly thickness ranges from 10 to 50 ft; however, thicknesses exceed 100 ft in places.

Inter-glacial alluvial aquifer (Qco).—The inter-glacial alluvial aquifer is present in the subsurface along the northern and western periphery of the glacial upland, and in a few isolated bodies in the upland interior (fig. 6). Surface exposures of the unit occur along the southern edge of the Skagit River valley. The unit consists primarily of sand, gravel, silt, and clay, with minor lenses of gravel and cobbles, and commonly thickness ranges from 10 to 50 ft; however, thicknesses exceed 100 ft in places. In most of the study area, the inter-glacial alluvial aquifer is overlain by either the glaciolacustrine-distal outwash (Qgl) or till (Qgt) confining units, and groundwater occurs under confined conditions. Unconfined conditions occur in limited areas where the aquifer may not be fully saturated or where it is exposed at land surface.

Older till confining unit (Qot).—The presence of the older till confining unit in the subsurface along the western periphery of the glacial upland (fig. 7) is based on the identification of glacial till deposits in 12 wells, and subsurface geologic interpretations from Dragovich and others (2002). Deposits associated with the older till confining unit were not identified in any of the other wells used in this study and substantial uncertainty exists about the actual extent and thickness of this unit in the remainder of the study area. The potential presence of this unit in the subsurface along the northern periphery of the glaciated upland was inferred based on the units occurrence in the sediments to the south (Dragovich and others, 2002), and the need to characterize areas of residual sediment thickness between the base of the overlying inter-glacial alluvial aquifer and the underlying top of bedrock. Limited well data indicate that thicknesses of Qot typically range from 10 to 20 ft, and locally exceed 50 ft. This low-permeability unit is composed of terrestrial glacial diamicton consisting of various proportions of clay, silt, sand, and gravel, with scattered cobbles, and boulders.

Older outwash and alluvial aquifer (Qooa).—The presence of the older outwash and alluvial aquifer in the subsurface along the western periphery of the glacial upland (fig. 8) is based on the identification of older outwash and alluvial deposits in eight wells, and subsurface geologic interpretations from Dragovich and others (2002). Deposits associated with the older outwash and alluvial aquifer were not identified in any of the other wells used in this study and substantial uncertainty exists about the actual extent and thickness of this unit in the remainder of the study area. The potential presence of this unit in the subsurface along the northern periphery of the glaciated upland was inferred based on the unit's occurrence in the sediments to the south (Dragovich and others, 2002), and the need to characterize areas of residual sediment thickness between the base of the overlying older till confining unit and the underlying top of bedrock. The unit is composed of glacial (oo) and non-glacial (Qc_w) alluvial deposits and consists primarily of sand, and gravel, with varying amounts of silt and clay. Limited well data indicate thicknesses of Qooa typically range from 50 to 100 ft, and locally exceed 200 ft (fig. 8). Groundwater in this aquifer is confined by the overlying older till confining unit (Qot).

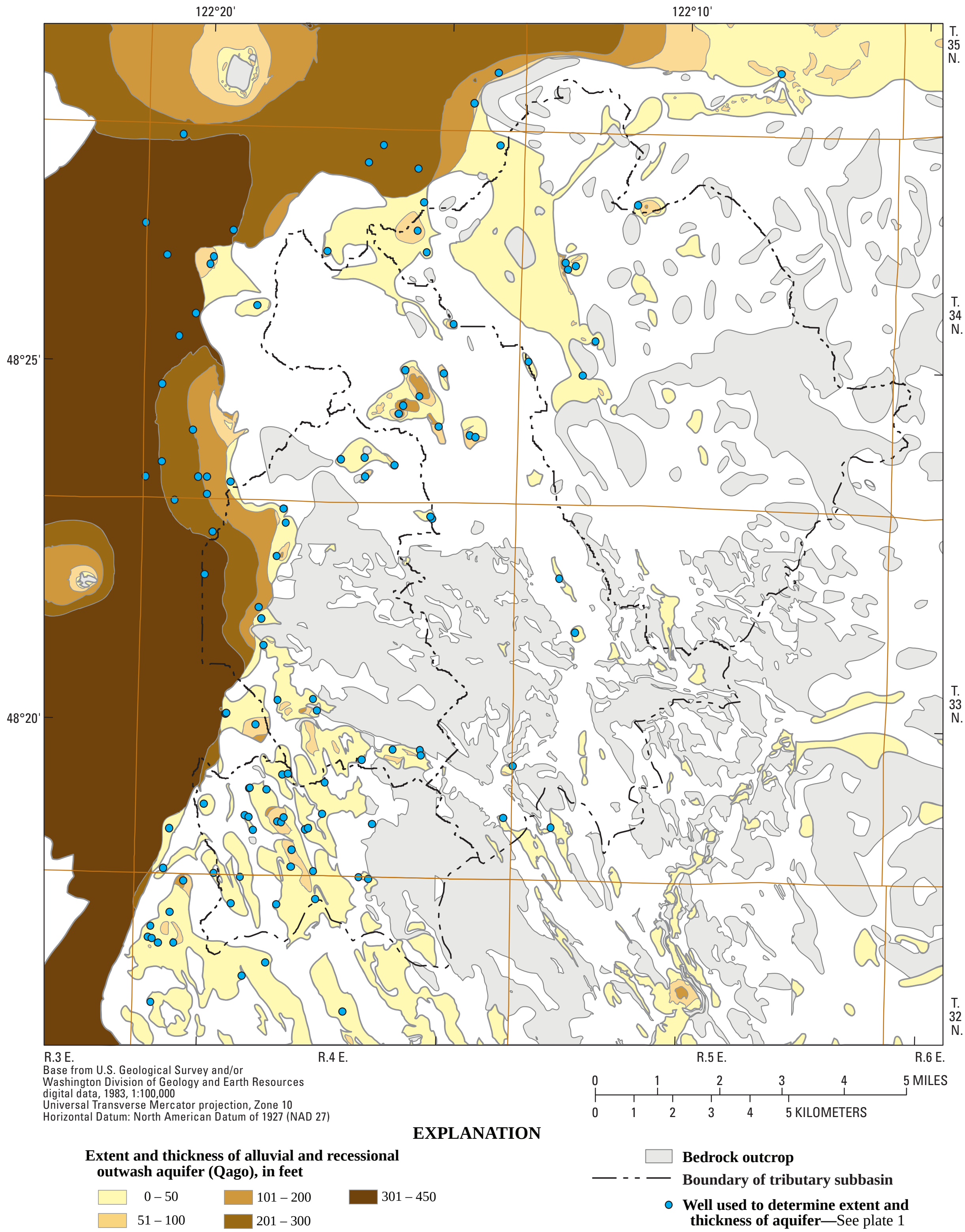


Figure 2. Extent and thickness of alluvial and recessional outwash aquifer (Qago) in tributary subbasins and vicinity, lower Skagit River basin, Washington.

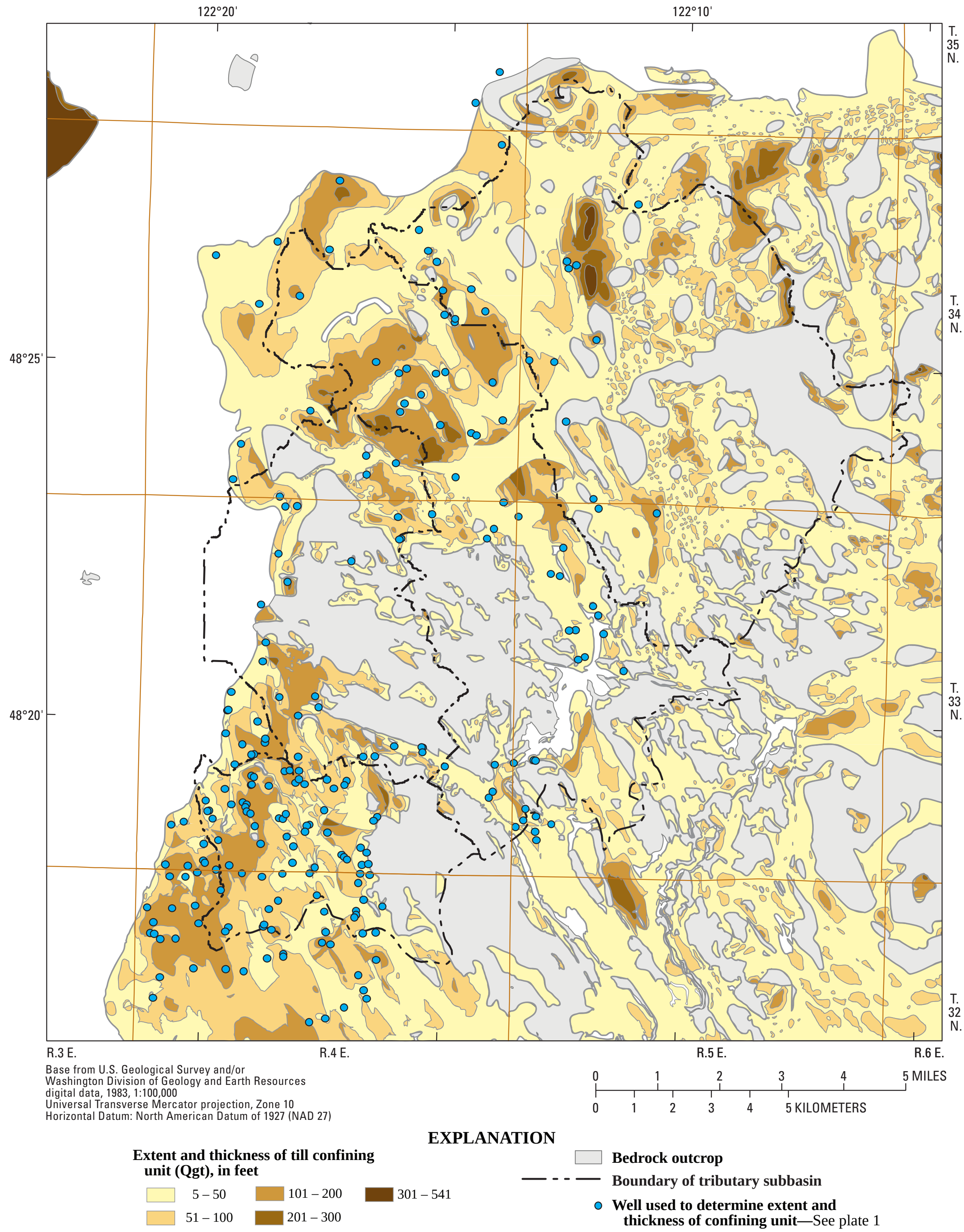


Figure 3. Extent and thickness of till confining unit (Qgt) in tributary subbasins and vicinity, lower Skagit River basin, Washington.

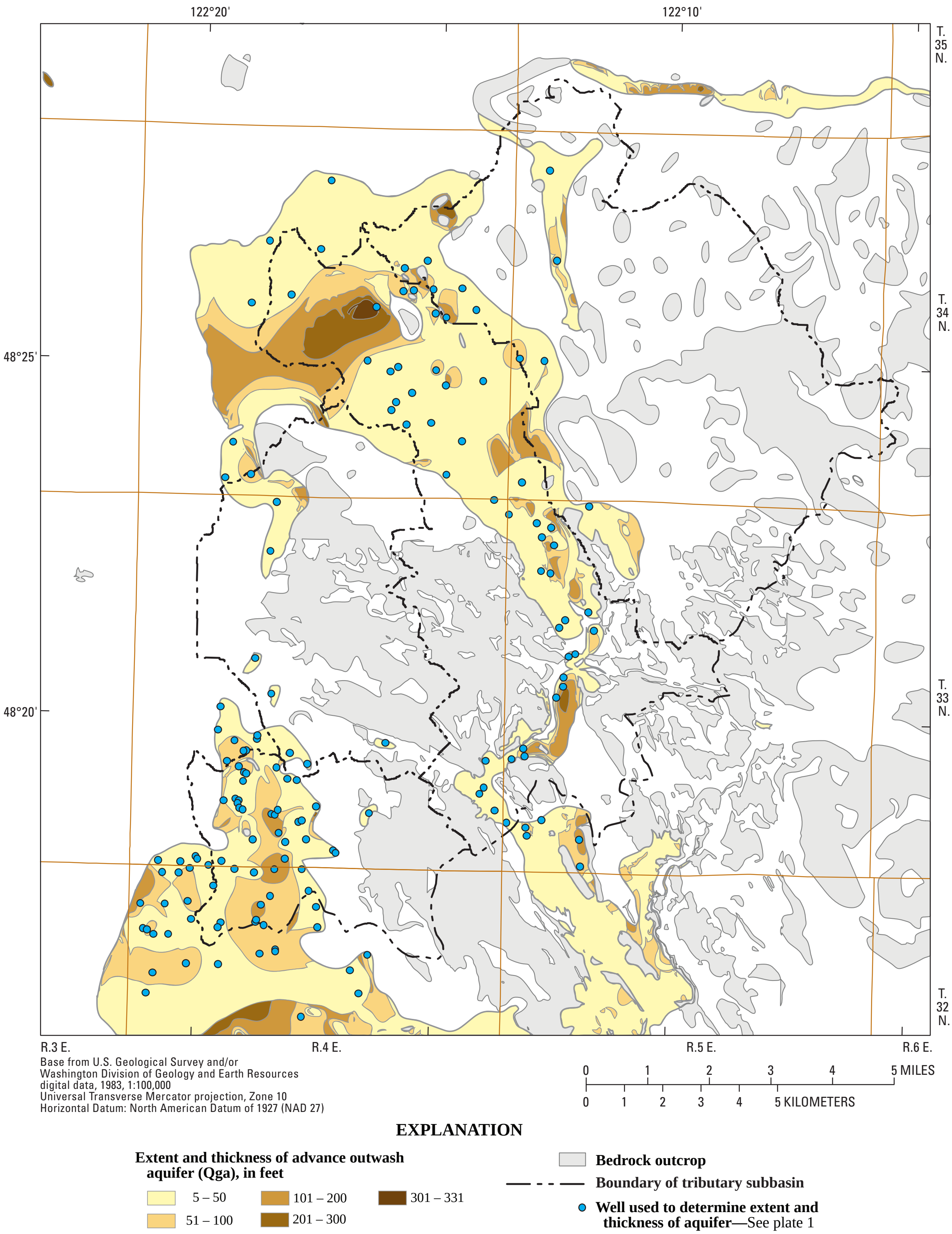


Figure 4. Extent and thickness of advance outwash aquifer (Qga) in tributary subbasins and vicinity, lower Skagit River basin, Washington.

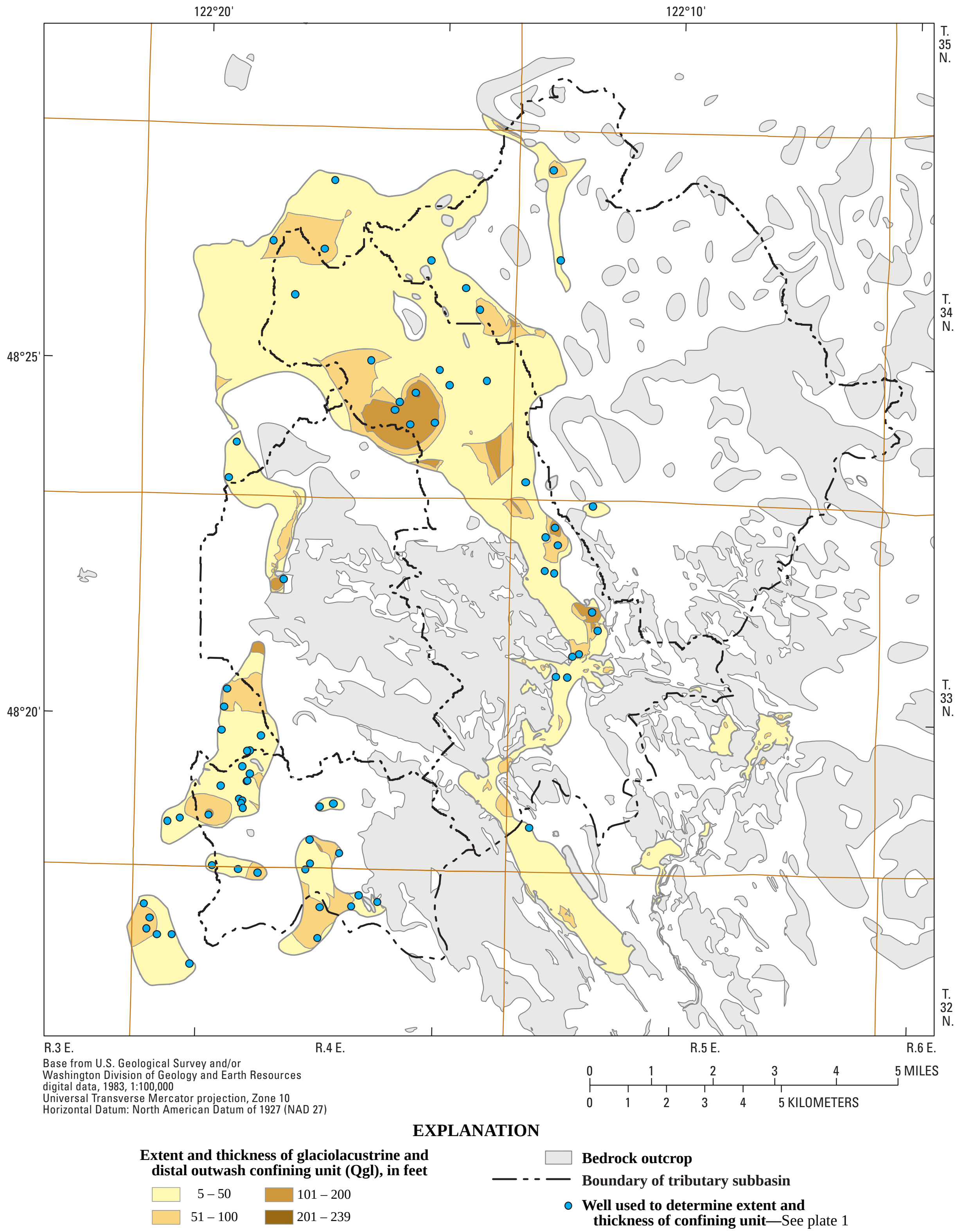


Figure 5. Extent and thickness of glaciolacustrine and distal outwash confining unit (Qgl) in tributary subbasins and vicinity, lower Skagit River basin, Washington.

