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Shallow Groundwater Movement in the Skagit River Delta Area, Skagit County, Washington

Scientific Investigations Report 2009–5208

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

Cover: Photograph of the Skagit River delat area, Skagit County, Washington. Image

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KEN SALAZAR, Secretary

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

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Conversion Factors and Datums

Inch/Pound to SI

Multiply	By	To obtain
	Length	
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 mi^2)	259.0	square hectometer (hm^2)
square foot (ft^2)	0.0929	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Hydraulic gradient	
foot per foot (ft/ft)	1	meter per meter (m/m)
foot per mile (ft/mi)	0.1984	meter per kilometer (m/km)

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

°C=(°F-32)/1.8

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88), referred to in this report as “sea level.”

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

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

Shallow Groundwater Movement in the Skagit River Delta Area, Skagit County, Washington

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Abstract

Shallow groundwater movement in an area between the lower Skagit River and Puget Sound was characterized by the U.S. Geological Survey to assist Skagit County and the Washington State Department of Ecology with the identification of areas where water withdrawals from existing and new wells could adversely affect streamflow in the Skagit River. The shallow groundwater system consists of alluvial, lahar runout, and recessional outwash deposits composed of sand, gravel, and cobbles, with minor lenses of silt and clay. Upland areas are underlain by glacial till and outwash deposits that show evidence of terrestrial and shallow marine depositional environments. Bedrock exposures are limited to a few upland outcrops in the southwestern part of the study area, and consist of metamorphic, sedimentary, and igneous rocks.

Water levels were measured in 47 wells on a quarterly basis (August 2007, November 2007, February 2008, and May 2008). Measurements from 34 wells completed in the shallow groundwater system were used to construct groundwater-level and flow-direction maps and perform a linear-regression analysis to estimate the overall, time averaged shallow groundwater-flow direction and gradient. Groundwater flow in the shallow groundwater system generally moves in a southwestward direction away from the Skagit River and toward the Swinomish Channel and Skagit Bay. Local groundwater flow towards the river was inferred during February 2008 in areas west and southwest of Mount Vernon. Water-level altitudes varied seasonally, however, and generally ranged from less than 3 feet (August 2007) in the west to about 15 feet (May 2008) in the east. The time-averaged, shallow groundwater-flow direction derived from regression analysis, 8.5° south of west, was similar to flow directions depicted on the quarterly water-level maps.

Seasonal changes in groundwater levels in most wells in the Skagit River Delta follow a typical pattern for shallow wells in western Washington. Water levels rise from October through March, when precipitation is high, and decline from April through September, when precipitation is lower. Groundwater levels in wells along the eastern margin of the study area also are likely influenced by stage on the Skagit River. Water levels in these wells remained elevated through April, and did not seem to begin to decline until the end of May in response to declining river stage. Groundwater levels in a well equipped with a continuous water-level recorder exhibited periodic fluctuations that are characteristic of ocean tides. This well is less than 1 mile east of the tidally influenced Swinomish Channel, and exhibited water-level fluctuations that correspond closely to predicted tidal extremes obtained from a tide gage near La Conner, Washington.

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 affecting 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 for new groundwater withdrawals in basins where all available water is appropriate. 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 affected streamflow.

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 part of the 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 affect streamflow in the Skagit River or its tributaries. Skagit County, as the land use authority for unincorporated areas without access to public water systems, requires a scientifically credible basis for implementing land use restrictions to protect instream resources.

In June 2006, the U.S. Geological Survey (USGS) in cooperation with Skagit County, the Washington State Department of Ecology, and Skagit County Public Utility District No. 1, began a project to characterize shallow groundwater movement in an area between the lower Skagit River and Puget Sound, referred to as the "Skagit River Delta" in this report (fig. 1), and to investigate the possible presence of a groundwater divide to assist in the identification of areas where wells could have an adverse affect on flow in the Skagit River, and therefore would be subject to regulation under the Skagit River Instream-Flow Rule.

Purpose and Scope

This report presents information used to characterize shallow groundwater movement in the part of the Skagit River Delta north of the North Fork distributary. The report includes seasonal water-level maps, a linear-regression analysis of water levels, and descriptions of groundwater-flow direction, gradient, and seasonal fluctuations. Groundwater level and Skagit River stage data were collected by the USGS quarterly from August 2007 through May 2008.

Description of Study Area

The study area covers about 42 mi^2 along the lower Skagit River before it enters Skagit Bay in southwest Skagit County, Washington (fig. 1). The area is bounded by the Skagit River to the east and south; an approximate watershed divide between the Samish and Skagit Rivers to the north; and Padilla Bay, Swinomish Channel, and Skagit Bay (all parts of Puget Sound) to the west. The Skagit River occupies a large, relatively flat alluvial valley that primarily is underlain by fluvial and deltaic sand and gravel deposits associated with the present and ancient Skagit River, and locally preserved lahar-runout deposits originating from Glacier Peak (located outside the study area to the southeast). Local upland areas are underlain by glacial till and outwash deposits that show evidence of 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. Surficial exposures of bedrock are limited to a few upland outcrops in the southwestern part of the study area.

Land-surface altitude in the study area ranges from near sea level adjacent to the Swinomish Channel to about 130 ft in upland areas. The study area has a temperate marine climate with warm, dry summers and cool, wet winters. 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 (1971–2000) precipitation at Mount Vernon is 32.7 in. (National Oceanic and Atmospheric Administration, 2007). Summers (June–August) typically are dry with a mean precipitation of 4.5 in. at Mount Vernon. Winters (December–February) are wetter than summers with a mean precipitation of 11.0 in. at Mount Vernon. The mean monthly temperature at Mount Vernon ranges from about 40°F in January to about 63°F in August (National Oceanic and Atmospheric Administration, 2007).

Geologic Setting

A brief summary of major geologic events in the study area is described below, and is based on the work of Hansen and Mackin (1949), Easterbrook (1969), Marcus (1981), Johnson (1982), Tabor (1994), Booth (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 low-grade metamorphic rocks, formed during Late Jurassic or Early Cretaceous continental margin subduction, and sedimentary units deposited in alluvial fan, braided stream, and near shore shallow marine settings.

Continental glaciers advanced into Skagit County several times during the Pleistocene Epoch. This ice is part of the Cordilleran ice sheet, and is known as the Puget Lobe. The most recent period of glaciation, the Vashon Stade of the 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, and eventually covered 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 meltwater, was accomplished through Holocene fluvial, estuarine, and deltaic deposition and volcanic-lahar deposits originating from Glacier Peak.

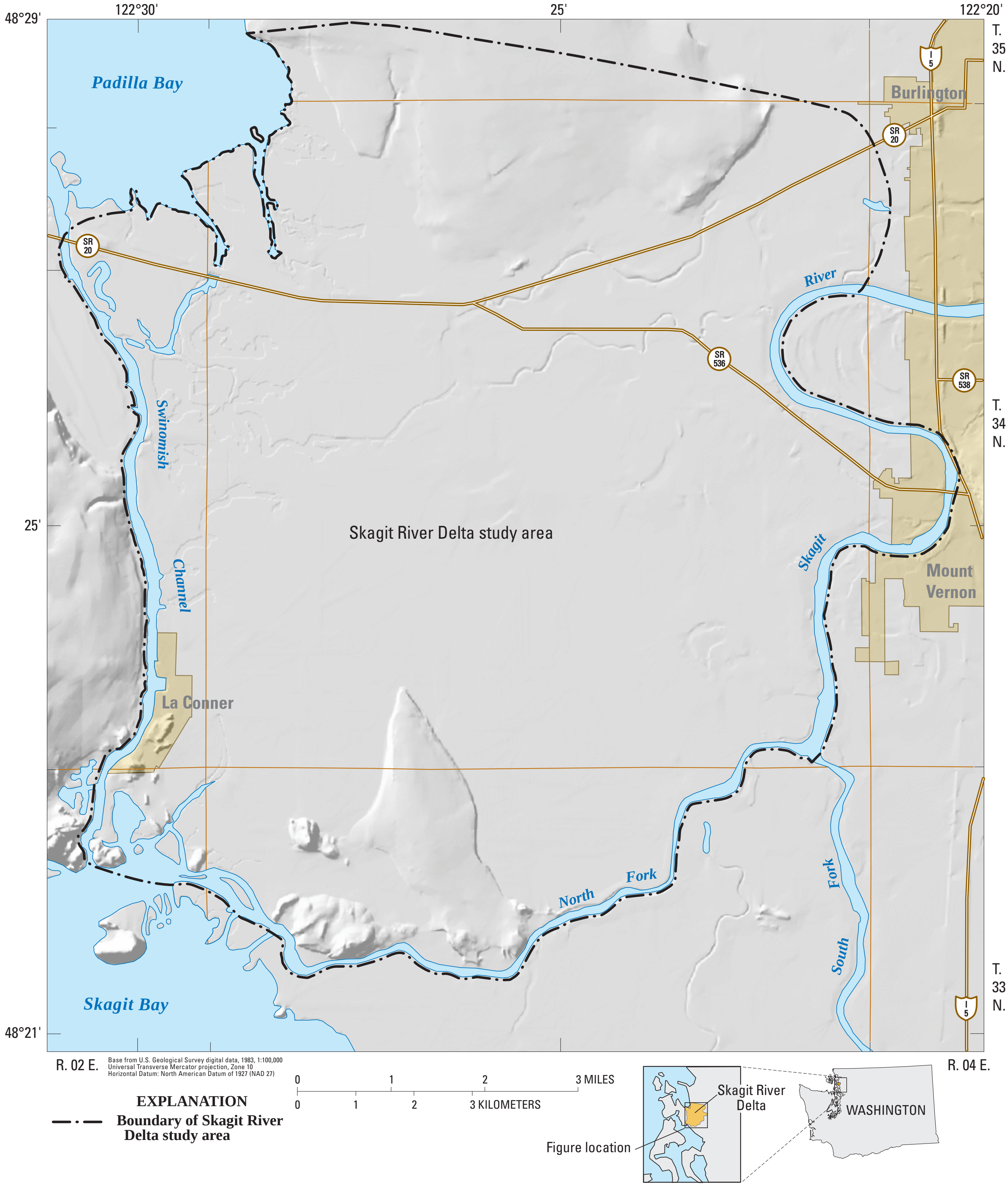

Figure 1. Location of the Skagit River Delta study area, Skagit County, Washington.