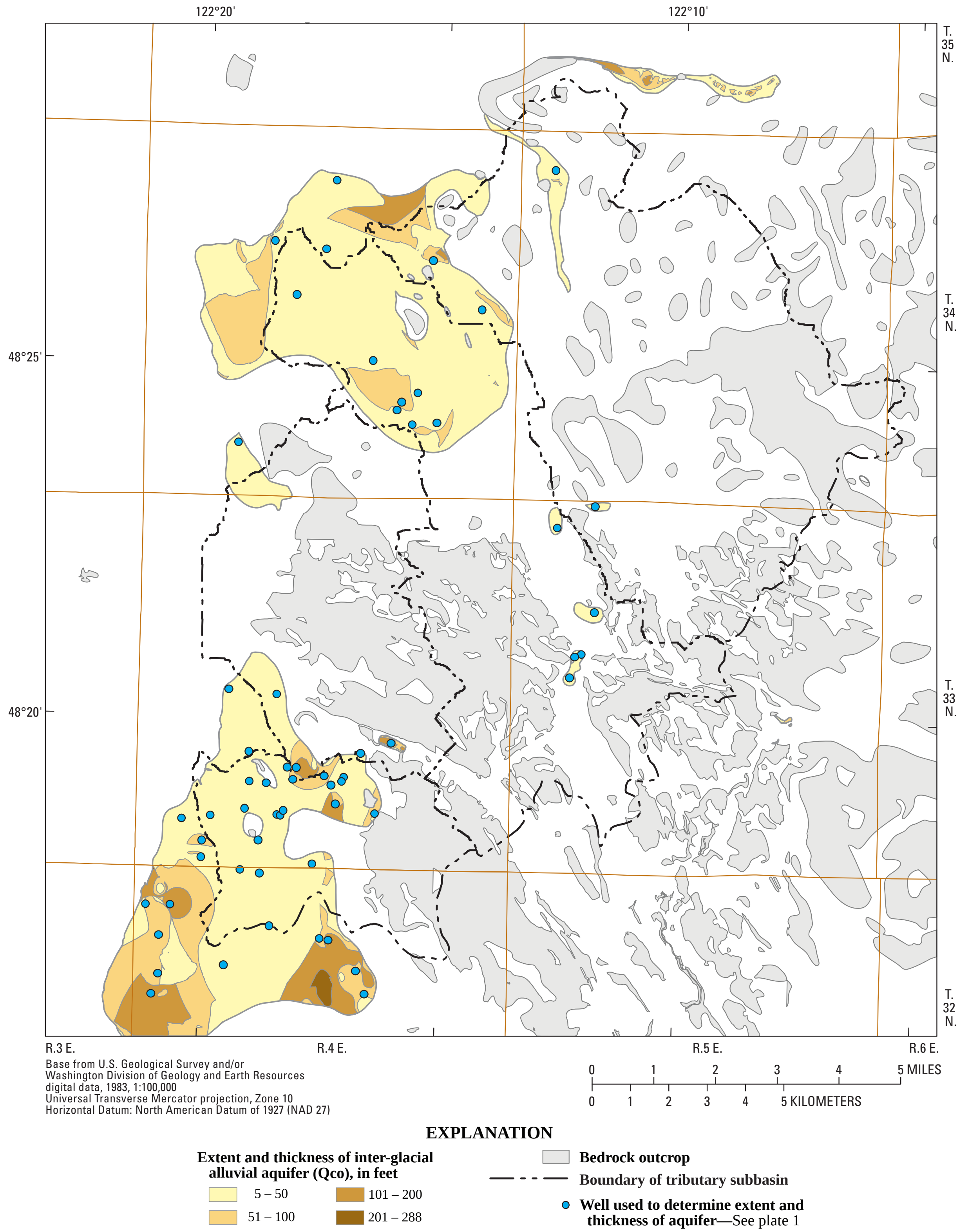


Figure 6. Extent and thickness of inter-glacial alluvial aquifer (Qco) in tributary subbasins and vicinity, lower Skagit River basin, Washington.

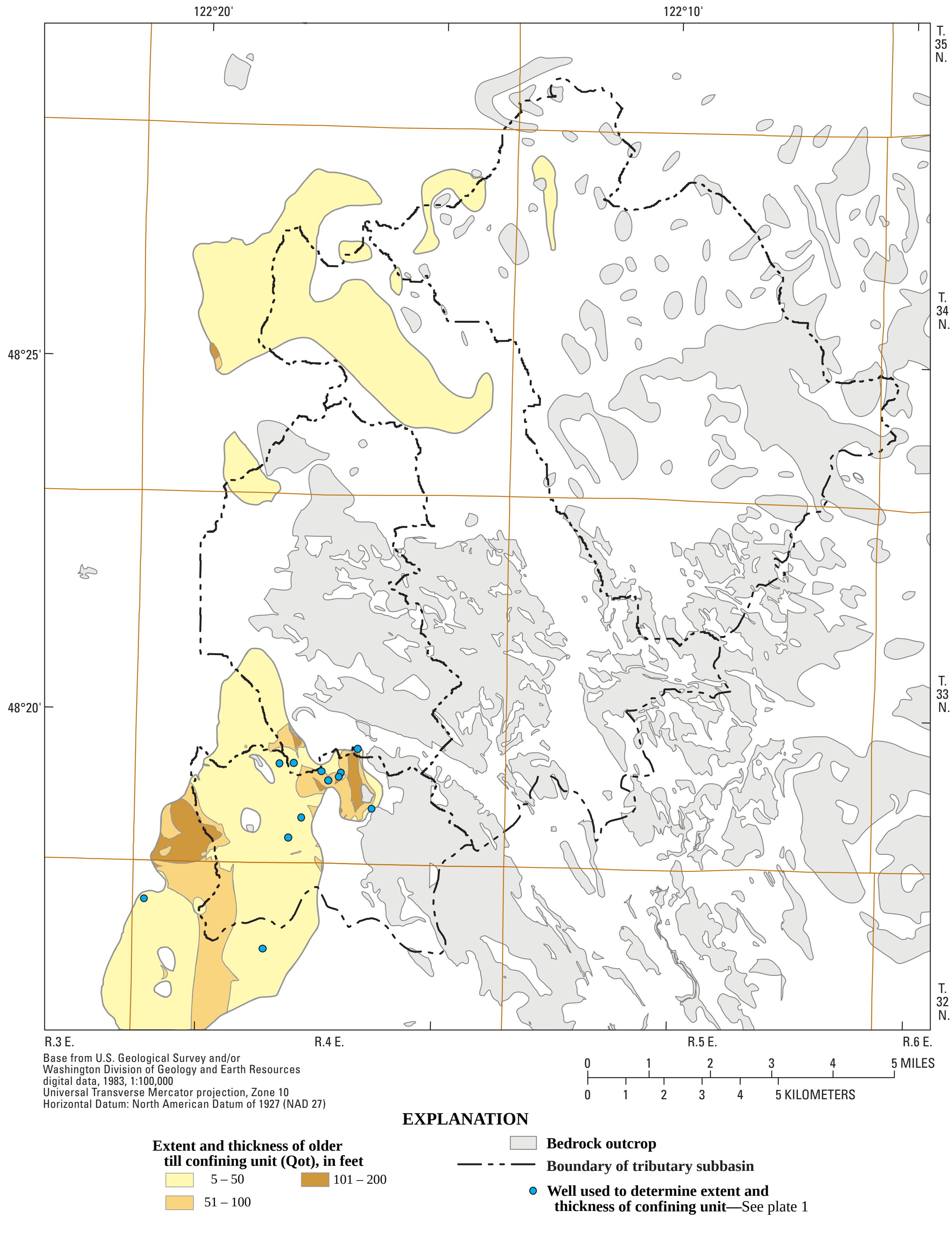


Figure 7. Extent and thickness of older till confining unit (Qot) in tributary subbasins and vicinity, lower Skagit River basin, Washington.

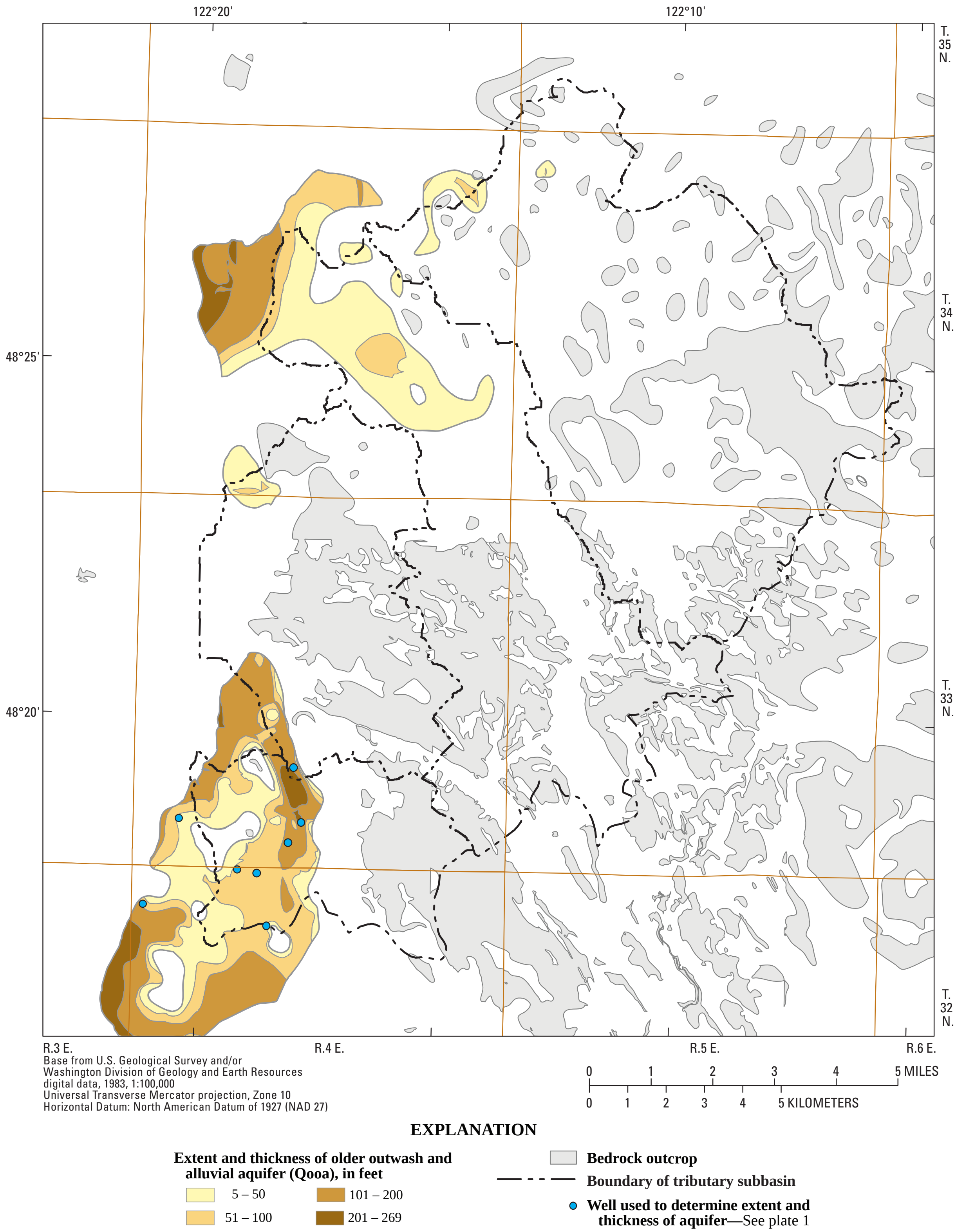


Figure 8. Extent and thickness of older outwash and alluvial aquifer (Qooa) in tributary subbasins and vicinity, lower Skagit River basin, Washington.

Sedimentary aquifer (OEc).—The sedimentary aquifer crops out in large parts of the glacial upland and mountains in central and southern portions of the study area, and also is present in the subsurface throughout this same area (fig. 9). The aquifer is largely absent in the mountains along the eastern margin of the study area. The unit consists primarily of pebble and cobble conglomerate (OEc_b), and medium- to coarse-grained sandstone (OEc_b and Ec_{bc}), with fine-grained intervals of mudstone, siltstone, coal, and shale. Groundwater in the sedimentary aquifer is unconfined where it crops out; however, confined conditions are likely where it is fully saturated and overlain by glacial confining units. Fine-grained intervals within the aquifer also may produce locally confined conditions.

Igneous and metamorphic bedrock unit (EJTP).—The igneous and metamorphic bedrock unit crops out along the northern margin of the glacial uplands in the mountains along the eastern margin of the study area, and within segments of the DDMFZ (fig. 9). This low-permeability unit is composed of volcanic (Evr) and metamorphic rocks (JTP) and consists of rhyolite, andesite, basalt, and complex assemblages of low-grade metasediments, metavolcanics, and meta-intrusives, and is considered to be non-water bearing except in localized areas of fracturing.

Hydraulic Conductivity

Hydraulic conductivity is a measure of a material's ability to transmit water, and hydraulic conductivity in unconsolidated sediment is dependent on the size, shape, distribution, and packing of the particles. Because these physical characteristics vary greatly within the glacial deposits of the study area, hydraulic conductivity values also are highly variable. Estimates of the magnitude and distribution of hydraulic conductivity were used to help understand groundwater movement and availability in the hydrogeologic units.

Horizontal hydraulic conductivity was estimated for the hydrogeologic units using drawdown data from drillers' logs that were observed after wells were pumped for a specified period. Only data from those wells that had a drillers' log containing discharge rate, time of pumping, drawdown, static water level, well-construction data, and lithologic log were used.

Two different sets of equations were used to estimate hydraulic conductivity, depending on well construction. For data from wells with a screened or perforated interval, the modified Theis equation (Ferris and others, 1962) was first used to estimate transmissivity of the pumped interval. Transmissivity is the product of horizontal hydraulic conductivity and thickness of the part of the hydrogeologic unit supplying water to the well. The modified equation is

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

where

s = drawdown in the well, in feet;

Q = discharge or pumping rate of the well, in cubic feet per day;

T = transmissivity of the hydrogeologic unit, in feet squared per day;

t = length of time the well was pumped, in days,

r = radius of the well, in feet; and

S = storage coefficient, a dimensionless number, assumed to be 0.0001 for confined units and 0.1 for unconfined units.

Assumptions for using equation 1 are that aquifers are homogeneous, isotropic, and infinite in extent; wells fully penetrate the aquifer; flow to the well is horizontal; and water is released instantaneously from storage. Additionally, for unconfined aquifers, drawdown is assumed to be small in relation to the saturated thickness of the aquifer. Although many of the assumptions are not precisely met, the field conditions in the study area approximate most of the assumptions and the calculated hydraulic conductivities are likely reasonable estimates.

A computer program was used to solve equation 1 for transmissivity (*T*) using Newton's iterative method (Carnahan and others, 1969). The difference in computed transmissivity between using 0.1 and 0.0001 for the storage coefficient was a factor of only about 2. Next, the following equation was used to calculate horizontal hydraulic conductivity:

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

where

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

b = thickness, in feet, approximated using the length of the open interval as reported in the drillers' report.

The use of the length of a well's open interval for *b* may overestimate values of K_h because the equations assume that all water flows horizontally within a layer of this thickness. Although some of the flow will be outside this region, the amount can be expected to be small because in most sedimentary deposits, vertical flow is inhibited by layering.