Well-Numbering System

Wells in the study area were assigned a local number that identifies each well within the Public Land Survey rectangular grid system for Washington State (fig. 2). For example, for well 34N/03E-09L01, the number and letter preceding the slash (34N) indicates the township north of the Willamette Base Line. The number and letter between the slash and the hyphen (03E) indicates the range east of the Willamette Meridian. The number following the hyphen (09) indicates the section number within the township. The letter following the section number (L) indicates the 40-acre quarter-quarter tract within the section. The number following the quarter-quarter tract (01) is a sequence number used to distinguish individual wells in the same quarter-quarter tract. A "D" following the sequence number indicates a well that has been deepened.

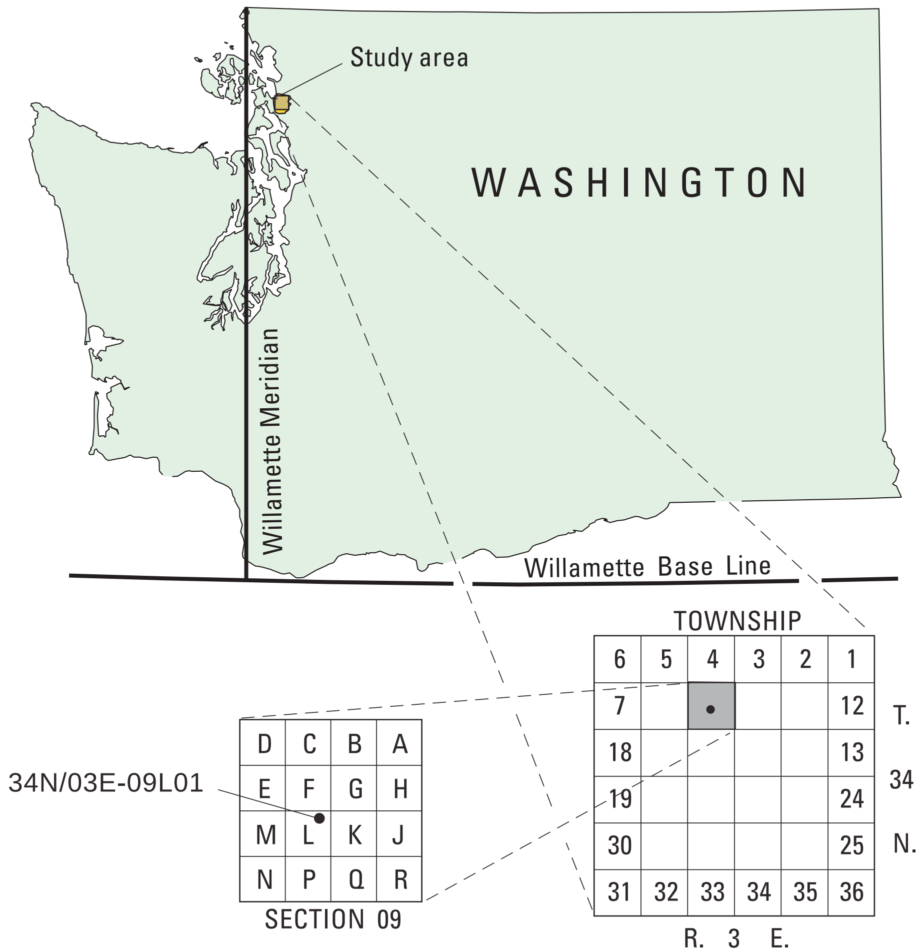

Figure 2. Well numbering system used in Washington.

Methods of Investigation

Methods used to compile and analyze information to characterize shallow groundwater movement in the study area include measurement of water levels in wells, estimates of Skagit River stage, construction of water-level maps, and determination of ocean tides.

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 detected during well construction. This information was obtained through the measurement of water levels in wells, and the evaluation of lithologic descriptions from well drillers' logs. Lithologic information was used to identify wells completed in the shallow groundwater system. Well records were compiled from USGS and Washington State Department of Ecology 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 the drillers' 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 in August 2007, permission was obtained to measure water levels in 43 wells (fig. 3) on a quarterly basis (August 2007, November 2007, February 2008, and May 2008). Four additional wells were added to the quarterly monitoring network as they became available for measurement. One of these wells (34N/03E-35N01) was installed for this study using a rotary drill rig and constructed of 6 in. steel casing and 0.01 in. stainless steel screen. Four quarterly monitoring wells were instrumented with continuous water-level recorders (fig. 3).

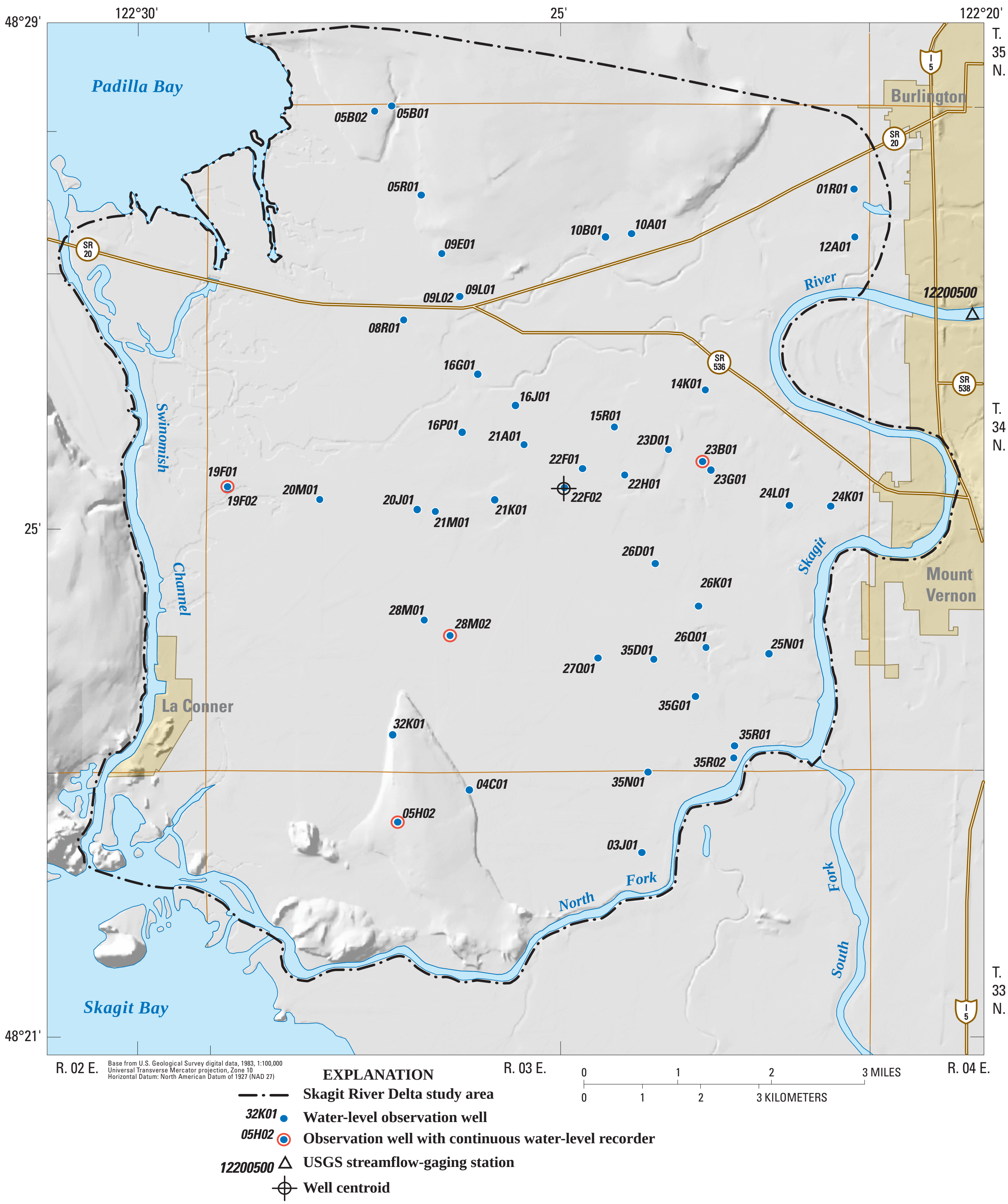

Figure 3. Location of wells and U.S. Geological Survey streamflow-gaging station, Skagit River Delta area, Washington.

The depth to groundwater below land surface was measured using a calibrated electric tape or graduated steel tape, both with accuracy to 0.01 ft. Latitude and longitude locations were determined for each well using a Global Positioning System receiver with a horizontal accuracy of one-tenth of a second (about 10 ft). Altitudes of the land surface at each well were interpolated from USGS 1:24,000–scale topographic maps, with an accuracy ranging from ±5 ft (low-relief areas) to ±10 ft (high-relief areas). Light Detection and Ranging (LiDAR) derived values for the altitude of land surface became available after completion of the field inventory, and were used to determine the altitude of land surface at each well for the computation of water-level altitudes. LiDAR data were collected and processed by a private vendor under contract with the USGS. Vertical accuracy was evaluated for internal consistency (repeatability), and conformance with independent ground-control points.