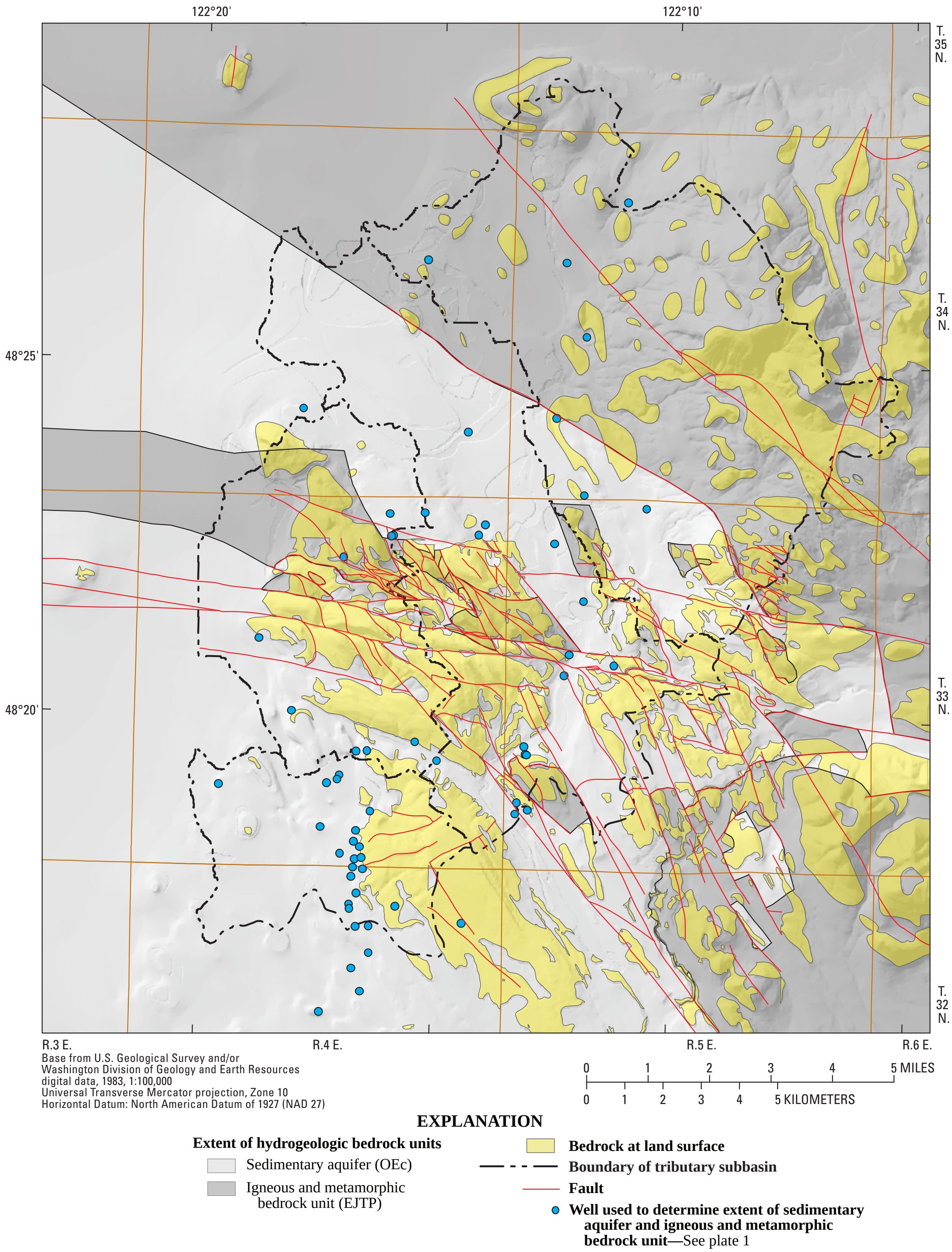


Figure 9. Extent of sedimentary aquifer (OEc) and igneous and metamorphic bedrock unit (EJTP) in tributary subbasins and vicinity, lower Skagit River basin, Washington.

For data from wells having only an open end, a second equation was used to estimate hydraulic conductivities. Bear (1979) provides an equation for hemispherical flow to an open-ended well just penetrating a hydrogeologic unit. When modified for spherical flow to an open-ended well within a unit, the equation becomes

$$K_h = \frac{Q}{4\pi sr}, \tag{3}$$

This equation is based on the assumption that horizontal and vertical hydraulic conductivities are equal, which is not likely for the deposits in the study area. The result of violating this assumption probably is an underestimate of K_h by an unknown amount.

Horizontal hydraulic conductivities were calculated for those wells with available data, and statistical summaries were prepared by hydrogeologic unit (table 3). The values of estimated median hydraulic conductivity for the aquifers are similar in magnitude to values reported by Freeze and Cherry (1979) for similar materials: Qago, 47 ft/d; Qga, 48 ft/d; Qco, 57 ft/d: Qooa, 26 ft/d; and OEc, 0.27 ft/d (table 3). Estimated median hydraulic conductivity for the confining units (Qgt, 13 ft/d; Qgl, 26 ft/d; Qot, 11 ft/d) and bedrock unit (EJTP, 0.13 ft/d) are higher than is typical for most of the material in these units because the available data for confining units usually are from wells that are preferentially open to lenses of coarse material, or in the case of bedrock, where fractures exist. As a result, the data are biased toward the more productive zones in these units and are not representative of the entire unit.

Groundwater Movement

This section describes the movement of groundwater in the aquifer system in the study area, and includes discussions of recharge, flow direction, discharge, exchange of water between the aquifer system and creeks, and temporal fluctuations in groundwater levels. These processes occur within the physical domain described by the hydrogeologic framework, and are influenced by the hydrogeologic characteristics of the aquifer system in which they occur, and other factors, including streamflow, and the spatial distribution of precipitation and land cover.

Recharge

Precipitation is the dominant source of water recharging the groundwater system in the study area, and it is reasonable to expect variations in recharge to be related to spatial and temporal variations in precipitation. However, factors, such as the permeability of surficial hydrogeologic units and land-cover characteristics, also affect recharge; therefore, the relation between precipitation and recharge is likely to vary according to hydrogeologic and land-cover characteristics. The distribution of recharge from precipitation in the four tributary subbasins was estimated by applying precipitation-recharge relations based on regression equations developed for areas in Washington State (Bidlake and Payne, 2001) that incorporate the effects of surficial hydrogeology and tree canopy characteristics. The effects of impervious surfaces on the distribution of recharge from precipitation also were estimated in the study area.

Table 3. Statistical summary of hydraulic conductivity values by hydrogeologic unit in tributary subbasins and vicinity, lower Skagit River basin, Washington.

[–. no data]

Hydrogeologic unit		Number of wells	Hydraulic conductivity (feet per day)		
			Minimum	Median	Maximum
Qago	Alluvial and recessional outwash aquifer	13	0.04	47	1,322
Qgt	Till confining unit	4	6.7	13	89
Qga	Advance outwash aquifer	30	2.6	48	722
Qgl	Glaciolacustrine and distal outwash confining unit	1	–	[1]26	–
Qco	Inter-glacial alluvial aquifer	8	1.4	57	393
Qot	Older till confining unit	1	–	[1]11	–
Qooa	Older outwash and alluvial aquifer	1	–	[1]26	–
OEc	Sedimentary aquifer	16	.05	.27	20
EJTP	Igneous and metamorphic bedrock unit	5	.04	.13	40

[1]Single measurement values represented as median.

Average annual precipitation totals were calculated from daily values for the study period (September 1, 2006, to August 31, 2008), obtained from the National Climate Data Center, NCDC, (www.ncdc.noaa.gov), for three active National Weather Service (NWS) stations near the study area: Sedro-Woolley (NWS station 457507), Arlington (NWS station 450257), and Anacortes (NWS station 450176). These point data were extrapolated across the study area based on the spatial distribution of normal precipitation (average annual precipitation for 1971–2000) provided by the computer program Parameter-elevation Regressions on Independent Slopes Model, PRISM, (Daly and others, 1994; Oregon State University, 2009). The PRISM model estimates the distribution of normal annual precipitation based on a statistical method that takes into account altitude and spatial variation.

Normal annual precipitation at each NWS station was obtained by sampling the PRISM distribution at the three station locations; allowing the PRISM distribution to be scaled for extrapolation. The normal precipitation was compared to the average annual precipitation for the study period (September 1, 2006, to August 31, 2008) at the NWS stations and a regression equation was developed for the three points:

$$P_{actual} = 4.35 \text{ in/yr} + 0.911 \times P_{normal}$$

This relation was used to estimate the distribution of average annual precipitation for the study period throughout the study area (fig. 10), based on the PRISM distribution of normal precipitation. The tributary subbasins received about 284,000 acre-ft or about 56 in. of precipitation during an average year (September 1, 2006, to August 31, 2008). Precipitation during an average year for each subbasin was: East Fork Nookachamps Creek, 136,920 acre-ft (70 in/yr); Nookachamps Creek, 74,820 acre-ft (49 in/yr); Carpenter Creek, 46,610 acre-ft (46 in/yr); and Fisher Creek, 25,730 acre-ft (47 in/yr).

The effects of surficial hydrogeology on the distribution of recharge from precipitation (fig. 11) were estimated based on regression equations developed by Bidlake and Payne (2001) for soils in western Washington formed on glacial outwash and alluvial sediments, and soils formed on glacial till and fine-grained sediments. Recharge estimates for aquifer units (outwash and alluvium) exposed at land surface in the study area were based on the regression equation developed for soils formed on glacial outwash and alluvial sediments; recharge estimates for confining units (till and lacustrine) were based on the regression equation developed for soils formed on glacial till and fine-grained sediments. Recharge estimates for areas where sedimentary and bedrock units are exposed at land surface required the approximation of additional precipitation-recharge equations for this study that were based on a qualitative comparison of the hydrogeologic properties of unconsolidated, sedimentary, and bedrock units. Recharge characteristics of the sedimentary aquifer were estimated to be less than unconsolidated aquifers and greater than unconsolidated confining units, and a precipitation-recharge relation was selected for the sedimentary aquifer that plots mid-way between these unconsolidated units (fig. 11). Recharge characteristics of the bedrock unit were estimated to be less than the unconsolidated confining units, and a precipitation-recharge relation was selected for the bedrock unit that represents one-half the recharge of the unconsolidated confining units.

The effect of evaporative loss associated with the interception of precipitation by tree canopy on recharge from precipitation (fig. 11) was estimated for unconsolidated and bedrock aquifers using equations from Bidlake and Payne (2001), and tree canopy distribution data obtained from the National Land Cover Database, NLCD (2001). Interception loss was applied to areas with more than 50 percent tree canopy (fig. 10). Urban centers in the study area manage storm water by discharging runoff to rivers or streams rather than by infiltrating to groundwater, therefore, recharge within city limits was reduced according to the percentage of impervious surface (figs. 10 and 12) derived from the National Land Cover Database (2001). No direct recharge from precipitation was assumed for areas covered by lakes.

GIS techniques were used to combine the data coverages described above, and calculate the distribution of groundwater recharge from precipitation at a 1,000 ft cell size in the four tributary subbasins (fig. 13). Recharge rates range from less than1 in/yr in urban areas underlain by impervious surfaces to about 46 in/yr in mountainous terrain underlain by till deposits with less than 50 percent tree canopy along the eastern margin of East Fork Nookachamps Creek subbasin where precipitation locally exceeds 120 in/yr. Summing the recharge areas shown in figure 13 indicates that the groundwater system within the subbasins receives about 92,400 acre-ft or about 18 in. of recharge from precipitation during an average year (September 1, 2006, to August 31, 2008). The calculated recharge from precipitation during an average year for each subbasin was: East Fork Nookachamps Creek, 41,060 acre-ft (21 in/yr); Nookachamps Creek, 23,840 acre-ft (16 in/yr); Carpenter Creek, 17,200 acre-ft (17 in/yr); and Fisher Creek, 10,300 acre-ft (19 in/yr).

Precipitation-recharge relations developed by Bidlake and Payne (2001) included only annual precipitation as much as 60 in/yr, whereas, areas along the eastern boundary of the tributary subbasins locally receive greater than 120 in/yr. To estimate recharge for areas receiving between 60 and 120 in. of annual precipitation, regression equation lines were extended using a constant slope from 60 to 120 in/yr. The upper limits of the precipitation-recharge relation are poorly understood and a reduction in the efficiency of groundwater recharge from precipitation likely takes place at some point, resulting in the potential for over estimation of recharge (William Bidlake, U.S. Geological Survey, oral commun., 2009).

In addition to groundwater recharge from precipitation, groundwater recharge from creeks also occurs in the study area along losing creek reaches. The total amount of groundwater recharge from creeks was not quantified, but this total is reflected in the computation of the total net groundwater discharge to creeks used in the water budget.

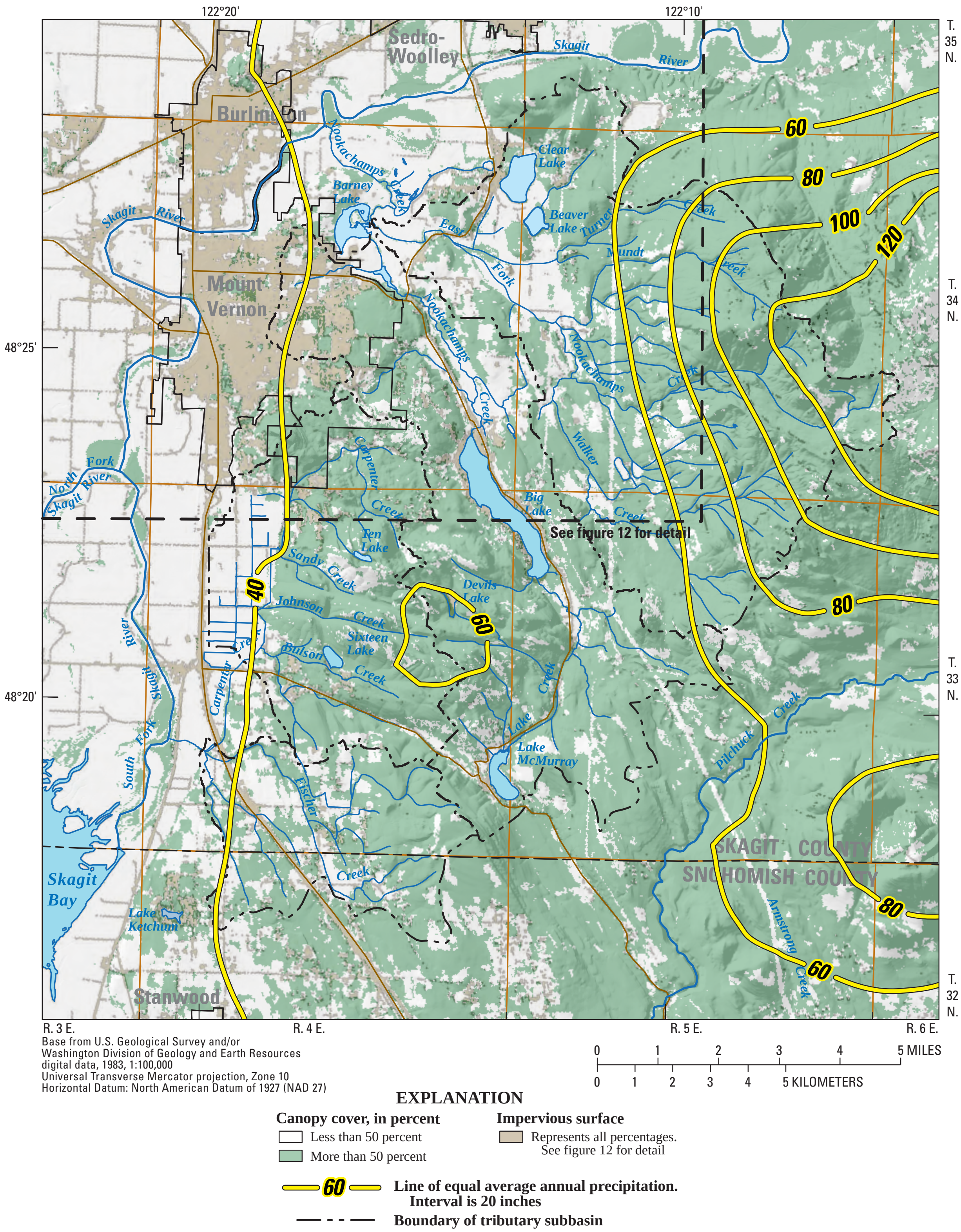


Figure 10. Average annual precipitation, canopy cover, and impervious surface across the tributary subbasins and vicinity, lower Skagit River basin, Washington, September 2006–August 2008.