All water-level measurements were made by USGS personnel according to standardized techniques of the USGS (Drost, 2005). Well information collected during the field inventory and the quarterly monitoring-network measurement periods were entered into the USGS National Water Information System (NWIS) database and published in Fasser and Julich (2009).

River Stage

Estimates of Skagit River stage (the altitude of the water surface in the river) were used to constrain groundwater-level contours along the eastern margin of the study area, and to infer groundwater recharge from or groundwater discharge to the river. Daily values of river stage were obtained for USGS steamflow-gaging station 12200500 (Skagit River near Mount Vernon, Wash.; fig. 3) and a mean gage height was computed for each of the quarterly monitoring-network measurement periods. The initial measurement period (August 2007) required locating suitable wells and obtaining owner permission and took 8 days to complete. All subsequent quarterly measurements (November 2007, February 2008, and May 2008) were accomplished in 2 days. Values of river stage reported in vertical datum NGVD 29 were converted to the datum used for the monitoring network, NAVD 88, using the on-line program VERTCON (http://www.ngs.noaa.gov/cgi-bin/VERTCON/vert_con.prl) provided by the National Geodetic Survey.

River stage at the USGS steamflow-gaging station was extrapolated along the length of the Skagit River within the study area using several data coverages and Geographic Information System (GIS) procedures. Spatial data points were developed to represent the centerline of the river based on available coverages of hydrography, aerial photography, USGS quadrangle topographic maps, and LiDAR imagery. These data were cross checked, and adjusted using ArcMap™, version 9.3, by ESRI Inc., to produce a consistent rendering of river hydrography. The points for the centerline were converted to x and y coordinates (NAD 83 State Plane Washington North) in the software, and exported to Microsoft Excel®. The distances between centerline points were computed and summed to obtain a total distance from the mouth of the Skagit River. River channel distance was measured along the North Fork of the Skagit River, and extended out of the study area to open water in Skagit Bay, where water levels were expected to average to mean sea level. The total river mile distance from open water to the USGS gage was computed to be 17.5 mi. GIS points were then interpolated at one-half-river-mile intervals, and each point was assigned a river-stage value by proportionally adjusting the stage value at the USGS gage (for example, by a factor of (river mile)/17.5).

These estimates of river stage were considered during construction of groundwater-level maps and were compared to nearby groundwater levels measured in the delta to help infer the nature of the hydraulic connection between the Skagit River and adjacent groundwater system. In areas where estimates of river stage were higher than nearby groundwater levels, the potential for groundwater recharge from the river exists, and the orientation of groundwater-level contours were drawn to reflect surface-water recharge.

The linear interpolation described above might differ from the actual stream-stage values due to unaccounted for variations in river hydraulics such as changes in cross section, gradient, and the effects of distributary channels (such as the South Fork of the Skagit River), and tidal influence. To check the procedure, LiDAR altitudes were obtained with GIS at the points used for estimating river miles. Despite the fact that the laser is reflected and/or absorbed rather than directed back to the detector, it seems that sufficient LiDAR elevation points are picked up immediately along the banks of the river to give a good estimate of river stage along the river. Linear regression of the LiDAR data indicated a linear relation between river mile and LIDAR derived river stage of 0.99 ft/mi, corresponding to a river stage value of approximately 16.5 ft at the USGS gaging station. The computed mean gage height at the USGS gaging station for the quarterly measurement periods ranged from 16.46 to 25.63 ft. The regression analysis of LiDAR data gave a good fit to the linear interpolation of river stage with a root-mean-square error of 1.75 ft for the data points available, and supports the use of linear interpolation to estimate river stage.

Groundwater-Level and Flow-Direction Maps

Of the 47 wells inventoried (fig. 3), measurements from 34 wells completed in alluvial deposits (shallow groundwater system) were used in the construction of groundwater-level and flow-direction maps, and linear-regression analysis. Groundwater level (altitude) was calculated by subtracting depth to water from the LiDAR derived ground-surface altitude at each well. Groundwater-level altitude contours and flow lines were generated manually for each of the quarterly measurement periods. Wells completed in glacial deposits or below confining clay layers within the alluvium were not included in the construction of groundwater-level and flow-direction maps or linear-regression analysis because water levels from these wells are likely influenced by hydrogeologic conditions that are distinctly different from those controlling water levels in the shallow groundwater system. Furthermore, upland areas consisting of relatively low permeability glacial deposits and bedrock were interpreted as probable shallow groundwater-flow barriers.

Water levels in well 22F02 were influenced by active pumping during all quarterly measurements, and water levels in well 26Q01 were significantly lower than surrounding wells leading to uncertainties regarding the accuracy of well-construction and lithologic information or the possibility of nearby pumping. Therefore, water-level data from these two wells were not used in the construction of groundwater-level and flow-direction maps or linear-regression analysis. Water levels in wells 08R01 and 20J01 were influenced by pumping during the August 2007 quarterly measurement and were not used for the construction of maps or regression analysis. Some wells only had partial water-level records (water levels were not available for all quarterly measurements) and were only used in the construction of maps and regression analysis for quarterly measurements in which data were available. Hydrographs of groundwater levels were generated for all inventoried wells and published in Fasser and Julich (2009).

A linear-regression analysis of groundwater altitudes in the Skagit Delta area was done to estimate the overall, time-averaged shallow groundwater-flow direction and gradient. The data used in the regression analysis were similar to those used for construction of the groundwater-altitude maps and included: (1) x and y coordinates for the wells according to the NAD 83 State Plane projection in feet for Washington (North) and (2) quarterly groundwater altitudes from the 34 wells completed in alluvial deposits.

The regression analysis was calculated using Microsoft Excel® Data Analysis tool. Each set of quarterly water-level measurements was analyzed separately, and then the seasonal regression coefficients were combined to obtain an overall (annual) flow regime description. The groundwater altitudes (z) were input as the dependent variable and the two columns of x and y coordinates of the wells were entered as the independent variables. In this case, linear regression was used to estimate coefficients a_0, a_1, and a_2 that describe a planar surface for the potentiometric surface as:

$$z_{est} = a_0 + a_1 * x + a_2 * y \,, \quad (1)$$

where

z_{est} is estimated elevation of the potentiometric surface at location (x,y);

a_0 is intercept constant;

a_1 is slope of the surface in the x direction; and

a_2 is slope of the surface in the y direction.

These coefficients were then used to estimate the common hydrogeologic parameters of the groundwater regime for that quarterly measurement:

Gradient = SQRT ($a_1^2 + a_2^2$) is the slope of the potentiometric surface.

Direction = ATAN2 (a_1, a_2) is the upstream/downstream direction of the surface.

Then, the relative water level was calculated as the elevation of the plane at the geographic center of all well locations (centroid; fig. 3):

$$\text{Water level at the centroid} = z_{cent} = a_0 + a_1 * x_{cent} + a_2 * y_{cent}$$

After measurements for all four sets of quarterly measurements were processed through the regression method, an estimate of direction and gradient of the annual groundwater system was calculated by averaging the regression coefficients from each of the quarterly measurements, for example:

$$a_{0,\ annual} = (a_{0,\ August} + a_{0,\ November} + a_{0,\ February} + a_{0,\ May}) / 4$$

After averaging to get the annual coefficients, the annual gradient, direction, and water level at the centroid were calculated from the annual regression coefficients.

Ocean Tides

Predicted values of tidal extremes were used in an analysis of possible correlation between groundwater-level fluctuation at monitoring well 19F01 (fig. 3) and ocean tides. The tide data were obtained from the closest National Oceanic and Atmospheric Administration tide gage (National Oceanic and Atmospheric Administration, 2009) that had calibrated tidal coefficients (tide gage 9448558 “La Conner, Swinomish Slough, Wash.”). The resulting analysis (discussed later in this report) is only approximate, because of several factors: (1) the groundwater-level data from well 19F01 also were influenced by recharge or other factors; (2) the tidal record used in the analysis is only of predicted astronomical highs and lows, not actual measured tidal levels, that may have been affected by wind and barometric pressure; (3) the location for the predicted tide is at La Conner, more than 2 mi to the south, not at the point in Swinomish Channel closest to the well, and different tidal components may travel differently along the narrow and shallow channel; and (4) high tides seem to have less influence on the well than do low tides (estimated from the correlation coefficients), although this may be caused by tidal attenuation along the Swinomish Channel.

Hydrogeology

A simplified surficial geologic map (fig. 4) for the Skagit River Delta area was constructed based on previous mapping by Schuster (2000). Geologic units were grouped into one of five new unit designations (table 1) based on similarities in lithologic and hydrogeologic characteristics. The hydrogeologic characteristics attributed to these units are similar to those defined for similar units by other investigations in areas adjacent to this study (Thomas and others, 1997; Dragovich and Grisamer, 1998; GeoEngineers, 2003). Descriptions of the units used in this study are given below.

The alluvial and recessional outwash aquifer (Qago) is present throughout the low lying areas of the Skagit River Delta and represents: (1) active or abandoned channel and overbank deposits associated with the present and ancient Skagit River, (2) lahar-runout deposits, originating from Glacier Peak, and (3) terrestrial and marine recessional and deltaic glacial-outwash deposits. This unit comprises the shallow groundwater system in the study area, and consists of sand, gravel, and cobbles, with minor lenses of silt and clay. 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 confining layers of clay.

The till confining unit (Qgt) is present within local upland areas and shows evidence of terrestrial and shallow marine depositional environments. This low-permeability unit is composed of glacial diamicton and 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.

Exposures of advance outwash aquifer (Qga) deposits are limited to a few areas along the base of the glacial upland, and the presence of this unit is inferred, at least in places, beneath the till confining unit within upland areas. The unit consists primarily of sand and gravel with minor amounts of silt and scattered layers of pebble-cobble gravel and local silt and clay interbeds. Groundwater in this aquifer is potentially confined by the overlying till confining unit, however, unconfined conditions may occur locally where it is not fully saturated or exposed at land surface.

Generally, glacial deposits are believed to be largely absent beneath low lying areas of the Skagit River Delta to a depth of approximately 300 ft below sea level, likely due to removal by southward flowing subglacial meltwater, 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 deposits in wells from low lying areas of the delta, and similar interpretations from previous investigations (Dragovich and Grisamer, 1998; GeoEngineers, 2003). Glacial deposits in upland areas within the delta likely represent erosion remnants of a previously more continuous distribution of glacial units.

The sedimentary bedrock aquifer (OEc) crops out within and adjacent to uplands in the southern part of the study area; a lack of outcrop and well-log information makes it difficult to determine the extent of this unit in the subsurface. The unit consists primarily of pebble and cobble conglomerate and medium- to coarse-grained sandstone, with fine-grained intervals of mudstone, siltstone, coal, and shale. Groundwater in the bedrock aquifer is unconfined where it crops out; however, confined conditions are likely where it is fully saturated and overlain by glacial till and glaciolacustrine units. Fine-grained intervals within the sedimentary bedrock aquifer also may produce locally confined conditions.

The igneous and metamorphic confining unit (KJ) crops out within and adjacent to uplands in the southwestern part of the study area; a lack of outcrop and well-log information makes it difficult to determine the extent of this unit in the subsurface. This low-permeability unit is composed of igneous and metamorphic rocks and consists of a complex assemblage of volcaniclastic deposits, and low-grade metasediments, and metavolcanics. This unit is considered to be nonwater bearing except in localized areas of fracturing.

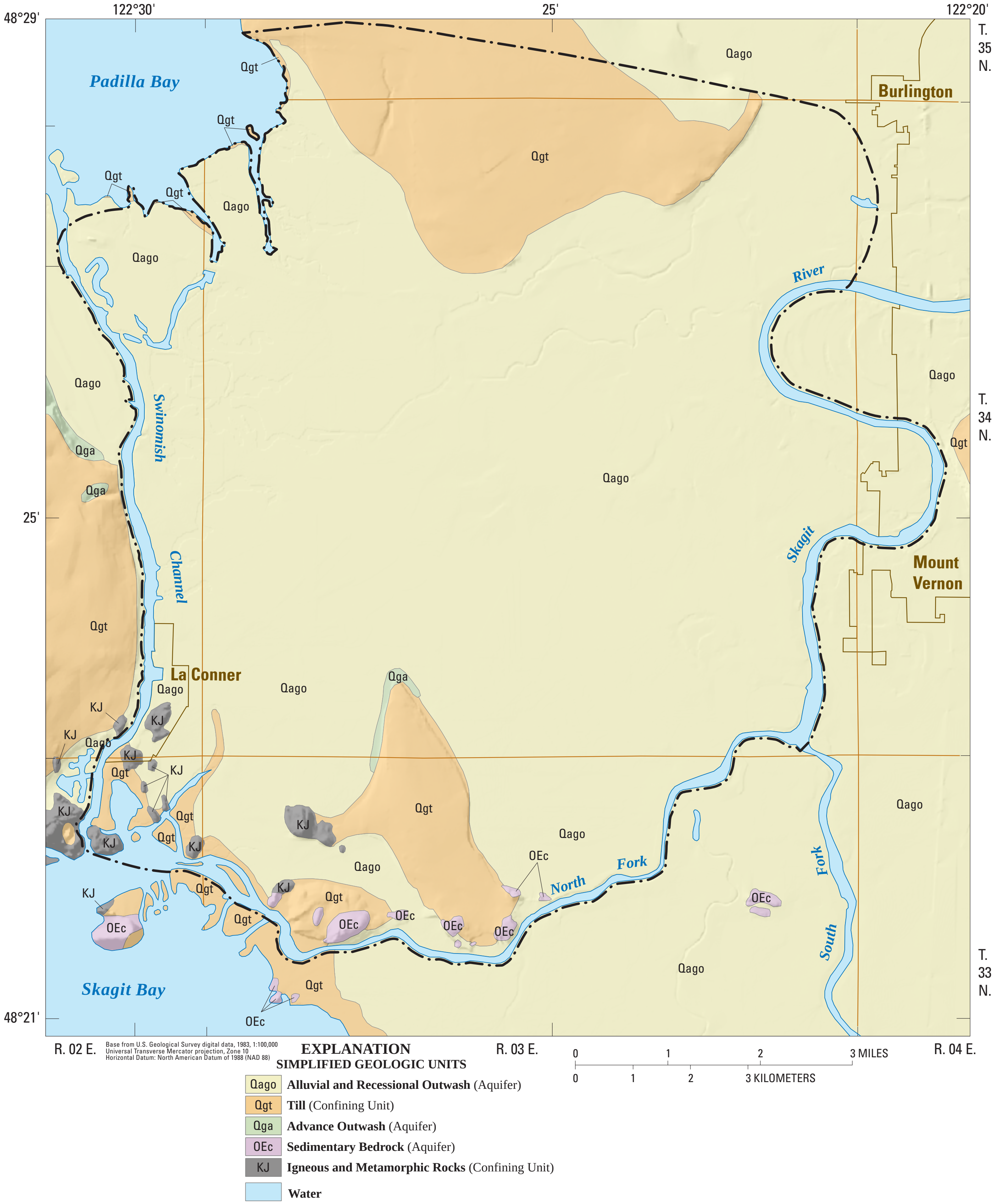

Figure 4. Skagit River Delta area, Washington.

Table 1. Hydrogeologic characteristics of simplified geologic units used in this study and correlation with previous unit designations.

[Geologic units used in this report are simplified and are from Schuster (2000). **Symbol:** –, not applicable]

Period	Epoch	Hydrogeologic characteristic of units	Simplified geologic units	Geologic units
Quaternary	Holocene to Pleistocene	Alluvial and Recessional Outwash Aquifer	Qago	Qac, Qas, Qf, Qvlk, Qgom
	Pleistocene	Till Confining Unit	Qgt	Qp, Qls, Qgdme, Qgt
		Advance Outwash Aquifer	Qga	Qga, Qgas
Tertiary	Oligocen to Eocene	Sedimentary Bedrock Aquifer	OEc	OEcb, Ecc
Cretaceous to Jurassic	–	Igneous and Metamorphic Confining Unit	KJ	KJvcf, KJmsg, KJmvg

Groundwater Movement

The direction of horizontal groundwater movement can be inferred from maps of water-level altitude contours. 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. Water-level altitude maps and regression analysis were used to determine shallow groundwater-flow directions and gradients in the Skagit River Delta area.

Groundwater-Flow Directions

Groundwater flow in the alluvial and recessional outwash aquifer generally moves in a southwestward direction away from the Skagit River and towards the Swinomish Channel and Skagit Bay (figs. 5–8). Local groundwater flow toward the river was inferred during February 2008 in an area west of Mount Vernon near well 24K01, and in an area southwest of Mount Vernon near wells 35R01 and 35R02. Water-level altitude contours in these areas indicate a south to south eastward groundwater-flow direction (fig. 7). Contours in these areas do not indicate groundwater flow to the river during the other quarterly measurement periods, and flow to the river in these areas likely is seasonal or transient in nature. Water-level altitudes in well 35R02 also were greater than nearby estimates of river stage during November 2007 and May 2008 (figs. 6 and 8; however, water-level altitude contours near this well indicate a westward groundwater-flow direction away from the river. Water-level altitudes varied seasonally, however, generally ranged from 1 to 2 ft (August 2007, fig. 7) in the west to about 15 ft (May 2008, fig. 8) in the east. Concave and convex bends in the water-level altitude contours indicate the presence of convergent and divergent groundwater-flow patterns on a local scale. These flow patterns likely reflect variations in hydraulic conditions within the aquifer resulting from spatial variations in aquifer material properties (clay, silt, and sand). Local groundwater withdrawals and agricultural drainage systems also may influence the groundwater-flow patterns.

The fitted regression coefficients and calculated groundwater gradient, flow direction, and water level at the centroid are presented in table 2. An estimate of goodness of fit (statistical parameter R^2) for the regression also is given for each seasonal estimate. The high R^2 values indicate that the planar representations of the groundwater potentiometric surfaces are in good agreement with the quarterly water-level measurements. The large negative a_0 (intercept) coefficients are due to the origin of the State Plane System being far to the southwest and well away from the project area.

Contours of equal values of z (time-averaged groundwater altitude for the four quarterly measurements) were calculated algebraically from the annual a_0, a_1, and a_2 coefficients (fig. 9). Estimates of the overall (time averaged) groundwater-flow direction (8.5° south of west) and gradient (2.67 ft/mi) also were computed (table 2).