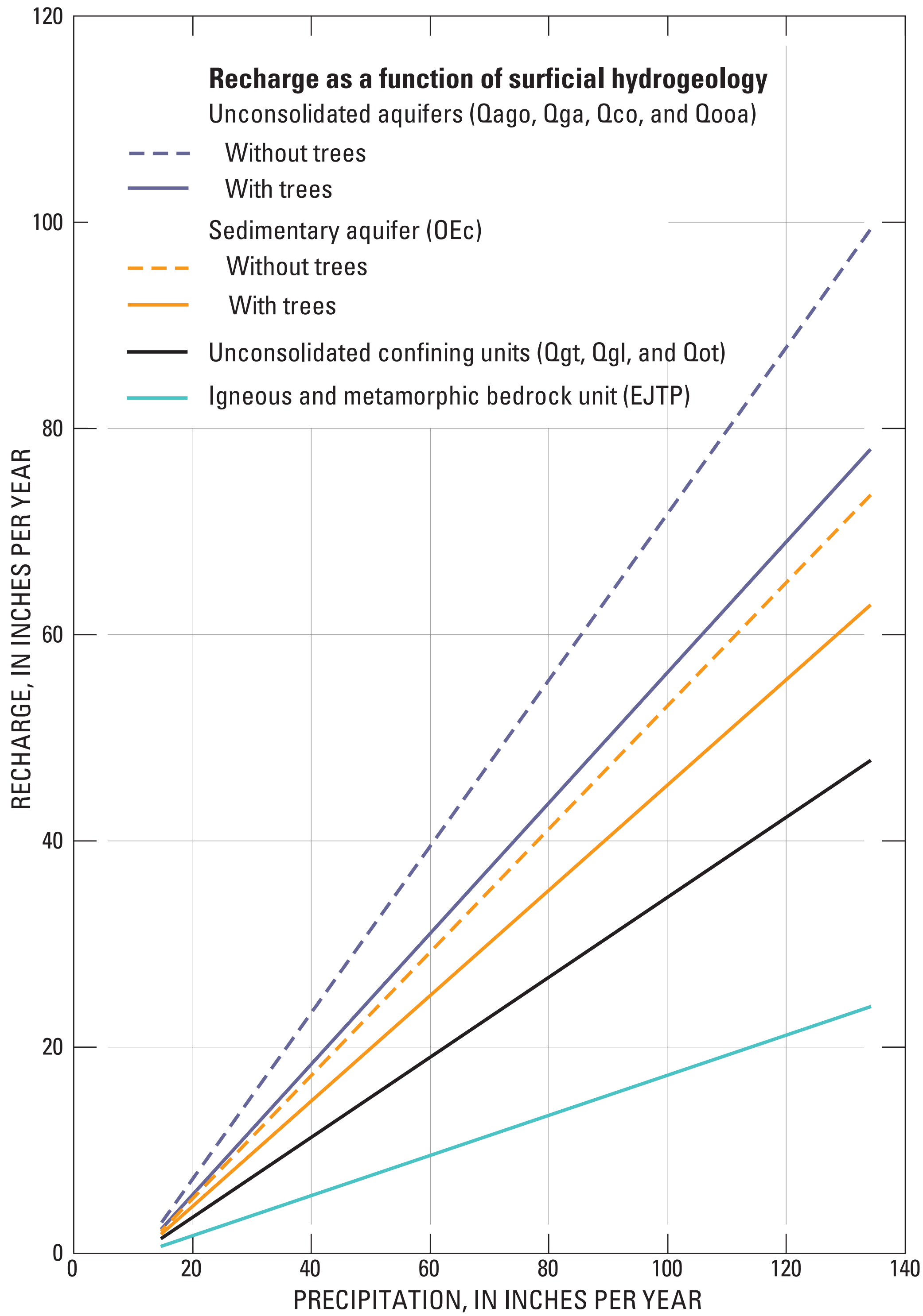


Figure 11. Precipitation-recharge relations used in this study, lower Skagit River basin, Washington.

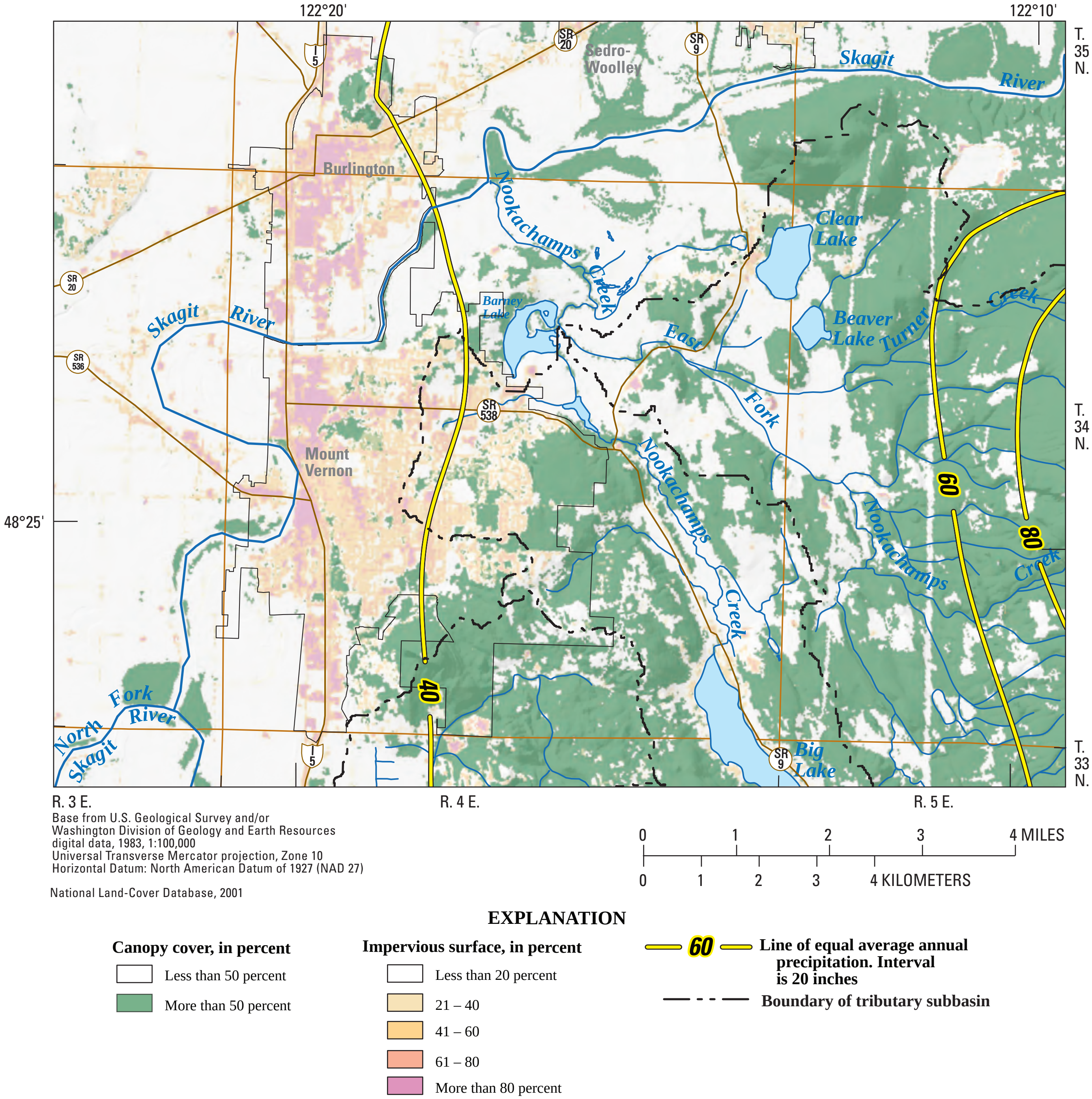


Figure 12. Detail of distribution of impervious surfaces in tributary subbasins and vicinity, lower Skagit River basin, Washington, September 2006–August 2008.

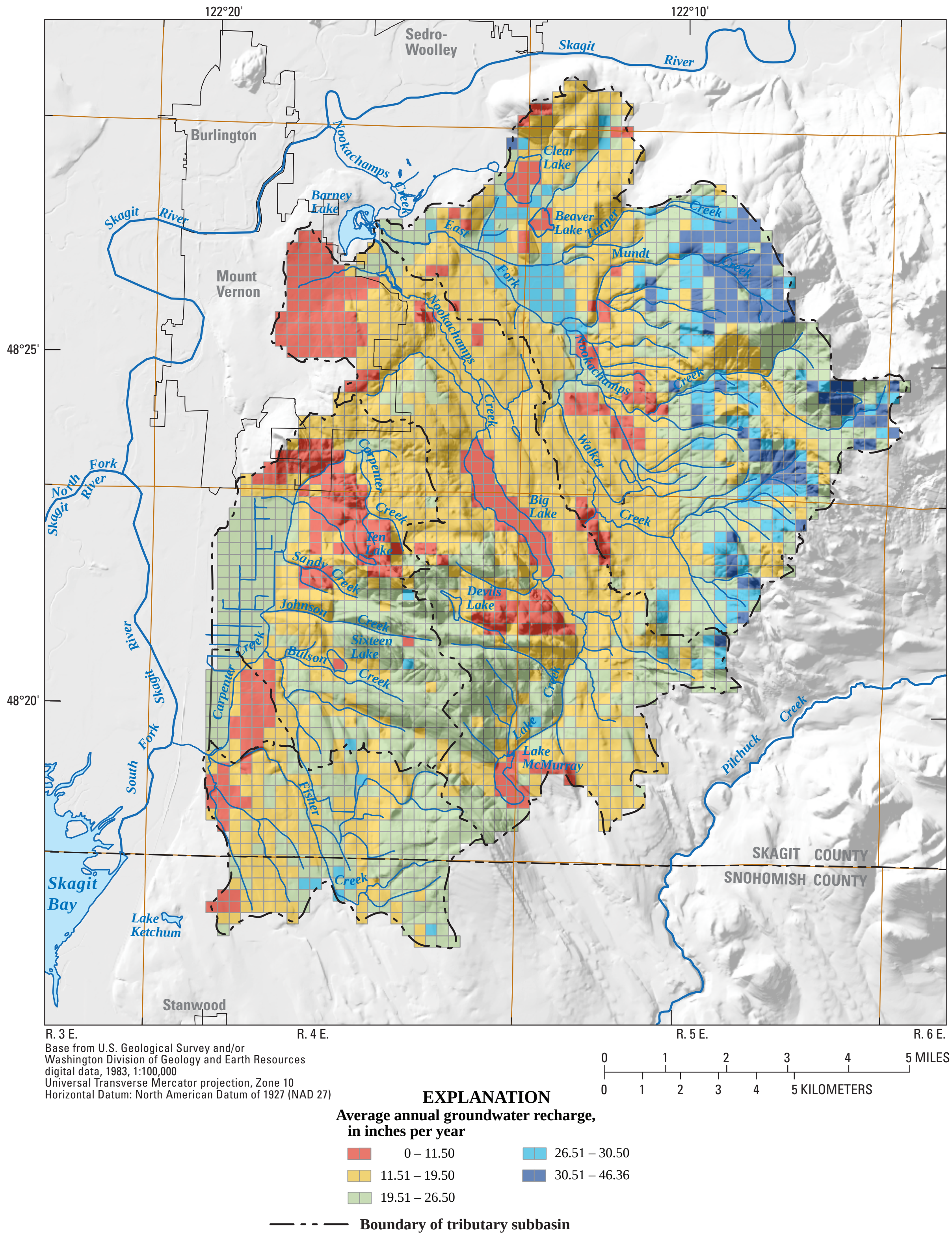


Figure 13. Distribution of average annual groundwater recharge from precipitation in tributary subbasins and vicinity, lower Skagit River basin, Washington, September 2006–August 2008.

Groundwater-Flow Directions

The direction of horizontal groundwater flow can be inferred from contour maps of water-level altitudes. The direction of groundwater flow generally is from areas of recharge to areas of discharge in the direction of decreasing water-level altitudes and perpendicular to the water-level altitude contours. Groundwater levels measured monthly (October 2006 through September 2008) were used to infer direction of groundwater flow in study area aquifers (figs. 14 through 18). The mean water-level value for October 2006 through September 2008 was used to represent the water-level altitude at monitoring wells measured monthly for this analysis. Synoptic groundwater levels measured during the field inventory (August through October 2006) were used only in areas where monthly water-level data were not available, and in places field inventory values do not correlate well with water-level altitude contours based on monthly data. Water-level contours for most aquifer units are based on limited water-level data, and are subject to some uncertainty. Water-level contours were not drawn for the alluvial and recessional outwash aquifer (Qago) because of the discontinuous nature of the unit within the tributary subbasins. Water-level contours also were not drawn for large parts of the advance outwash (Qga), inter-glacial alluvial (Qco), and older outwash and alluvial (Qooa) aquifers due to limited water-level data for these units.

Groundwater flow in the Qago aquifer likely follows the land-surface gradient, with water generally moving in a northwesterly direction from high-altitude areas in the upper portions of the tributary subbasins towards the Skagit River and Puget Sound (fig. 14). This generalized flow pattern is likely complicated by the presence of large areas of low permeability glacial till (Qgt) that separate discontinuous bodies of Qago and act as local groundwater-flow barriers.

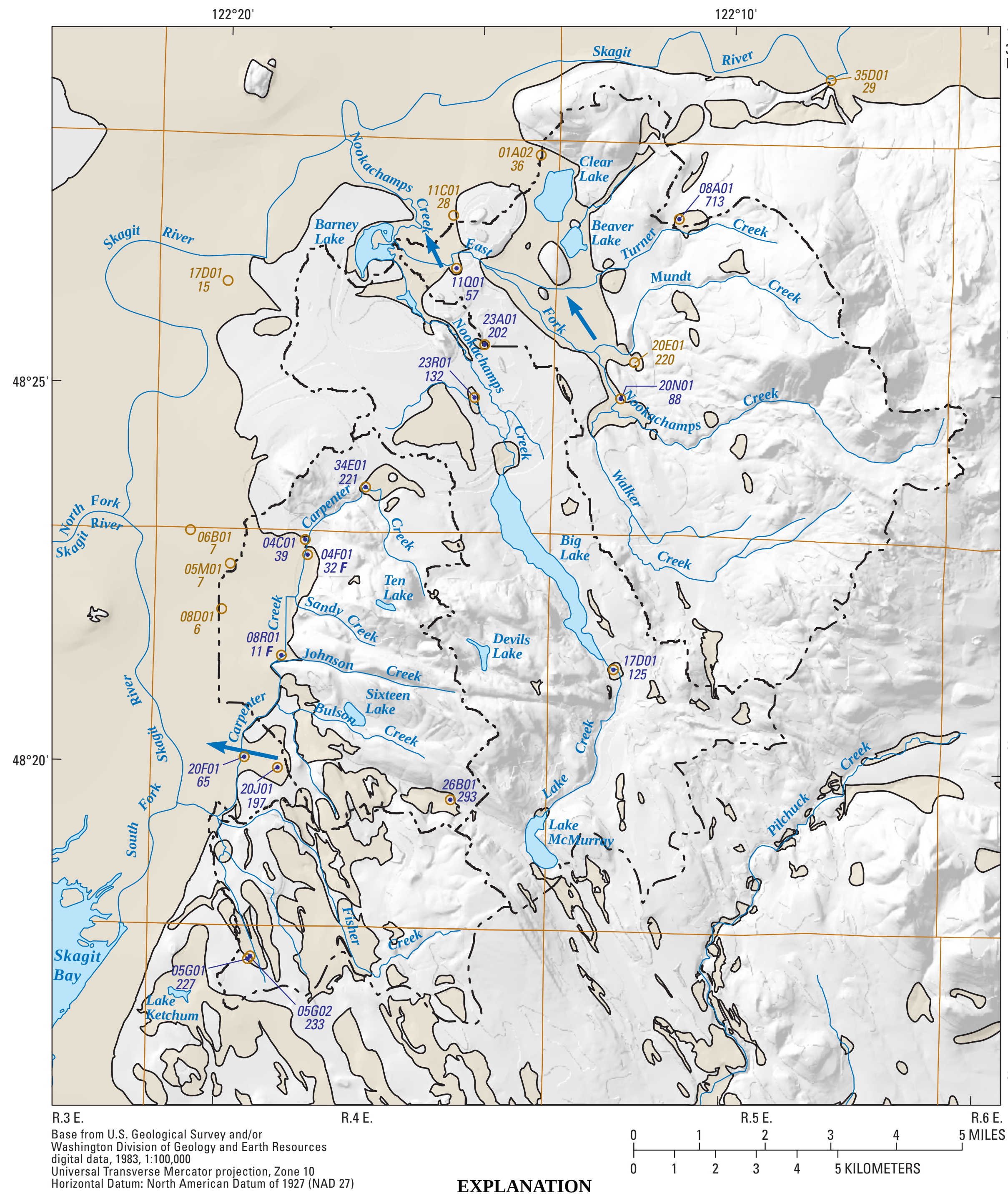
In the southern part of the study area, groundwater flow in the advance outwash aquifer (Qga) is towards the west in the direction of the Skagit River and Puget Sound (fig. 15). North to northwestward groundwater flows beneath major tributary river valleys, and localized radial flow are inferred from widely spaced water-level data in central and northern parts of the area.

Groundwater flow in the inter-glacial alluvial (Qco) and older outwash and alluvial (Qooa) aquifers is towards the west in the direction of the Skagit River and Puget Sound in the southern part of the study area (figs. 16 and 17, respectively). Widely spaced water-level data in the northern part of the area suggest a northwestward and southeastward direction of groundwater flow in the inter-glacial alluvial aquifer (Qco).

Directions of groundwater flow in the sedimentary aquifer (OEc) likely reflect both local and regional flow patterns (fig. 18). Recharge to the sedimentary aquifer (OEc) aquifer preferentially occurs in mountainous areas where the unit is exposed at land surface (figs. 9 and 13). Water-level altitudes in these areas reflect local topographic relief (fig. 18) and suggest radial flow from bedrock highs down beneath the surrounding unconsolidated sediments. Westward groundwater flow in the sedimentary aquifer (OEc) occurs along the mountain front in the eastern part of the study area, and is coincident with a regional westward decrease in land-surface altitude from the mountains to the Puget Sound.

Vertical gradients and flow in the groundwater system are difficult to determine because extents and thicknesses of hydrogeologic units vary considerably throughout the study area, the presence of confining units within and between aquifers is highly variable, and water-level data for comparison between adjacent units are widely spaced. Water-level altitude differences between the advance outwash (Qga) and inter-glacial alluvial (Qco) aquifers in the southwestern part of the study area, where sufficient contoured data were available to make a comparison, suggest downward vertical flow (figs. 15 and 16).

The potential for upward groundwater movement, indicated by the presence of flowing wells, was observed at several locations within the aquifer units. Confining clays within the alluvial and recessional outwash aquifer (Qago) likely produce intermittent flowing conditions observed at two wells along the eastern margin of the Skagit River valley (fig. 14). Upward flow in the advance outwash (Qga) aquifer is suggested by the presence of three continuously flowing wells near Big Lake, and two intermittent flowing wells located along the mountain front (fig. 15). Confined groundwater conditions are attributed to the presence of overlying till deposits (Qtv) at both of these locations. A continuously flowing well completed in the older outwash and alluvial aquifer (Qooa) indicates the potential for upward flow in the southwestern part of the study area (fig. 17), and upward flow in the sedimentary aquifer (OEc) is indicated by an intermittent flowing well adjacent to Lake McMurray (fig. 18).



EXPLANATION

Alluvial and recessional outwash aquifer (Qago)

Inferred direction of groundwater flow

Boundary of tributary subbasin

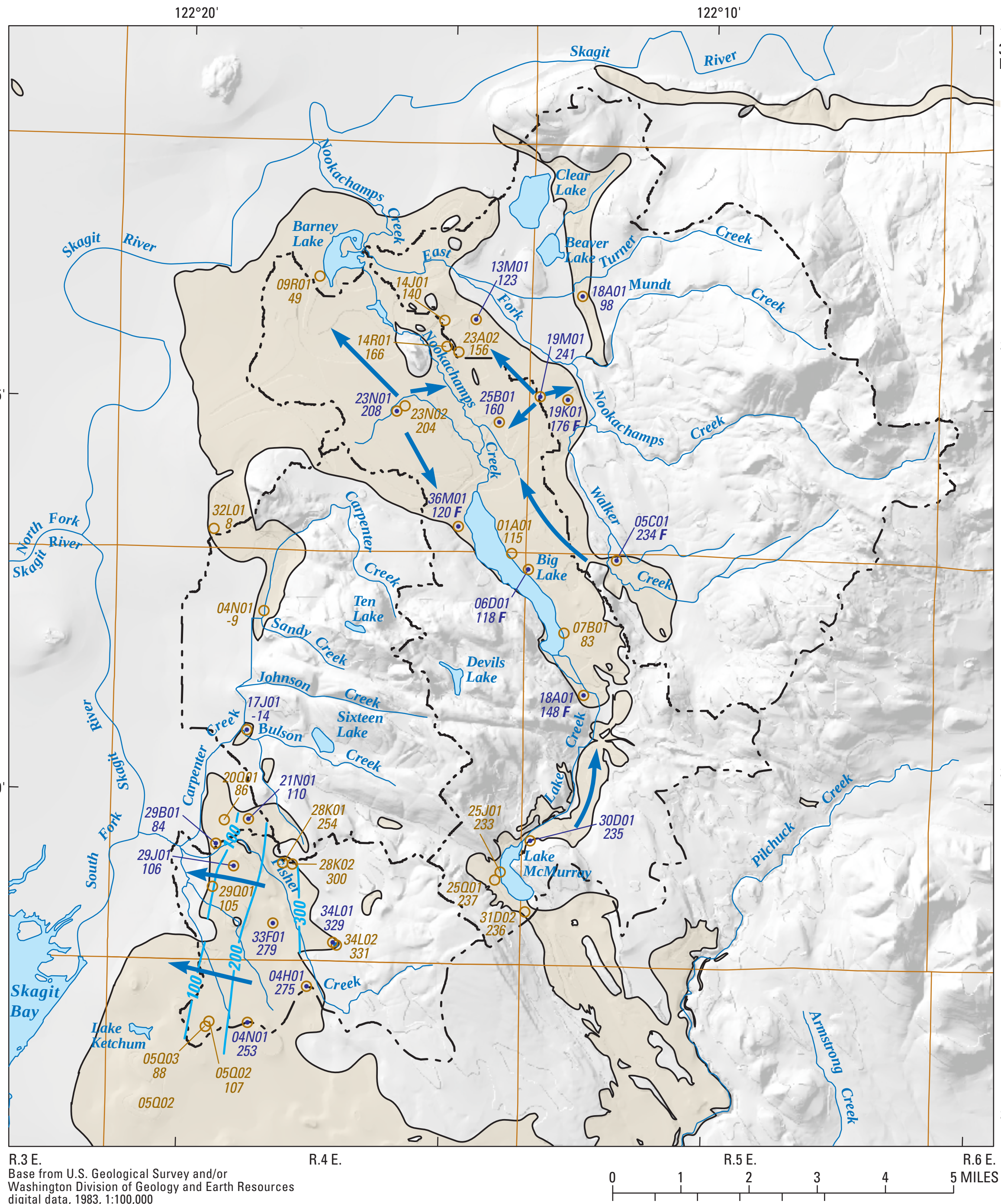
Measurement location and water-level altitude, in feet above North American Vertical Datum of 1988 (NAVD 88)

05G02 233 **Well used to measure water-level altitudes on a monthly basis**—The mean water-level altitude for October 2006 through September 2008 was used to represent the water-level altitude at each of the wells monitored on a monthly basis. Numbers are well No. (top) and water-level altitude (bottom)

08D01 6 **Field inventory well used to measure synoptic water-level altitudes**—Synoptic water-level altitude for August through October 2006 was used only in areas where monthly water-level data were not available. Numbers are well No. (top) and water-level altitude (bottom)

F **Flowing well**

Figure 14. Water-level altitudes and direction of groundwater flow in alluvial and recessional outwash aquifer (Qago) in tributary subbasins and vicinity, lower Skagit River basin, Washington, August 2006–September 2008.



Base from U.S. Geological Survey and/or
Washington Division of Geology and Earth Resources
digital data, 1983, 1:100,000
Universal Transverse Mercator projection, Zone 10
Horizontal Datum: North American Datum of 1927 (NAD 27)

EXPLANATION

Advance outwash aquifer (Qga)

Approximate water-level contour—Shows altitude of water level in advance outwash aquifer, October 2006–September 2008. Contour interval, 100 feet. Datum is North American Vertical Datum of 1988 (NAVD 88)

Boundary of tributary subbasin

Inferred direction of groundwater flow

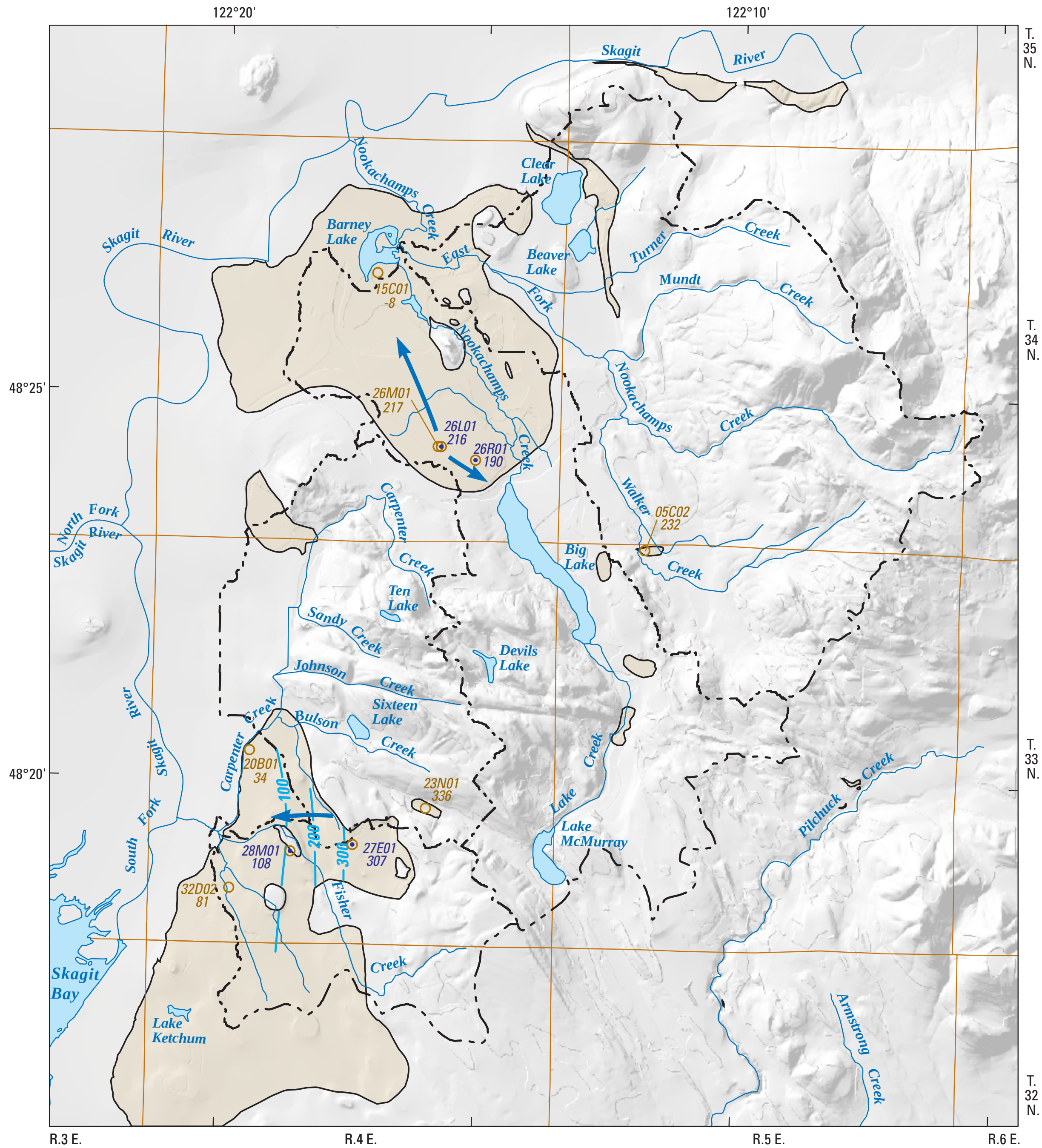
Measurement location and water-level altitude, in feet above North American Vertical Datum of 1988 (NAVD 88)

04N01 253 **Well used to measure water-level altitudes on a monthly basis**—The mean water-level altitude for October 2006 through September 2008 was used to represent the water-level altitude at each of the wells monitored on a monthly basis. Numbers are well No. (top) and water-level altitude (bottom)

05Q02 107 **Field inventory well used to measure synoptic water-level altitudes**—Synoptic water-level altitude for August through October 2006 was used only in areas where monthly water-level data were not available. Numbers are well No. (top) and water-level altitude (bottom)

F **Flowing well**

Figure 15. Water-level altitudes and direction of groundwater flow in advance outwash aquifer (Qga) in tributary subbasins and vicinity, lower Skagit River basin, Washington, August 2006–September 2008.



Base from U.S. Geological Survey and/or
Washington Division of Geology and Earth Resources
digital data, 1983, 1:100,000
Universal Transverse Mercator projection, Zone 10
Horizontal Datum: North American Datum of 1927 (NAD 27)

EXPLANATION

Inter-glacial alluvial aquifer (Qco)

Approximate water-level contour—Shows altitude of water level in inter-glacial alluvial aquifer, October 2006–September 2008. Contour interval, 100 feet. Datum is North American Vertical Datum of 1988 (NAVD 88)

Boundary of tributary subbasins

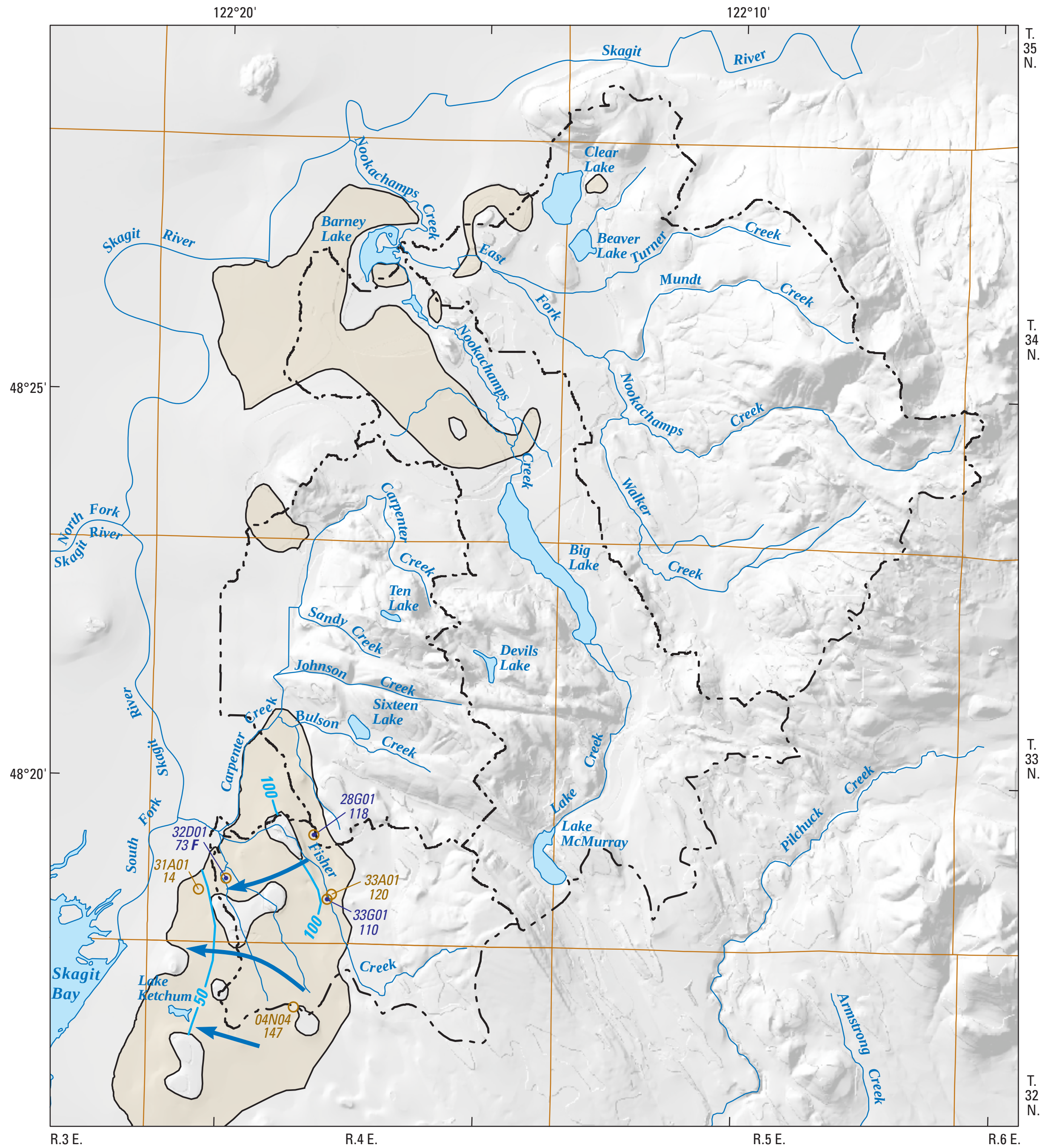
Inferred direction of groundwater flow

Measurement location and water-level altitude, in feet above North American Vertical Datum of 1988 (NAVD 88)

28M01 108 **Well used to measure water-level altitudes on a monthly basis**—The mean water-level altitude for October 2006 through September 2008 was used to represent the water-level altitude at each of the wells monitored on a monthly basis. Numbers are well No. (top) and water-level altitude (bottom)

32D02 81 **Field inventory well used to measure synoptic water-level altitudes**—Synoptic water-level altitude for August through October 2006 was used only in areas where monthly water-level data were not available. Numbers are well No. (top) and water-level altitude (bottom)

Figure 16. Water-level altitudes and direction of groundwater flow in inter-glacial alluvial aquifer (Qco) in tributary subbasins and vicinity, lower Skagit River basin, Washington, August 2006–September 2008.