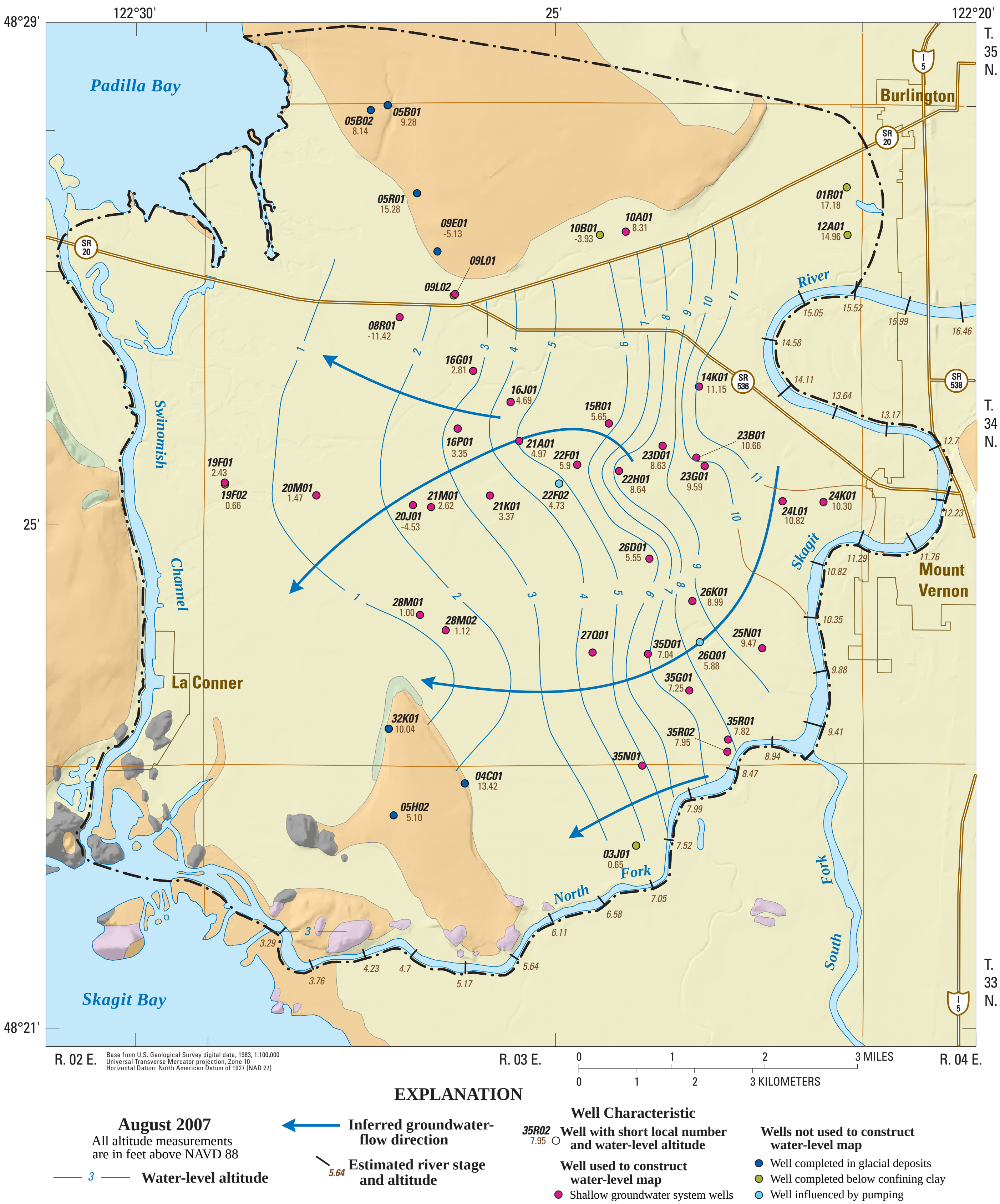

Figure 5. Water-level altitude and inferred groundwater-flow directions in the alluvial and recessional outwash aquifer, Skagit River Delta area, Washington, August 2007.

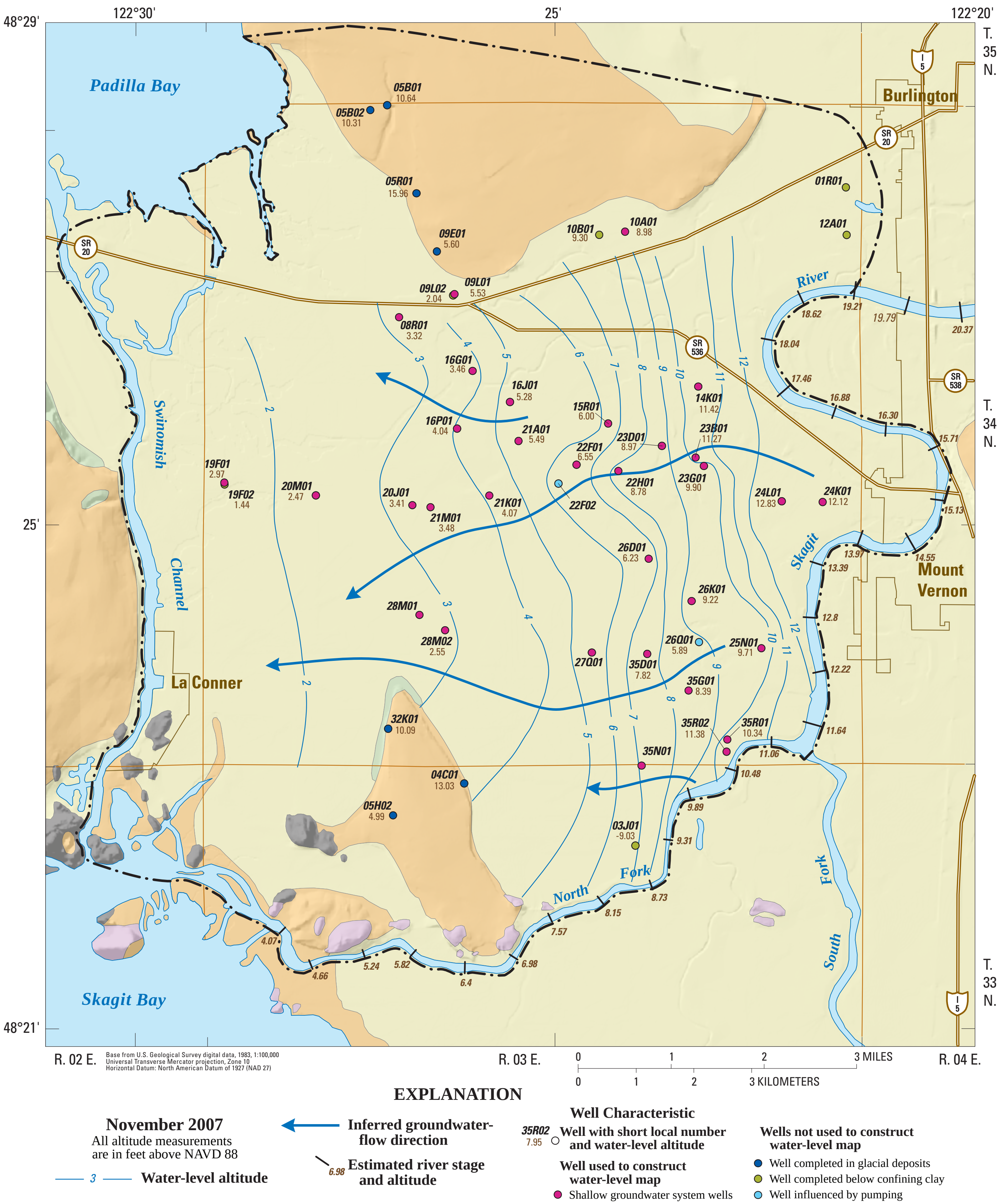

Figure 6. Water-level altitude and inferred groundwater-flow directions in the alluvial and recessional outwash aquifer, Skagit River Delta area, Washington, November 2007.

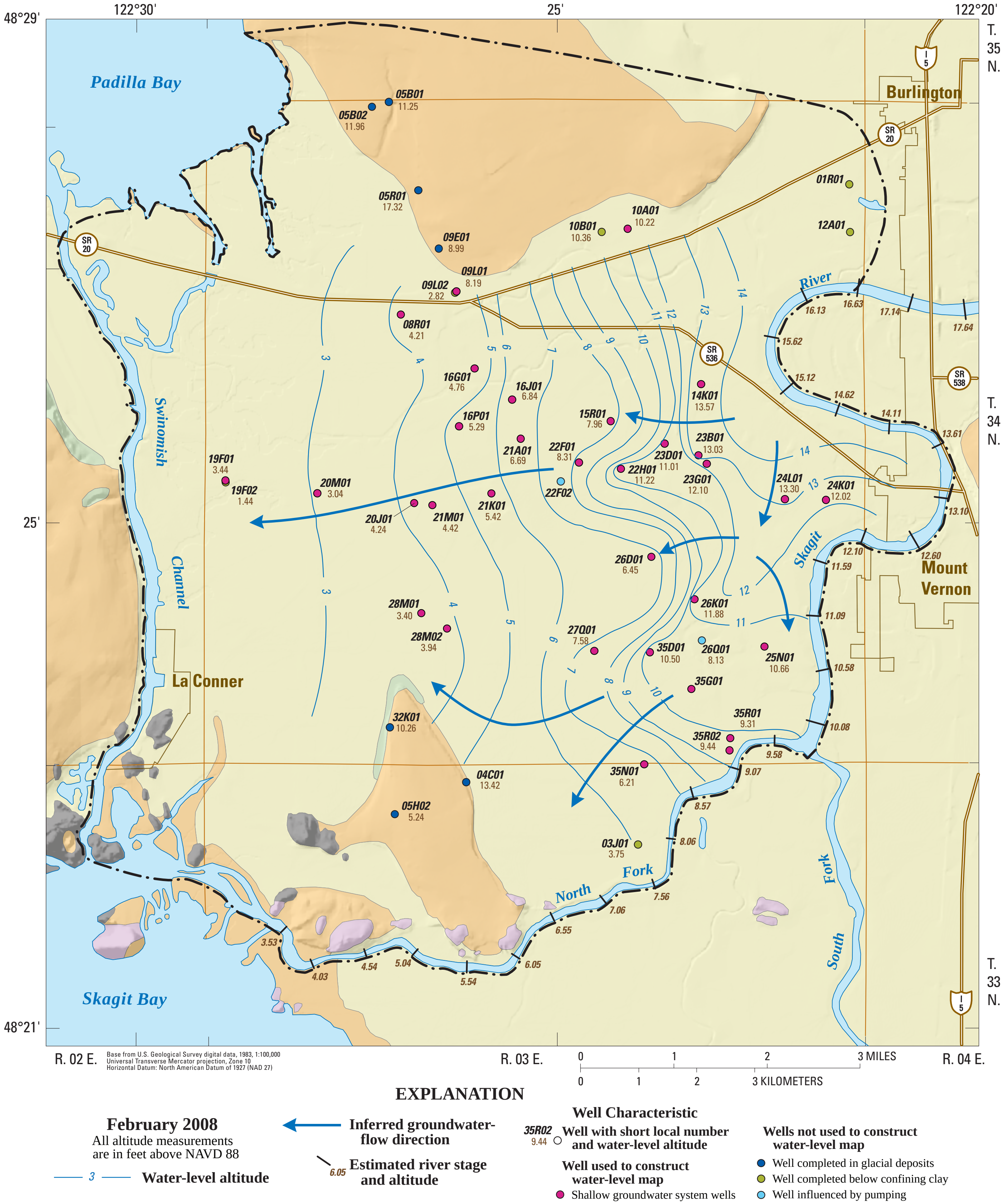

Figure 7. Water-level altitude and inferred groundwater-flow directions in the alluvial and recessional outwash aquifer, Skagit River Delta area, Washington, February 2008.