Base from U.S. Geological Survey and/or Washington Division of Geology and Earth Resources digital data, 1983, 1:100,000
Universal Transverse Mercator projection, Zone 10
Horizontal Datum: North American Datum of 1927 (NAD 27)

0 1 2 3 4 5 MILES

0 1 2 3 4 5 KILOMETERS

EXPLANATION

Older outwash and alluvial aquifer (Qooa)

Approximate water-level contour—Shows altitude of water level in older outwash and alluvial aquifer, October 2006–September 2008. Contour interval, 50 feet. Datum is North American Vertical Datum of 1988 (NAVD 88)

Boundary of tributary subbasin

Inferred direction of groundwater flow

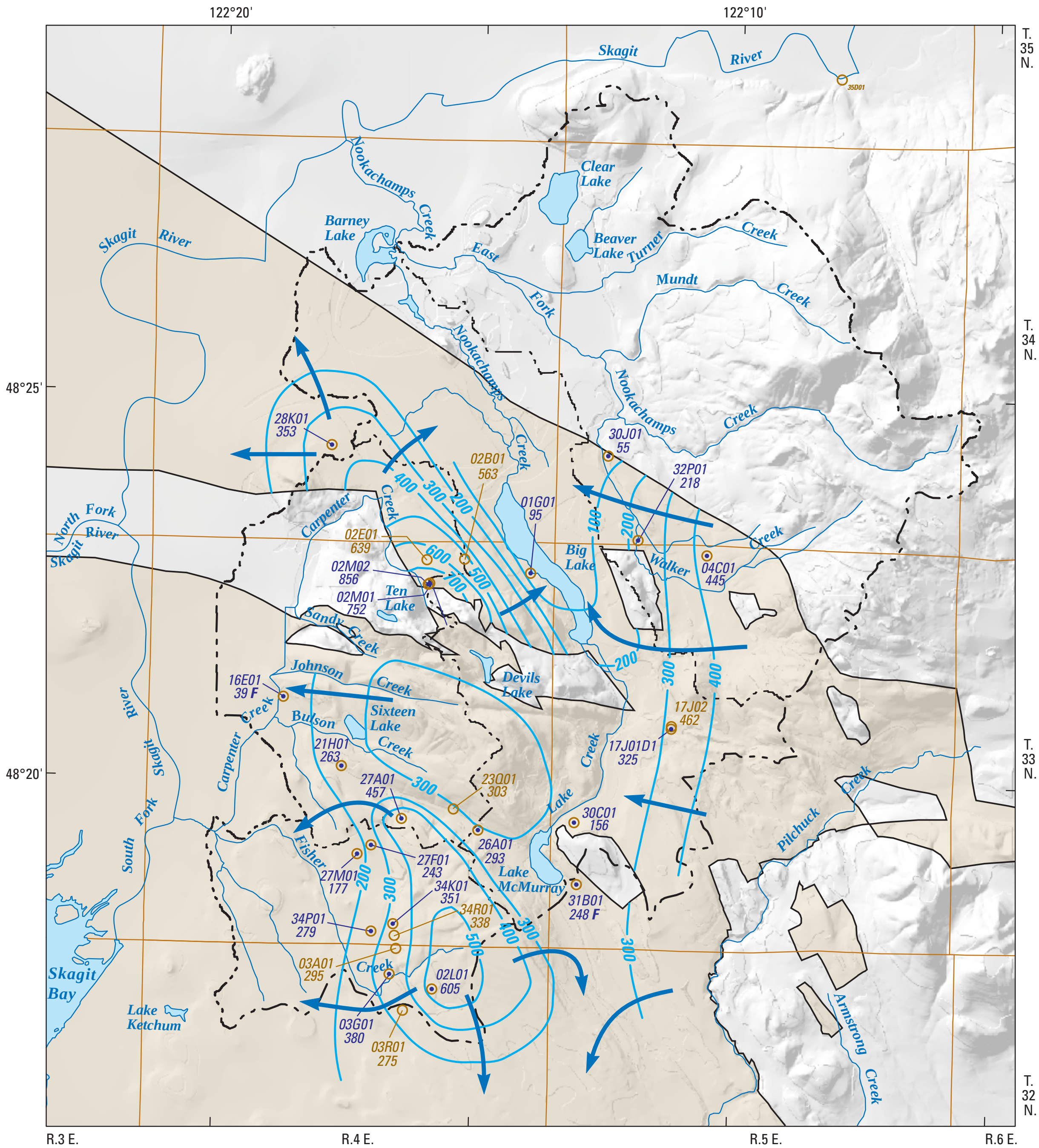
Measurement location and water-level altitude, in feet above North American Vertical Datum of 1988 (NAVD 88)

33G01 110 **Well used to measure water-level altitudes on a monthly basis**—The mean water-level altitude for October 2006 through September 2008 was used to represent the water-level altitude at each of the wells monitored on a monthly basis. Numbers are well No. (top) and water-level altitude (bottom)

04N04 147 **Field inventory well used to measure synoptic water-level altitudes**—Synoptic water-level altitude for August through October 2006 was used only in areas where monthly water-level data were not available. Numbers are well No. (top) and water-level altitude (bottom)

F **Flowing well**

Figure 17. Water-level altitudes and direction of groundwater flow in older outwash and alluvial aquifer (Qooa) in tributary subbasins and vicinity, lower Skagit River basin, Washington, August 2006–September 2008.



Base from U.S. Geological Survey and/or Washington Division of Geology and Earth Resources digital data, 1983, 1:100,000
Universal Transverse Mercator projection, Zone 10
Horizontal Datum: North American Datum of 1927 (NAD 27)

0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

EXPLANATION

- **Sedimentary aquifer (OEc)**
- **Approximate water-level contour**—Shows altitude of water level in sedimentary aquifer, October 2006–September 2008. Contour interval, 50 feet. Datum is North American Vertical Datum of 1988 (NAVD 88)
- **Boundary of tributary subbasin**
- **Inferred direction of groundwater flow**

Measurement location and water-level altitude, in feet above North American Vertical Datum of 1988 (NAVD 88)

- 03G01 380 **Well used to measure water-level altitudes on a monthly basis**—The mean water-level altitude for October 2006 through September 2008 was used to represent the water-level altitude at each of the wells monitored on a monthly basis. Numbers are well No. (top) and water-level altitude (bottom)
- 03A01 295 **Field inventory well used to measure synoptic water-level altitudes**—Synoptic water-level altitude for August through October 2006 was used only in areas where monthly water-level data were not available. Numbers are well No. (top) and water-level altitude (bottom)
- *F* **Flowing well**

Figure 18. Water-level altitudes and direction of groundwater flow in the sedimentary aquifer (OEc) in tributary subbasins and vicinity, lower Skagit River basin, Washington, August 2006–September 2008.

Discharge

Groundwater in the study area discharges as seepage to streams, lakes, springs, and marshes; as evapotranspiration of shallow groundwater; as submarine seepage to Puget Sound; and as withdrawals from wells. Groundwater discharge sustains the late-summer and early-fall streamflow (baseflow) of creeks in the study area. Estimates of groundwater discharge to creeks in the tributary subbasins were based on synoptic streamflow measurements made in August 2007 and June 2008 at seven locations (table 4 and pl. 1); a streamflow measurement for Carpenter Creek obtained from Pitz and Garrigues (2000); and estimates of evaporative loss from lakes within measured reaches (National Oceanic and Atmospheric Administration, 1982). Estimates of daily evaporative loss from lakes were used to account for losses in baseflow during synoptic streamflow measurements (August 2007 and June 2008). These estimates were based on maps of annual evaporation for shallow lakes near the study area (National Oceanic and Atmospheric Administration, 1982). Maps were developed using data from Class A pan evaporation stations and other spatially distributed meteorological data for 1956–70. The accuracy of the maps is a function of the number of nearby data stations and their proximity to the area of interest; the closest stations are located in the southern Puget Sound area. Estimates of annual evaporation assume long-term thermal stability of lake water. Daily values of evaporation were estimated using the average monthly percentage of annual evaporation derived from Class A pan evaporation data (National Oceanic and Atmospheric Administration, 1982) for 1956–70.

Precipitation totals at Sedro-Woolley for June, July, and August 2007 were 2.48, 1.31, and 1.24 in., respectively (Western Regional Climate Center, 2008). The normal (average annual precipitation for the period 1971-2000) precipitation at Sedro-Woolley for these months is 2.85, 1.77, and 1.62 in. (National Oceanic and Atmospheric Administration, 2007). Precipitation totals at Sedro-Woolley for April, May, and June 2008 were 4.40, 2.97, and 3.13 in., respectively (Western Regional Climate Center, 2008). The normal precipitation (average precipitation for selected months for the period 1971–2000) at Sedro-Woolley for these months is 3.76, 3.03, and 2.85 in. (National Oceanic and Atmospheric Administration, 2007).

Groundwater discharge estimates represent flow from contributing areas upstream of the synoptic streamflow-measurement sites (57.7 mi^2) and do not include contributing areas in downstream parts of the subbasins (36.6 mi^2). A total net of about 13.15 ft^3/s (9,520 acre-ft/yr) of groundwater discharged to creeks measured during August 2007, and approximately 129.6 ft^3/s (93,830 acre-ft/yr) of groundwater discharged to creeks measured during June 2008 (table 4). These data reflect seasonal variability in groundwater discharge to creeks, however, much of the likely annual variation in discharge (dryer and wetter conditions) is not represented by these data. Many small streams were not measured, but they may collectively receive a significant quantity of groundwater discharge at times throughout the year. The time averaged (mean of the 2007 and 2008 discharge measurements) area weighted groundwater discharge for the entire tributary subbasin area was estimated to be 83.43 ft^3/s (60,400 acre-ft/yr). This value includes area-weighted estimates of groundwater discharge for portions of subbasins that were downstream of synoptic measurement sites. Area weighting values (measured discharge divided by the contributing area upstream of the measurement site) were derived for each of the tributary subbasins to better represent spatial variation in groundwater discharge characteristics. The use of a time averaged groundwater discharge estimate to compute the area weighted groundwater discharge in the study area may not accurately represent the total annual variation in discharge, and likely introduces some error into this calculation. The time averaged (period of record for each streamflow-gaging station), area-weighted streamflow for the entire tributary subbasin area was estimated to be 221.8 ft^3/s (160,600 acre-ft/yr).

Groundwater withdrawals from wells in the tributary subbasins in 2008 were an estimated 2,200 acre-ft. This quantity represents gross withdrawals (public-water supply, domestic use, and crop irrigation) and does not reflect the quantity of water returned to the groundwater system through septic tanks or through irrigation-return flows to shallow aquifers. Public supply and domestic groundwater withdrawals were estimated using a typical water-use rate of 228 gal/d per connection. The typical use rate was estimated by multiplying a per-capita water-use rate of 84 gal/d (Lane, 2009) by an estimate of 2.71 people per connection (U.S. Census Bureau, 2000). The number of connections within the tributary subbasins area was estimated using the Skagit and Snohomish Counties assessor database, and the Washington State Department of Health database (Skagit County, 2008; Snohomish County, 2008; Washington State Department of Health, 2008). Crop irrigation withdrawals were estimated by multiplying crop specific application rates by the number of acres under production within the tributary subbasins for each crop type, and then accounting for irrigation method efficiency (U.S. Department of Agriculture, 2007; Washington State Department of Agriculture, 2008).

Table 4. Synoptic streamflow measurements used to determine groundwater discharge and estimates of evaporative loss from lakes in tributary subbasins and vicinity, lower Skagit River basin, Washington, August 2007 and June 2008.

[**Measurement site**: Site locations are shown in figure 22. **Accuracy rating** of U.S. Geological Survey measurements: F, fair; P, poor; estimated values are rated poor. ft^3/s, cubic feet per second]

Measurement site	Site No.	Date discharge measured	Discharge (ft^3/s)	Accuracy rating
East Fork Nookachamps Creek subbasin				
Inflow to Beaver Lake	12200022	08-07-07	0.19	F
		06-19-08	3.11	F
Turner Creek	12200015	08-07-07	0.50	F
		06-18-08	2.48	F
East Fork Nookachamps Creek	12200010	08-07-07	4.58	F
		06-19-08	66.1	F
Nookachamps Creek subbasin				
Nookachamps Creek	12199600	08-09-07	0.76	F
		06-19-08	33.1	F
Carpenter Creek subbasin				
Carpenter Creek	12200696	09-21-00	[1]2.22	F
		06-19-08	12.4	F
Fisher Creek subbasin				
Fisher Creek	12200701	08-07-07	0.49	P
		06-05-08	6.38	F
Tributary to Fisher Creek	1220070140	08-07-07	[2]0.01	P
		06-18-08	[2]2.00	P
Evaporative loss from lakes				
Evaporative loss from Big Lake		August 2007	[3]3.15	
		June 2008	[3]2.85	
Evaporative loss from Lake McMurray		August 2007	[3]0.97	
		June 2008	[3]0.88	
Evaporative loss from Sixteen Lake		August 2007	[3]0.28	
		June 2008	[3]0.25	
Total net measured streamflow		August 2007	13.15	
		June 2008	129.6	

[1] Streamflow measured on September 21, 2000; accuracy rating assumed to be fair (Pitz and Garrigues, 2000); backwater conditions observed by U.S. Geological Survey on August 8, 2007.

[2] Estimated by U.S. Geological Survey.

[3] Calculated daily evaporative loss derived from National Oceanic and Atmospheric Administration (1982) annual values.

Groundwater/Surface-Water Interactions

Characterization of the exchange of water between the groundwater system and creeks in the study area was based on synoptic streamflow measurements made in August 2007 and June 2008 at 27 creek locations and an Ecology streamflow-gaging station on East Fork Nookachamps Creek (table 5 and pl. 1); streamflow data for Carpenter Creek from Pitz and Garrigues (2000); and estimates of evaporative loss from lakes (National Oceanic and Atmospheric Administration, 1982). This information was used to identify stream reaches that either gain flow from or lose flow to the shallow groundwater system. August 2007 streamflow measurements were made during the low-flow season, usually July–August (fig. 19), to capture baseflow conditions. June 2008 measurements were made to document the exchange of water between the groundwater system and creeks at a higher baseflow condition with larger groundwater contributions. Streamflow during the August 2007 measurement period remained fairly constant at the Carpenter Creek and Fisher Creek gaging stations and was steadily decreasing at the Nookachamps Creek gaging station (fig. 20). Steadily decreasing streamflow in the study area was observed during the June 2008 measurement period (fig. 21).

The results of the synoptic streamflow measurements are presented in table 5. Most measurements were rated "fair," however, 17 measurements were rated "poor" due to suboptimal flow conditions (low velocity, shallow depth, and aquatic vegetation), or the necessity to estimate streamflow values (lack of access to stream). Inflow (table 5) to a measurement site is the sum of streamflows measured upstream of the measurement site (fig. 22). For example: the August 2007 inflow to the Walker Creek measurement site (12199890), 1.04 ft^3/s, is the sum of the streamflows measured at the upstream Walker Creek site (12199860), 0.98 ft^3/s, and the Tributary to Walker Creek site (12199870), 0.06 ft^3/s. Inflow is used to compute the difference between streamflow upstream of the site and at the site. The sign of the difference in streamflow (positive or negative value) indicates a gaining or losing creek reach.

Uncertainties associated with potential measurement error were too large at a few locations to make defensible conclusions regarding the delineation of gaining or losing creek reaches and those values are identified in italic font (table 5). Error-adjusted minimum and maximum values of measured streamflows were used to evaluate potential measurement error. Minimum and maximum values were computed by applying the measurement rating to the streamflow value; a "fair" measurement rating applies an error adjustment of ± 8 percent, and a "poor" rating applies an error adjustment of ±10 percent. For example: the August 2007 error-adjusted minimum and maximum values for inflow to Walker Creek (12199890), 0.95 and 1.13 ft^3/s, respectively, and the error-adjusted minimum and maximum values for flow at Walker Creek (12199890), 0.99 and 1.17 ft^3/s, respectively, result in a gain or loss uncertainty range (cumulative measurement error) of -0.14–0.22 ft^3/s. The uncertainty range was computed by subtracting the error-adjusted maximum value for inflow to Walker Creek (1.13 ft^3/s) from the error-adjusted minimum value for flow at Walker Creek (0.99 ft^3/s) to determine the lower uncertainty value (0.99 ft^3/s – 1.13 ft^3/s = -0.14 ft^3/s). The upper uncertainty value was computed by subtracting the error-adjusted minimum value for inflow to Walker Creek from the error-adjusted maximum value for flow at Walker Creek (1.17 ft^3/s – 0.95 ft^3/s = 0.22 ft^3/s). The uncertainty range suggests the possibility of either a gaining or losing creek reach, and does not support the delineation of a gaining reach indicated by the unadjusted value of 0.04 ft^3/s. Conclusions regarding delineation of gaining or losing creek reaches were able to be made at most locations (table 5). For example: the June 2008 error-adjusted minimum and maximum values for inflow to Walker Creek (12199890), 12.4 and 13.8 ft^3/s, respectively, and the error-adjusted minimum and maximum values for flow at Walker Creek (12199890), 15.5 and 18.1 ft^3/s, respectively, result in a gain or loss uncertainty range (cumulative measurement error) of 1.7 to 5.7 ft^3/s, and supports the delineation of a gaining reach indicated by the unadjusted value of 3.33 ft^3/s.

The synoptic streamflow data (table 5) illustrate a general pattern in which the upper reaches of creeks in the study area tended to gain flow from the groundwater system, and lower creek reaches tended to lose flow (fig. 22). Substantial inflows from tributaries to major creeks in the study area suggest the presence of groundwater discharge from upland areas underlain by bedrock. Pitz and Garrigues (2000) noted that discharge to tributaries of Carpenter Creek are likely derived in large part from groundwater fracture flow within upland bedrock areas during low-flow conditions. Groundwater discharge from permeable clastic units (OEc) also is a likely contributor to baseflow in upland areas.

Groundwater-Level Fluctuations

Groundwater levels fluctuate over time, both seasonally and long term, in response to changing rates of recharge to and discharge from the groundwater system. When recharge exceeds discharge, the amount of water stored in an aquifer increases and water levels rise; when discharge exceeds recharge, groundwater storage decreases and water levels decline. Groundwater levels also may respond to changes in nearby stream stage. When stream stage exceeds nearby groundwater levels, streamflow may recharge the aquifer, causing a rise in groundwater levels; when groundwater levels exceed nearby stream stage, discharge from the aquifer to the stream may occur, resulting in a decline in groundwater levels. Seasonal changes in groundwater levels that follow a typical pattern for shallow wells in western Washington were observed in many tributary subbasin wells (Fasser and Julich, 2009). Water levels rise from October through March, when precipitation and river stage are high, and decline from April through September, when precipitation and river stage are lower (figs. 23 and 24).

Table 5. Synoptic streamflow measurements and estimates of gains and losses in tributary subbasins, lower Skagit River basin, Washington, August 2007 and June 2008.