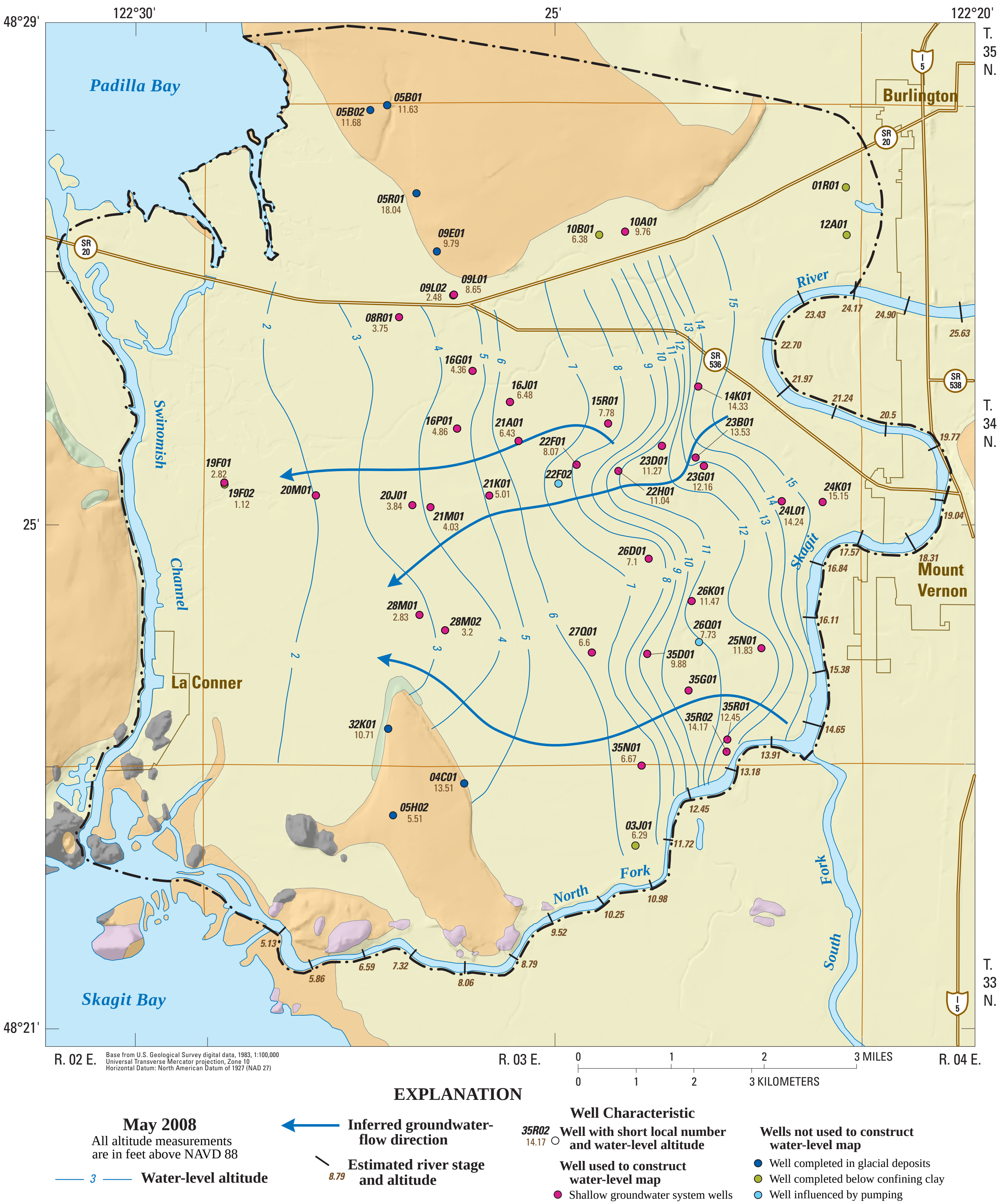

Figure 8. Water-level altitude and inferred groundwater-flow directions in the alluvial and recessional outwash aquifer, Skagit River Delta area, Washington, May 2008.

Table 2. Fitted regression coefficients and calculated hydrogeologic parameters for wells in the Skagit River Delta area, Washington, 2007 and 2008.

[**Abbreviations**: ft/ft, foot per foot; ft/mi, foot per mile; NAVD 88, North American Vertical Datum of 1988]

Measurement	August 2007	November 2007	February 2008	May 2008	Annual
Fitted coefficients, from Microsoft Excel®					
a_0 (Intercept)	-628.10	-589.49	-659.44	-768.90	-661.48
a_1 (x variable 1)	0.000456	0.000462	0.000488	0.000597	0.000501
a_2 (x variable 2)	0.000116	0.000030	0.000104	0.000051	0.000075
Calculated hydrogeologic parameters					
Gradient (ft/ft)	0.00047	0.00046	0.00050	0.00060	0.00051
Gradient (ft/mi)	2.49	2.44	2.63	3.16	2.67
Direction	W 14.3° S	W 3.7° S	W 12.1° S	W 4.9° S	W 8.5° S
Water level at centroid (feet above NAVD 88)	5.71	6.40	7.52	7.54	6.79
Goodness of fit, from Microsoft Excel®					
R^2	0.896	0.879	0.848	0.874	

The overall groundwater-flow direction derived from the regression analysis is similar to those depicted on the water-level maps; shallow groundwater flows slightly south of west from the mainstem of the Skagit River out to the Swinomish Channel and Skagit Bay. Regression analysis of the four quarterly measurements generally agrees with the annual analysis, with only slight variations in gradient or direction (table 2).

Time-averaged water levels in individual wells are always higher or lower than the fitted planar surface (fig. 9). Where measured water levels in a subarea are higher on average than the fitted plane, the potentiometric surface is diverging from the uniform planar flow direction; conversely where water levels in a subarea are lower than the plane the flow is converging. Differences in measured water levels and the plane indicate a pattern in which groundwater converges from the river meander, diverges into two preferential channel areas, converges to flow between the till outcrop uplands, and finally diverges to flow separately toward Skagit and Padilla Bays. Taking into account this final divergence, the sea level (z = 0) contour would coincide fairly well with sea level in the bays and the Swinomish Channel.

To compare the overall slope of the ground surface in the area with that of the groundwater surface, a similar regression calculation was performed on ground-surface elevation at the quarterly monitoring well locations used in the construction of the water-level maps. Ground surface slopes were determined to be slightly steeper (3.82 ft/mi) and slightly more to the southwest (W 24.0° S) than the groundwater potentiometric surface.

The potential for vertical groundwater movement within the alluvial and recessional outwash aquifer was evaluated in areas where a comparison of water-level altitudes could be made in closely spaced wells completed above and below clay layers within the aquifer (figs. 5–8). Wells completed below clay layers are widely spaced and along the margins of the study area, however, comparisons were possible at three locations (19F01/19F02, 09L01/09L02, and 10A01/10B01). Water-level altitude differences at the first two well-pair locations indicate the potential for year-round downward flow, with higher altitudes in wells completed above clay layers for all quarterly measurements. A more complex relation was observed at the last well-pair location in which higher altitudes in wells completed above clay layers were observed during August 2007 and May 2008 measurements indicating the potential for downward flow, and lower altitudes in wells completed above clay layers during the November 2007 and February 2008 measurements indicating the potential for upward groundwater flow.