[**Measurement site**: Site locations are shown in figure 22. **Inflow** is the sum of streamflows measured upstream of the measurement site. **Accuracy rating** of the U.S. Geological Survey measurements: F, fair; P, poor; estimated values also are rated poor. **Gain or Loss**: Uncertainties associated with potential measurement error were too large at a few locations to make defensible conclusions regarding the delineation of gaining or losing creek reaches and those values are identified in italic. ft^3/s, cubic feet per second]

Measurement site	Site No.	Date discharge measured	Discharge (ft^3/s)	Accuracy rating	Inflow (ft^3/s)	Gain or loss (ft^3/s)
East Fork Nookachamps Creek subbasin						
Walker Creek	12199860	08-08-07	0.98	F		
		06-17-08	12.8	F		
Tributary to Walker Creek	12199870	08-08-07	.06	P		
		06-17-08	.67	P		
Walker Creek	12199890	08-08-07	1.08	F	1.04	*0.04*
		06-18-08	16.8	F	13.47	3.33
East Fork Nookachamps Creek	12199900	08-07-07	4.29	F		
		06-19-08	51.4	F		
East Fork Nookachamps Creek	03G100	08-07-07	[1]5.10		4.29	.81
		06-19-08	[1]63.8		51.4	12.4
Mundt Creek	12200005	08-06-07	1.09	F		
		06-18-08	11.1	P		
East Fork Nookachamps Creek	12200010	08-07-07	4.58	F	6.19	-1.61
		06-19-08	66.1	F	74.9	*-8.8*
Turner Creek	12200015	08-07-07	.50	F		
		06-18-08	2.48	F		
Inflow to Beaver Lake	12200022	08-07-07	.19	F		
		06-19-08	3.11	F		
Nookachamps Creek subbasin						
Lake Creek	12199300	08-06-07	0.47	F		
		06-17-08	9.35	F		
Lake Creek	12199400	08-07-07	1.13	F	.47	.66
		06-17-08	19.2	F	9.35	9.85
Nookachamps Creek	1219949950	08-09-07	.60 F [2]3.75	F	1.13	2.62
		06-19-08	32.2 F [2]35.0	F	19.2	15.8
West Tributary to Nookachamps Creek	12199540	08-07-07	0.46	P		
		06-18-08	1.88	P		
East Tributary to Nookachamps Creek	12199560	08-09-07	.07	P		
		06-18-08	.39	P		
Nookachamps Creek	12199600	08-09-07	.76	F	1.13	-.37
		06-19-08	33.1	F	34.47	*-1.37*
Carpenter Creek subbasin						
Carpenter Creek	12200682	08-09-07	0.08	P		
		06-16-08	3.71	F		
Carpenter Creek	12200684	08-09-07	.22	P	0.08	0.14
		06-16-08	5.29	F	3.71	1.58
Carpenter Creek	12200685	08-09-07	.41	F	.22	.19
		06-16-08	8.89	F	5.29	3.60
Sandy Creek	12200686	07-23-07	.14	P		
		06-16-08	2.24	F		
Johnson Creek	12200688	08-09-07	.01	F		
		06-16-08	1.68	F		

Table 5. Synoptic streamflow measurements and estimates of gains and losses in tributary subbasins, lower Skagit River basin, Washington, August 2007 and June 2008.—Continued

[**Measurement site**: Site locations are shown in figure 23. **Inflow** is the sum of streamflows measured upstream of the measurement site. **Accuracy rating** of the U.S. Geological Survey measurements: F, fair; P, poor; estimated values also are rated poor. **Gain or Loss**: Uncertainties associated with potential measurement error were too large at a few locations to make defensible conclusions regarding the delineation of gaining or losing creek reaches and those values are identified in italic. ft^3/s, cubic feet per second]

Measurement site	Site No.	Date discharge measured	Discharge (ft^3/s)	Accuracy rating	Inflow (ft^3/s)	Gain or loss (ft^3/s)
Carpenter Creek subbasin—Continued						
Bulson Creek	12200692	08-08-07	0.41	F		
		06-17-08	5.13	F		
Tributary to Bulson Creek	12200694	08-08-07	.49	P		
		06-17-08	2.21	F		
Carpenter Creek	12200696	09-21-00	[3]2.22		1.46	0.76
		06-19-08	12.4	F	20.15	-7.75
Fisher Creek subbasin						
Fisher Creek	12200698	08-08-07	[4]0.01	P		
		06-18-08	[4]1.50	P		
Fisher Creek	12200699	08-07-07	.00		[4]0.01	-0.01
		06-18-08	5.80	F	[4]1.50	4.30
Fisher Creek	12200701	08-09-07	.49	P	.00	.49
		06-05-08	6.38	F	5.80	.58
Tributary to Fisher Creek	1220070120	08-07-07	.00			
		06-18-08	[4]1.00	P		
Tributary to Fisher Creek	1220070140	08-07-07	[4].01	P		
		06-18-08	[4]2.00	P		

[1] Daily mean streamflow at Ecology streamflow-gaging station; accuracy rating assumed to be fair.

[2] Includes measured streamflow plus evaporative loss from Big Lake (table 4).

[3] Streamflow measured on September 20, 2000, accuracy rating assumed to be fair (Pitz and Garrigues, 2000); backwater conditions observed by the U.S. Geological Survey on August 8, 2007.

[4] Estimated by U.S. Geological Survey.

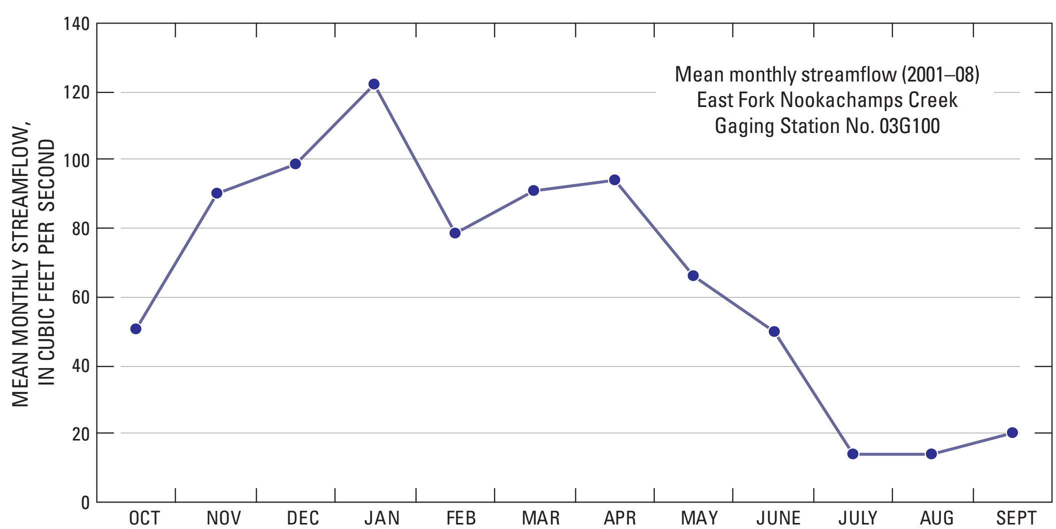


Figure 19. Mean monthly streamflow (2001–08) for East Fork Nookachamps Creek at Washington State Department of Ecology streamflow-gaging station 03G100, lower Skagit River basin, Washington.

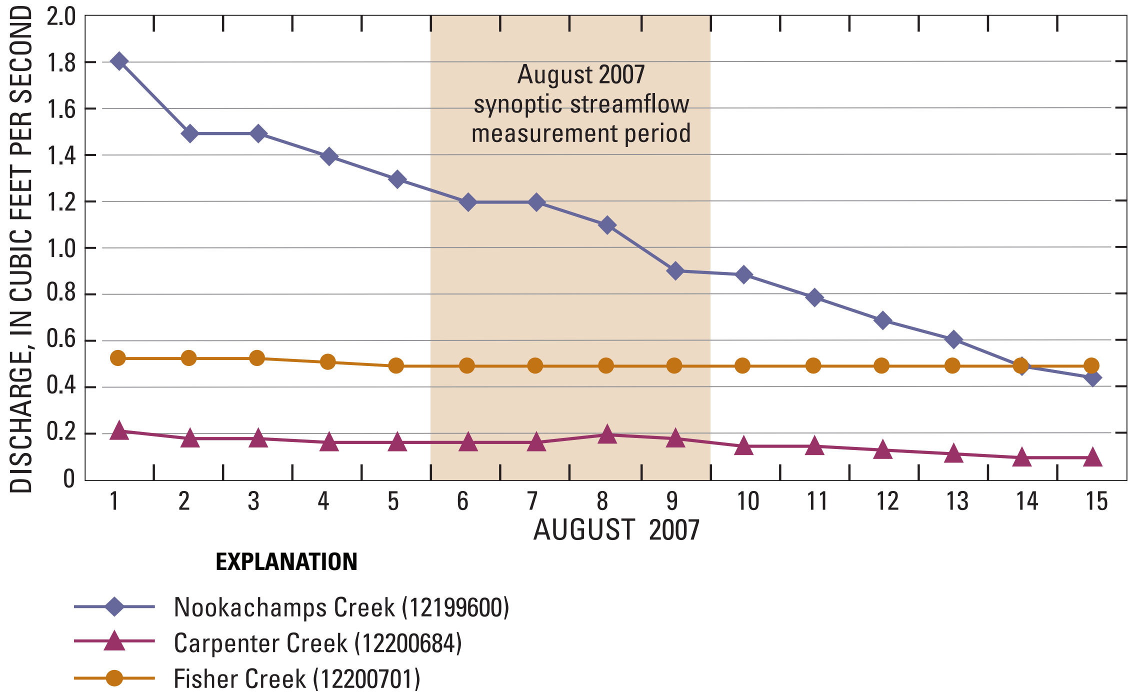


Figure 20. Daily streamflow for U.S. Geological Survey streamflow-gaging stations on Nookachamps (12199600), Carpenter (12200684), and Fisher (12200701) Creeks, lower Skagit River basin, Washington, August 1–15, 2007.

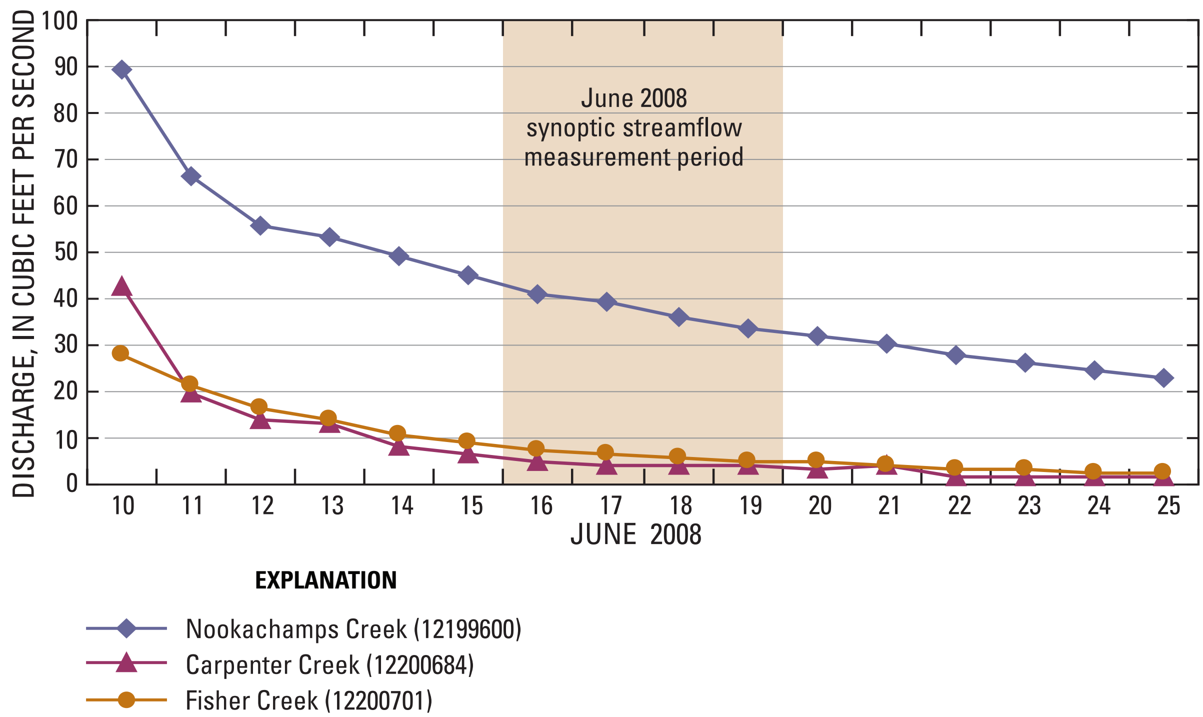


Figure 21. Daily streamflow for U.S. Geological Survey streamflow-gaging stations on Nookachamps (12199600), Carpenter (12200684), and Fisher (12200701) Creeks, lower Skagit River basin, Washington, June 10–25, 2008.

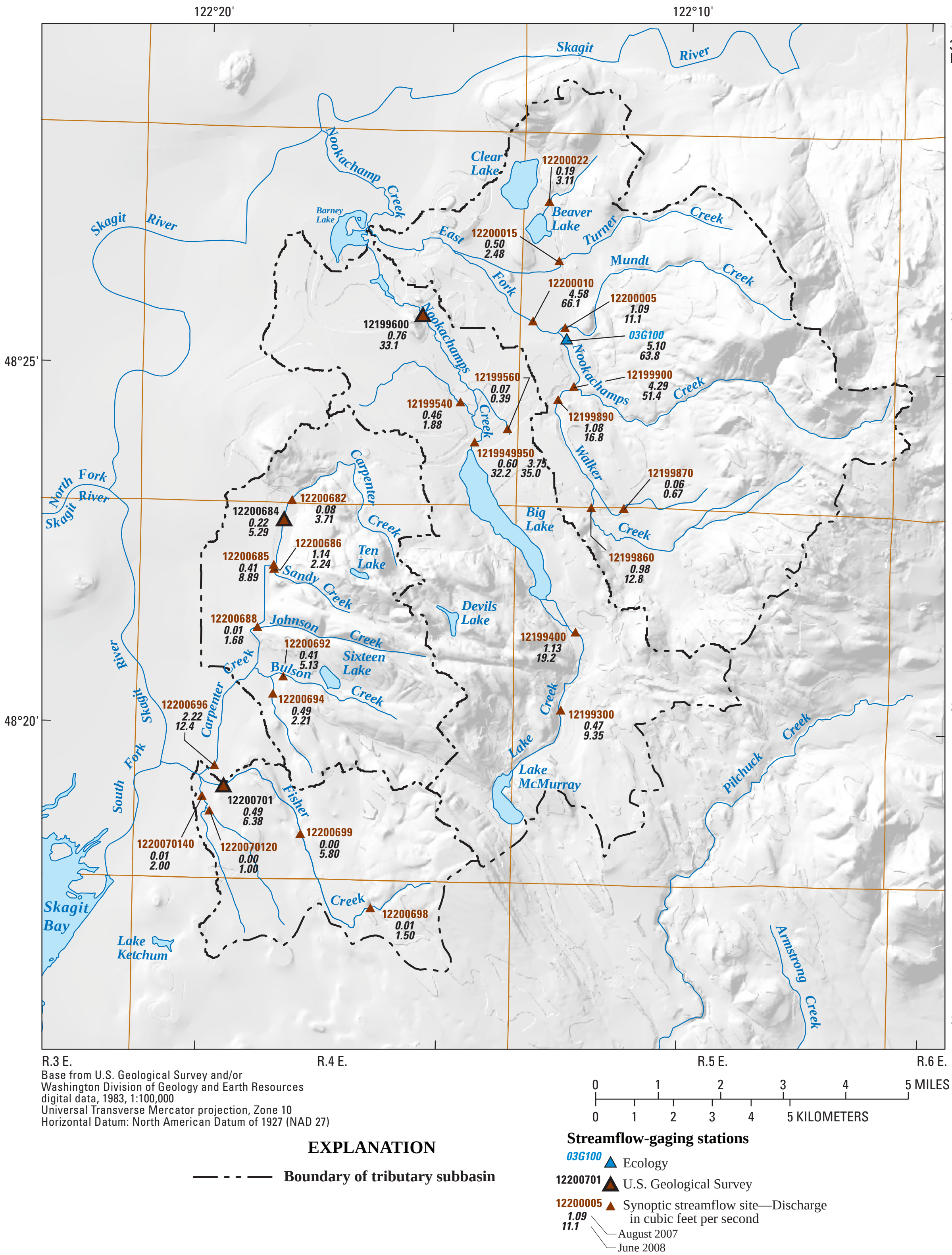


Figure 22. Locations of stream sites where streamflow was measured to determine groundwater discharge and delineate gaining and losing stream reaches in tributary subbasins and vicinity, lower Skagit River basin, Washington, August 2007 and June 2008.