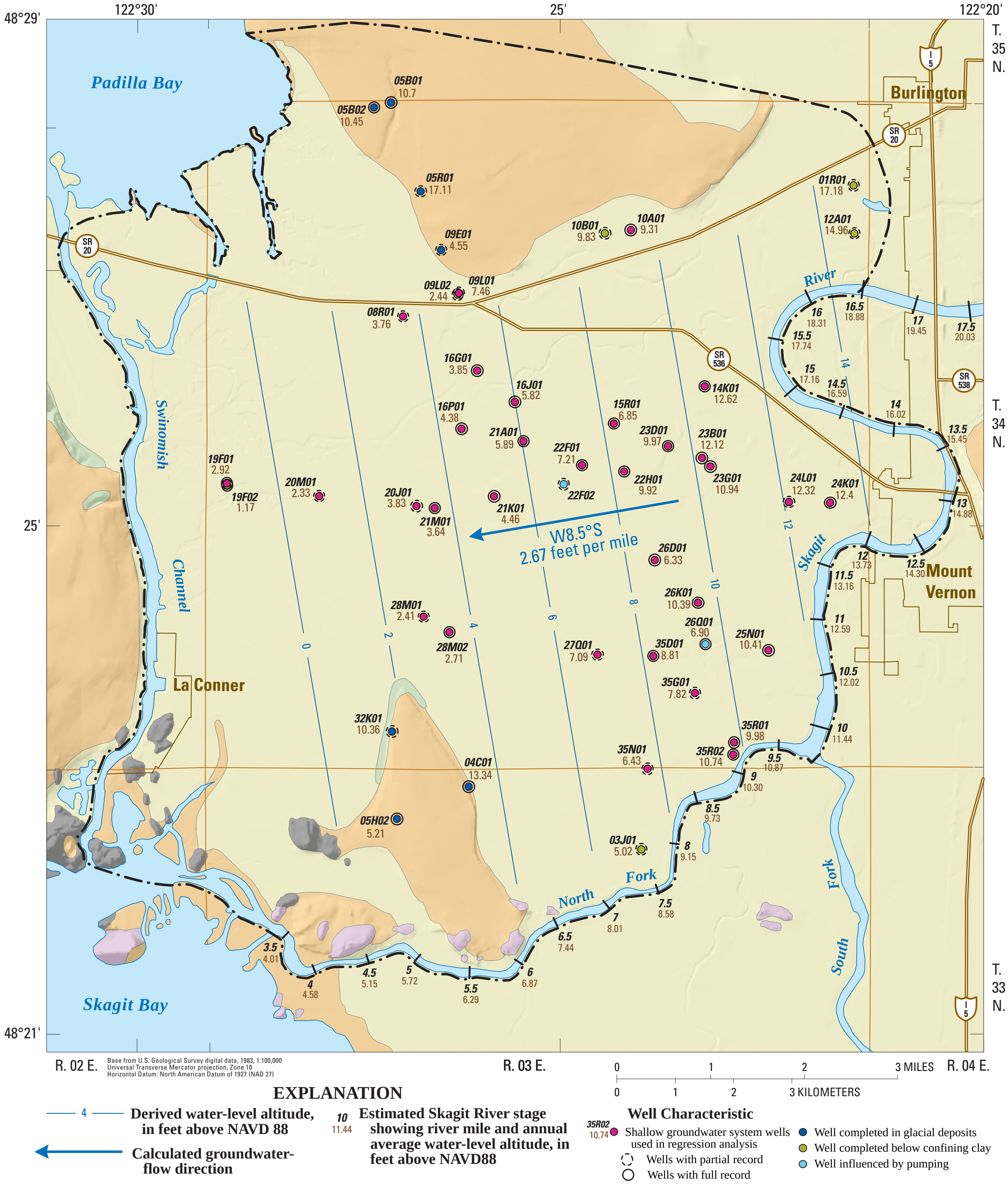

Figure 9. Regression analysis derived annual water-level altitude and calculated groundwater-flow direction in the alluvial and recessional outwash aquifer, Skagit River Delta area, Washington, 2007 and 2008.

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 in many of the wells in the Skagit River Delta follow a typical pattern for shallow wells in western Washington. Water levels rise in autumn and winter, when precipitation is high, and decline during spring and summer, when precipitation is low (fig. 10). Groundwater levels in wells along the eastern margin of the study area also are likely influenced by stage of the Skagit River (fig. 11). Water levels in these wells remained elevated through April, likely due to groundwater recharge from the river, and did not seem to begin to decline until the end of May in response to declining river stage (fig. 12).

Results of the regression analysis of quarterly groundwater levels, indicated by the calculated water level at the centroid (table 2), are in general agreement with the typical pattern for shallow wells in western Washington. Regression analysis also indicates the groundwater gradient was steepest in May, likely due to elevated groundwater levels associated with Skagit River stage, and that by August the water levels along the river declined in response to declining river stage, and the gradient was reduced (table 2). The groundwater gradient increases through the winter probably in response to groundwater recharge from precipitation.

Groundwater levels also may respond to changes in nearby ocean tides. Cyclical water-level fluctuations in a well equipped with a continuous water level recorder exhibited a periodicity that is characteristic of ocean tides (for example, component wave lengths of about 24 hours, and 12 hours and 25 minutes). The well (34N/03E-19F01) is north of the town of La Conner and less than a mile east of the Swinomish Channel, a tidally influenced surface-water body that connects Skagit Bay to the south to Padilla Bay to the north (fig. 3). Water-level fluctuations in the well correspond closely to predicted tidal extremes obtained from the National Oceanic and Atmospheric Administration tide gage near La Conner (fig. 13). Through a trial-and-error correlation analysis, it was noted that water levels in the well showed similar relative high and low points, with a delay of approximately 28 hours after the tidal high or low, and an attenuation factor of about 3 percent. The peak-to-peak fluctuation in the well was about 0.3 ft compared to the tidal fluctuation of about 10 ft at the La Conner gage.

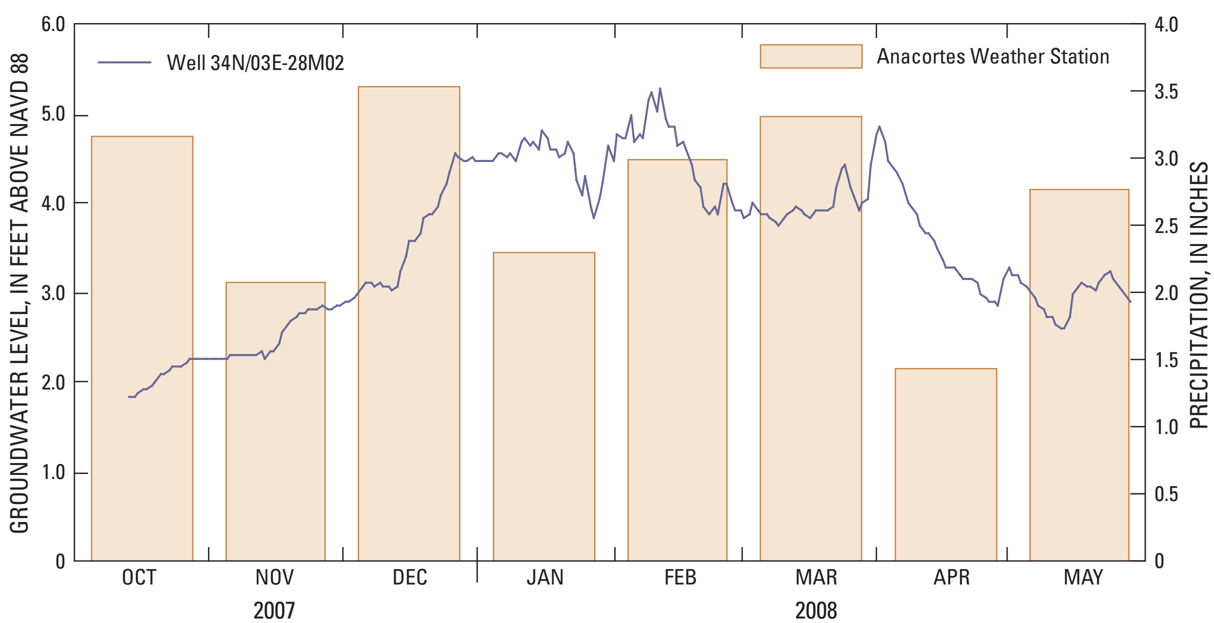

Figure 10. Water levels in well 34N/03E-28M02 and precipitation at Anacortes, Washington, October 2007 through May 2008.

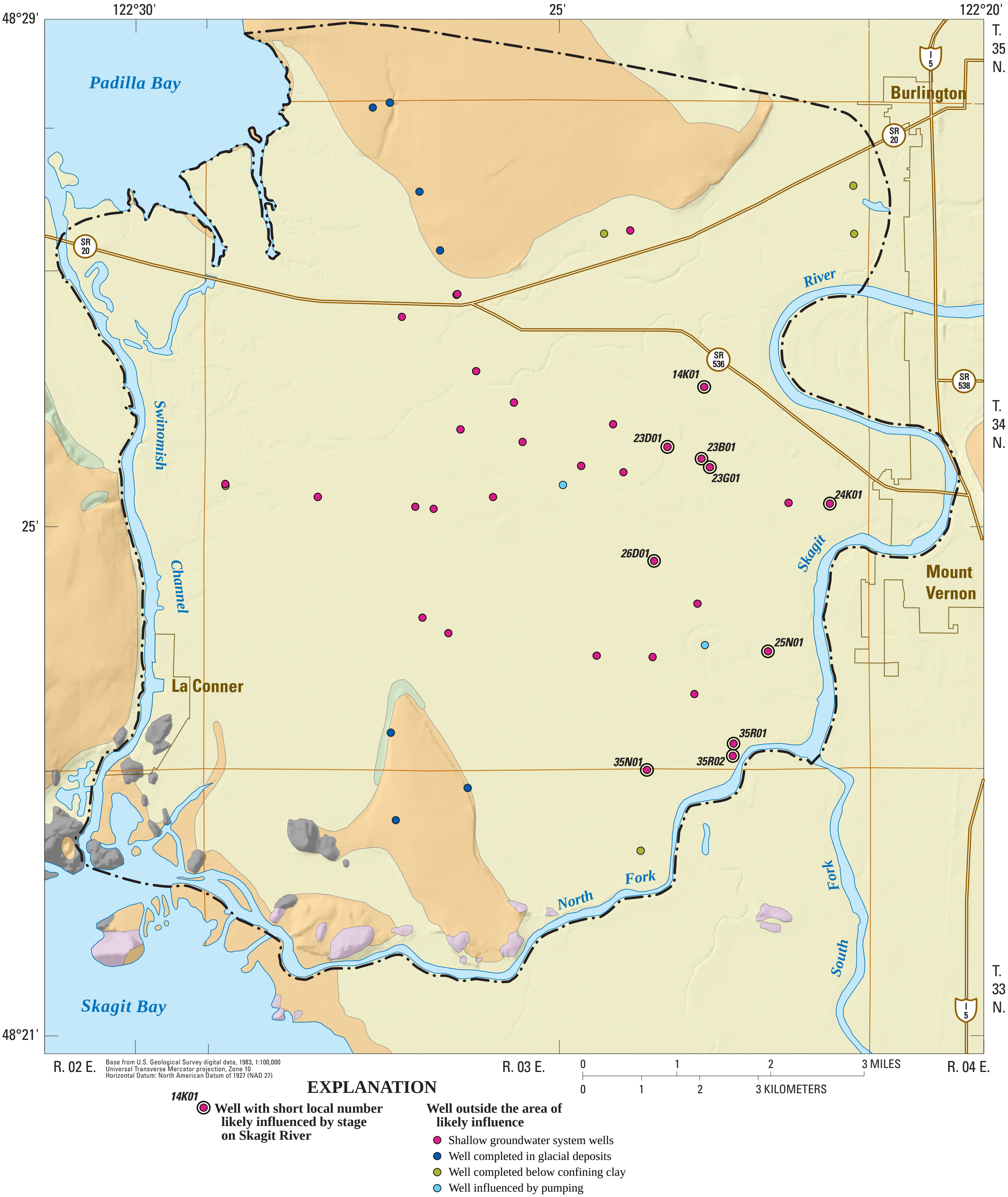

Figure 11. Wells that likely are influenced by stage on the Skagit River, Washington.

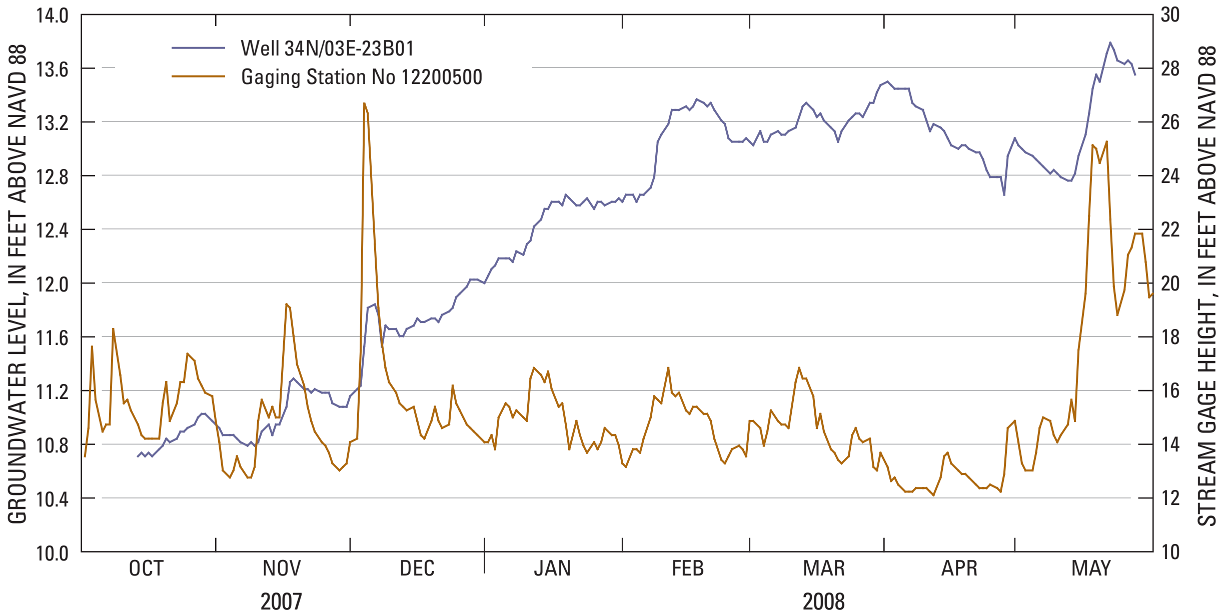

Figure 12. Water levels in well 34N/03E-23B01 and stream stage at U.S. Geological Survey streamflow-gaging station 12200500, Skagit River near Mount Vernon, Washington, October 2007 through May 2008.

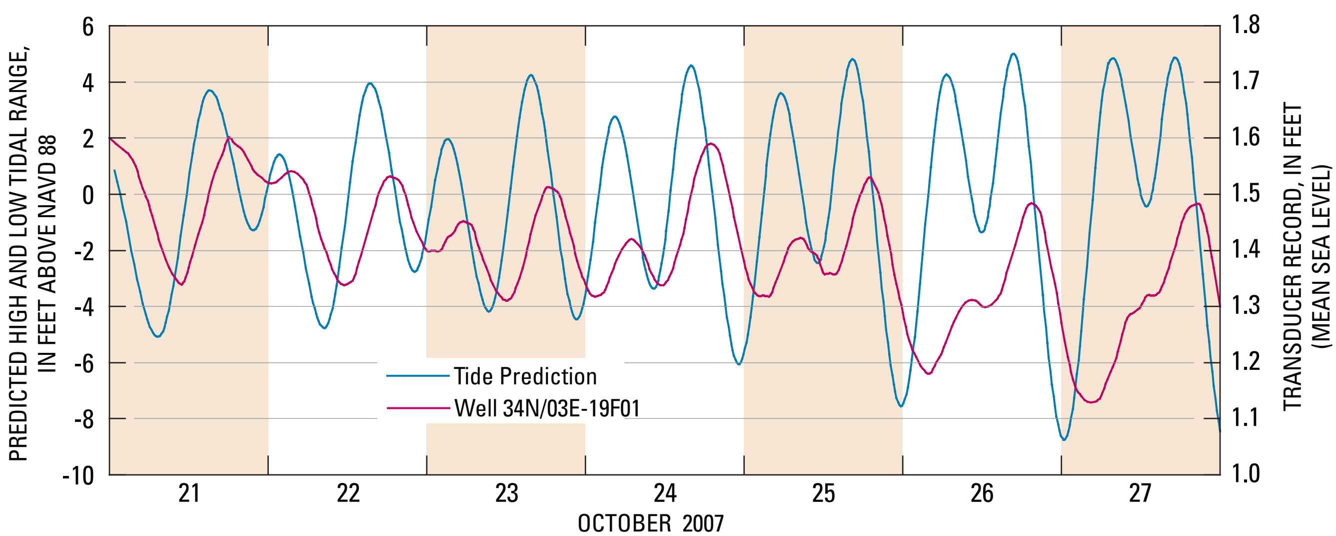

Figure 13. Water levels in well 34N/03E-19F01 and nearby tidal fluctuations near La Conner, Washington, October 2007.

Summary and Conclusions

Recent population growth along the Interstate 5 corridor near Mount Vernon, Washington, has led to increased domestic water use, with many new wells serving residents in the lower part of the Skagit River basin. 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 shallow groundwater movement in an area between the lower Skagit River and Puget Sound was conducted by the U.S. Geological Survey to assist Skagit County and the Washington Department of Ecology with the identification of areas where withdrawals from existing and new wells could have adverse impact on streamflow in the Skagit River.

Land-surface altitude in the study area ranges from near sea level adjacent to the Swinomish Channel to about 130 ft in upland areas. The shallow groundwater system consists of alluvial, lahar runout, and recessional outwash deposits composed of sand, gravel, and cobbles, with minor lenses of silt and clay. The 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 confining layers of clay. Upland areas are underlain by glacial till and outwash deposits that show evidence of terrestrial and shallow marine depositional environments. Bedrock exposures are limited to a few upland outcrops in the southwestern part of the study area, and consist of metamorphic, sedimentary, and igneous rocks.

Water levels were measured in 47 wells on a quarterly basis (August 2007, November 2007, February 2008, and May 2008), and measurements from 34 wells completed in the shallow groundwater system were used in the construction of groundwater-level maps and linear-regression analysis. Estimates of Skagit River stage were used to constrain groundwater-level contours along the eastern margin of the study area. Groundwater flow in the shallow groundwater system generally moves in a southwestward direction away from the Skagit River and towards the Swinomish Channel and Skagit Bay. Local groundwater flow towards the river was inferred during February 2008 in areas west and southwest of Mount Vernon. Water levels varied seasonally, however, generally ranged from less than 3 ft (August 2007) in the west to about 15 ft (May 2008) in the east. Concave and convex bends in the shape of water-level altitude contours indicate the presence of convergent and divergent groundwater flow patterns on a local scale, and likely reflect variations in hydraulic conditions within the aquifer resulting from spatial variations in aquifer material properties (clay, silt, and sand). The time-averaged shallow groundwater-flow direction derived from regression analysis (8.5° south of west) was similar to flow directions depicted on the quarterly water-level maps, with a gradient of 2.67 ft/mi,

Seasonal changes in groundwater levels in most of the wells in the Skagit River Delta follow a typical pattern for shallow wells in western Washington. Water levels rise in the fall and winter, when precipitation is high, and decline during the spring and summer, when precipitation is lower. Groundwater levels in wells along the eastern margin of the study area also are likely influenced by stage on the Skagit River. Water levels in these wells remained elevated through April, and did not begin to decline until the end of May, in response to declining river stage. Groundwater levels in a well equipped with a continuous water-level recorder exhibited periodic fluctuations that are characteristic of ocean tides (for example, component wave lengths of about 24 hours, and 12 hours and 25 minutes). The well (34N/03E-19F01) is less than a mile east of the Swinomish Channel (tidally influenced), and exhibited water-level fluctuations that correspond closely to predicted tidal extremes obtained from a tide gage near La Conner.

Acknowledgments

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