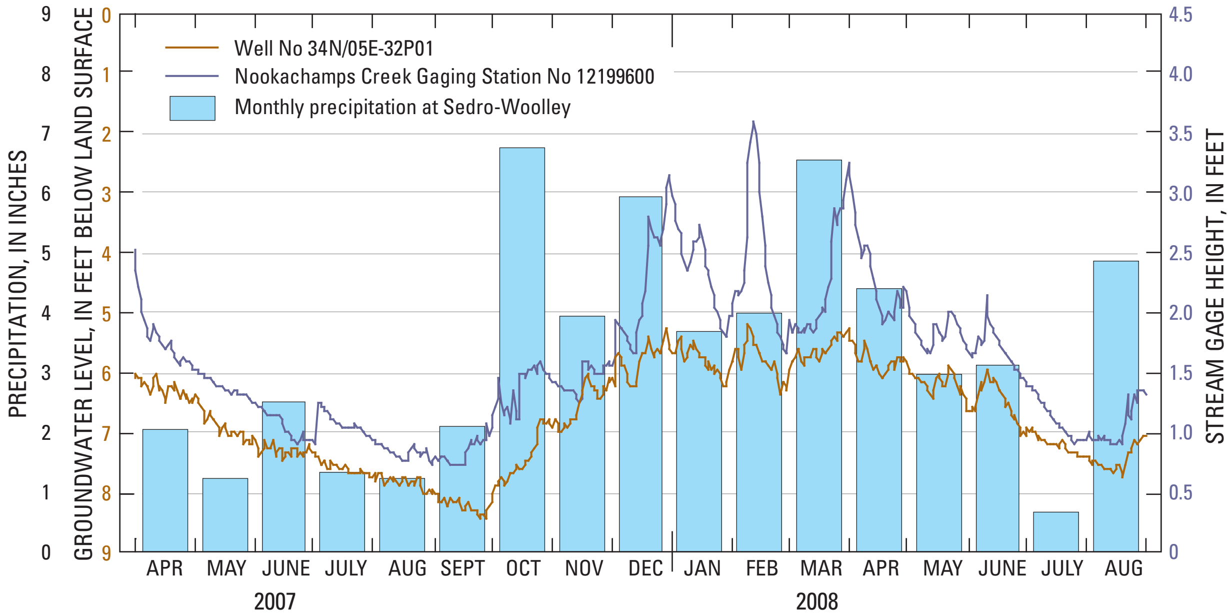


Figure 23. Water levels in well 34N/05E-32P01, stream stage at U.S. Geological Survey streamflow-gaging station on Nookachamps Creek (12199600), and precipitation at Sedro-Woolley, lower Skagit River basin, Washington, April 2007–August 2008.

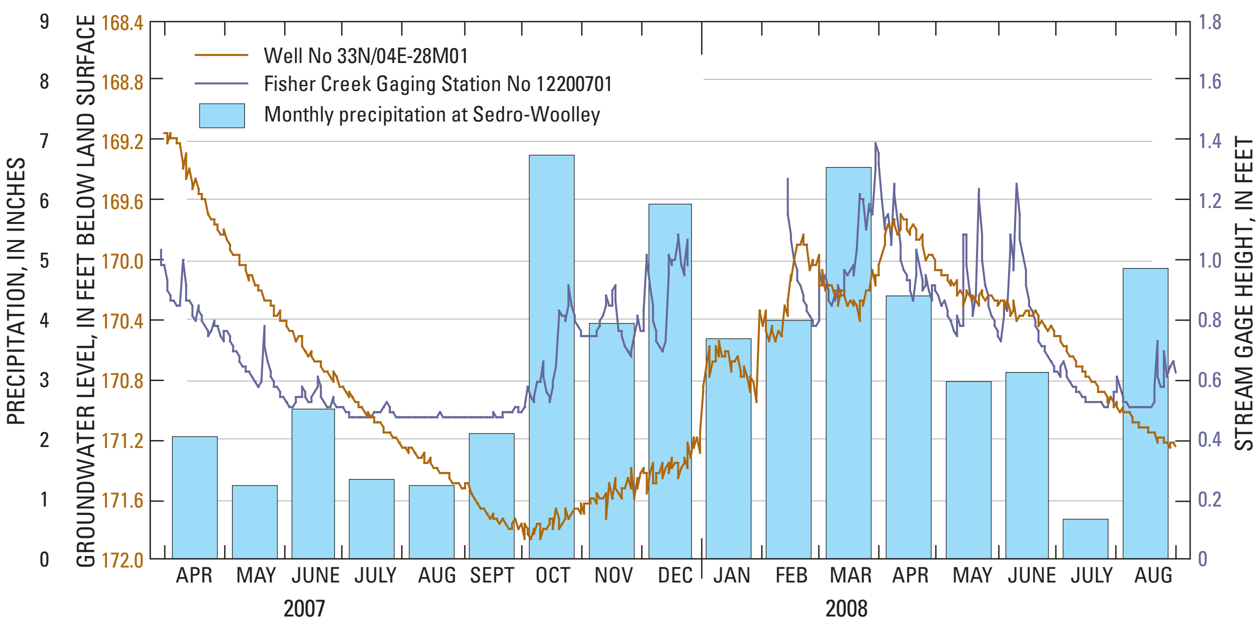


Figure 24. Water levels in well 33N/04E-28M01, stream stage at U.S. Geological Survey streamflow-gaging station on Fisher Creek (12200701), and precipitation at Sedro-Woolley, lower Skagit River basin, Washington, April 2007–August 2008.

The timing and magnitude of seasonal groundwater-level fluctuations in an aquifer system are related to the hydraulic characteristics of aquifer materials and adjacent confining units, the presence of unconfined or confined aquifer conditions, the depth to groundwater, and the depth of the well and screened intervals being measured. Water levels in deep wells typically respond to changes in recharge more slowly and with less magnitude than water levels in shallow wells, because deep wells are usually farther from the source of recharge, and variability is dampened. The largest water-level fluctuations observed during the monitoring period (October 2006 through September 2008) occurred in wells completed in the sedimentary aquifer (OEc), and ranged from about 3 to 27 ft (table 6). These unexpectedly large water-level fluctuations in relatively deep sedimentary aquifer wells may be attributed to several factors including the presence of water-bearing fractures (high conductivity and low storage) within local outcrop areas receiving precipitation recharge, and the relatively lower storage capacity of cemented sediments compared to sands and gravels (Freeze and Cherry, 1979; Fetter, 1988). Water levels in wells completed in the unconsolidated hydrogeologic units exhibited seasonal variations ranging from less than 1 to about 10 ft.

Water Budget

On a long-term basis, a hydrologic system is usually in a state of dynamic equilibrium; that is, inflow to the system equals outflow from the system, and there is little or no change in the amount of water stored within the system. An estimated water budget for average precipitation during the study period (September 1, 2006, to August 31, 2008) in the four tributary subbasin area, as well as each individual subbasin, is presented in table 7. The methods used to estimate values of precipitation, groundwater recharge, and groundwater discharge to creeks are described in previous sections of this report. Surface runoff, including shallow subsurface flow, was computed as a residual; that is, it represents the quantity that remains after groundwater discharge to creeks is subtracted from total streamflow. The value for evapotranspiration also is a residual and was computed as the quantity that remains after surface runoff plus groundwater recharge is subtracted from precipitation. Precipitation during the study period (September 1, 2006, to August 31, 2008) averaged an estimated 56 in/yr over the tributary subbasins. Approximately one-third (33 percent) of precipitation enters the groundwater system in the subbasins as groundwater recharge. Most of this recharge (65 percent) discharges to creeks, and only about 3 percent is withdrawn from wells. The remaining groundwater recharge (32 percent) leaves the subbasin groundwater system as discharge to the Skagit River and Puget Sound.

Table 6. Statistical summary of groundwater-level fluctuations and well depth by hydrogeologic unit in tributary subbasins and vicinity, lower Skagit River basin, Washington, October 2006 through September 2008.

[–, no data]

Hydrogeologic unit		Number of wells	Water-level fluctuation (feet)			Well depth (feet below land surface)		
			Minimum	Median	Maximum	Minimum	Median	Maximum
Qago	Alluvial and recessional outwash aquifer	7	2.72	5.96	7.37	17	35	58
Qgt	Till confining unit	5	1.65	5.82	6.78	10	20	35
Qga	Advance outwash aquifer	13	0.52	4.09	10.23	40	80	152
Qgl	Glaciolacustrine and distal outwash confining unit	2	1.25	4.34	7.42	25	103	180
Qco	Inter-glacial alluvial aquifer	4	0.96	1.69	2.57	126	268	366
Qot	Older till confining unit	0	–	–	–	–	–	–
Qooa	Older outwash and alluvial aquifer	2	3.00	3.21	3.42	240	248	256
OEc	Sedimentary aquifer	12	3.28	10.51	27.49	15	241	500
EJTP	Igneous and metamorphic bedrock unit	2	1.50	5.75	10.00	124	252	380

Table 7. Estimated average annual water budget for tributary subbasins, lower Skagit River basin, Washington, September 1, 2006, to August 31, 2008.

[<. less than]

Water-budget component	Quantity		Percent
	Inches per year	Acre-feet per year	
All subbasins			
Precipitation			
Fate of precipitation			
Surface runoff	20	100,200	35
Evapotranspiration	18	91,400	32
Groundwater recharge	18	92,400	33
Total precipitation	56	284,000	100
Fate of recharge			
Discharge to creeks	12	60,400	65
Other natural discharge	6	29,800	32
Withdrawals from wells	<1	2,200	3
Total recharge	18	92,400	100
East Fork Nookachamps Creek subbasin			
Precipitation			
Fate of precipitation			
Surface runoff	27	52,960	39
Evapotranspiration	22	42,900	31
Groundwater recharge	21	41,060	30
Total precipitation	70	136,920	100
Fate of recharge			
Discharge to creeks	18	34,740	85
Other natural discharge	3	6,300	15
Withdrawals from wells	<1	20	<1
Total recharge	21	41,060	100
Nookachamps Creek subbasin			
Precipitation			
Fate of precipitation			
Surface runoff	16	24,870	33
Evapotranspiration	17	26,110	35
Groundwater recharge	16	23,840	32
Total precipitation	49	74,820	100
Fate of recharge			
Discharge to creeks	11	16,610	70
Other natural discharge	5	7,020	30
Withdrawals from wells	<1	210	<1
Total recharge	16	23,840	100
Carpenter Creek subbasin			
Precipitation			
Fate of precipitation			
Surface runoff	18	17,720	38
Evapotranspiration	11	11,690	25
Groundwater recharge	17	17,200	37
Total precipitation	46	46,610	100
Fate of recharge			
Discharge to creeks	5	5,480	32
Other natural discharge	10	9,880	57
Withdrawals from wells	2	1,840	11
Total recharge	17	17,200	100
Fisher Creek subbasin			
Precipitation			
Fate of precipitation			
Surface runoff	8	4,610	18
Evapotranspiration	20	10,820	42
Groundwater recharge	19	10,300	40
Total precipitation	47	25,730	100
Fate of recharge			
Discharge to creeks	7	3,590	35
Other natural discharge	12	6,580	64
Withdrawals from wells	<1	130	1
Total recharge	19	10,300	100

Summary and Conclusions

Recent population growth along the Interstate 5 corridor near Mount Vernon, Washington, has led to increased water use, with many new domestic wells serving residents in the lower Skagit River basin in areas not served by a regional public-water system. Planning for future development in the lower basin, including the reservation of water for new domestic wells, requires identification of areas where withdrawals from existing and new wells could adversely impact streamflow in the Skagit River or its tributaries. A study to characterize the groundwater/surface-water flow system in four tributary subbasins of the lower Skagit River was conducted by the U.S. Geological Survey to assist Skagit County and the Washington State Department of Ecology in evaluating the effects of potential groundwater withdrawals and consumptive use on tributary streamflows.

The study area covers about 247 square miles along the Skagit River and its tributary subbasins in southwestern Skagit County and northwestern Snohomish County, Washington. The Skagit River occupies a large, relatively flat alluvial valley that is bounded to the south and east by upland and mountainous terrain. The alluvial valley primarily is underlain by fluvial sand and gravel deposits, and locally preserved lahar runout deposits. Upland areas contain laterally discontinuous bodies of glacial (till and outwash) and interglacial (fluvial and lacustrine) deposits of varying thickness that reflect both terrestrial and shallow marine depositional environments. Bedrock consisting of metamorphic rocks, sedimentary units, and igneous rocks underlies the alluvial valley and upland areas, and crops out throughout the mountainous terrain. The southwest flowing Skagit River receives streamflow from four tributary subbasins (East Fork Nookachamps Creek, Nookachamps Creek, Carpenter Creek, and Fisher Creek) that originate within the mountainous interior of the study area. The lower reaches of most creeks flow year-round, however, intermittent flow conditions are common in middle and upper creek reaches during the summer months.

A simplified surficial geologic map was compiled from previous mapping in the area, and geologic units were differentiated into nine hydrogeologic units: Alluvial and recessional outwash aquifer (Qago), Till confining unit (Qgt), Advance outwash aquifer (Qga), Glaciolacustrine and distal outwash confining unit (Qgl), Inter-glacial alluvial aquifer (Qco), Older till confining unit (Qot), Older outwash and alluvial aquifer (Qooa), Sedimentary aquifer (OEc), and Igneous and metamorphic bedrock unit (EJTP). A surficial hydrogeologic unit map was constructed and used with drillers' logs from 296 wells to produce four hydrogeologic sections, and unit extent and thickness maps.

Unconsolidated aquifers (Qago, Qga, Qco, and Qooa) typically consist of moderately to well-sorted alluvial and glacial outwash deposits of sand, gravel, and cobbles, with minor lenses of silt and clay. These units typically occur as discontinuous or isolated bodies, and are of highly variable thickness. Unconfined conditions exist in areas where aquifer units are present at land surface; however, much of the study area is mantled by glacial till, and confined aquifer conditions are common. Estimated hydraulic conductivity for the aquifers ranged from 0.27 ft/d (OEc) to 57 ft/d (Qco). Groundwater in the unconsolidated aquifers generally flows towards the northwest and west in the direction of the Skagit River and Puget Sound. This generalized flow pattern is likely complicated by the presence of low permeability confining units that separate discontinuous bodies of aquifer material and act as local groundwater flow barriers. Water-level altitude differences between the advance outwash (Qga) and inter-glacial alluvial (Qco) aquifers in the southwestern part of the study area suggest downward vertical flow. The potential for upward groundwater movement, indicated by the presence of flowing wells, was observed at several locations within the aquifer units.

Unconsolidated confining units (Qgt, Qgl, and Qot) typically consist of poorly sorted glacial till, glaciolacustrine, and landslide deposits of clay, silt, sand, gravel, cobbles, and boulders, with locally occurring sand and gravel lenses capable of providing water for domestic use. Estimated hydraulic conductivity for the confining units ranged from 0.13 ft/d (EJTP) to 26 ft/d (Qgl). The Vashon Till (Qgt) is present throughout much of the study area; other confining units are more limited in extent.

The sedimentary aquifer (OEc) is present in large parts of the glacial upland and mountains in central and southern parts of the study area and consists primarily of conglomerate and sandstone with fine-grained intervals. Confined conditions are likely where the aquifer is fully saturated and overlain by glacial confining units; fine-grained intervals within the aquifer also may produce locally confined conditions. Groundwater flow directions in the sedimentary aquifer likely reflect local topographic relief (radial flow from bedrock highs) and more regional westward flow from the mountains to the Puget Sound.

The igneous and metamorphic bedrock unit (EJTP) is present along the northern margin of the glacial uplands in the mountains along the eastern margin of the study area, and within segments of the Darington-Devils Mountain Fault Zone. This low-permeability unit is composed of volcanic and metamorphic rocks and consists of rhyolite, andesite, basalt, and complex assemblages of low-grade metasediments, metavolcanics, and meta-intrusives, and is considered to be non-water bearing except in localized areas of fracturing.

The largest groundwater level fluctuations observed during the monitoring period (October 2006 through September 2008) occurred in wells completed in the sedimentary aquifer, and ranged from about 3 to 27 feet. Water levels in wells completed in unconsolidated hydrogeologic units exhibited seasonal variations ranging from less than 1 to about 10 feet. Synoptic streamflow measurements made in August 2007 and June 2008 indicate groundwater discharge to creeks in the subbasins ranged from about 13.15 to 129.6 cubic feet per second (9,520 to 93,830 acre-feet per year), respectively. Streamflow measurements illustrate a general pattern in which the upper reaches of creeks in the study area tended to gain flow from the groundwater system, and lower creek reaches tended to lose water. Significant inflows from tributaries to major creeks in the study area suggest the presence of groundwater discharge from upland areas underlain by bedrock.

The groundwater system within the subbasins received an average (September 1, 2006, to August 31, 2008) of about 92,400 acre-feet or about 18 inches of recharge from precipitation a year. Most of this recharge (65 percent) discharges to creeks, and only about 3 percent is withdrawn from wells. The remaining groundwater recharge (32 percent) leaves the subbasin groundwater system as discharge to the Skagit River and Puget Sound.

Acknowledgments

The authors wish to thank the many well owners in the study area who provided access to their wells during this study, and special thanks go to the property owners who allowed observation wells to be installed on their property. Joe Dragovich and other staff of the Washington State Department of Natural Resources generously provided interpretive data that was crucial to the subsurface identification and delineation of geologic units, and the development of the hydrogeologic framework presented in this report. The authors gratefully acknowledge this significant contribution. The authors also wish to thank Skagit County and the Washington State Department of Ecology for providing assistance in the compilation of well information.

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

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Savoca and others— **Hydrogeologic Framework, Groundwater Movement, and Water Budget, Lower Skagit River Basin, Washington** —Scientific Investigations Report 2009–5270