Prepared in cooperation with the Pierce Conservation District and the Washington State Department of Ecology

Numerical Simulation of the Groundwater-Flow System in Chambers–Clover Creek Watershed and Vicinity, Pierce County, Washington

Scientific Investigations Report 2011–5086

Cover: Photograph showing confluence of Chambers Creek and Leach Creek.
Photograph taken by Don Russell, Chambers-Clover Creek project team member, 2009.

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By Kenneth H. Johnson and Mark E. Savoca, U.S. Geological Survey; and
Burt Clothier, Robinson-Noble Inc.

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Scientific Investigations Report 2011–5086

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

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Marcia K. McNutt, Director

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Conversion Factors and Datum

Inch/Pound to SI

Multiply	By	To obtain
Length		
Acre	0.0004047	hectare (ha)
Acre	0.0004047	square kilometer (km ²)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
section (640 acres or 1 mile ²)	259.0	square hectometer (hm ²)
square mile (mi ²)	259.0	hectare (ha)
square mile (mi ²)	259.0	square kilometer (km ²)

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

$$^{\circ}\text{F}=(1.8\times^{\circ}\text{C})+32$$

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

$$^{\circ}\text{C}=(^{\circ}\text{F}-32)/1.8$$

Datum

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 was referenced to the North American Datum of 1983 (NAD83)

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

Well-Numbering System

Wells in the state of Washington 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 20N/02E-26C01 indicates that the well is in township 20 north of the Willamette Base Line, and range 2 east of the Willamette Meridian. The numbers immediately following the hyphen indicate the section (26) within the township. (Most townships in the model area are divided into 36-mi² sections; however, Washington Territory Donation Land Claims of 1852-55 predate the Public Lands Survey and are not regular 1-mi² sections. These early Donation Land Claims are depicted on maps as irregularly sized and shaped sections and are assigned sequence numbers greater than 36.) The letter following the section (C) 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.

Numerical Simulation of the Groundwater-Flow System in the Chambers–Clover Creek Watershed and Vicinity, Pierce County, Washington

By Kenneth H. Johnson and Mark E. Savoca, U.S. Geological Survey; and Burt Clothier, Robinson-Noble Inc.

Abstract

A groundwater-flow model was developed to contribute to an improved understanding of water resources in the Chambers–Clover Creek Watershed. The model covers an area of about 491 square miles in western Pierce County, Washington, and is bounded to the northeast by the Puyallup River valley, to the southwest by the Nisqually River valley, and extends northwest to Puget Sound, and southeast to Tanwax Creek. The Puyallup and Nisqually Rivers occupy large, relatively flat alluvial valleys that are separated by a broad, poorly drained, upland area that covers most of the model area. Chambers and Clover Creeks drain much of the central uplands and flow westward to Puget Sound. The model area is underlain by a northwest-thickening sequence of unconsolidated glacial (till and outwash) and interglacial (fluvial and lacustrine) deposits. Ten unconsolidated hydrogeologic units in the model area form the basis of the groundwater-flow model.

Groundwater flow in the Chambers–Clover Creek Watershed and vicinity was simulated using the groundwater-flow model, MODFLOW-2000. The finite-difference model grid comprises 146 rows, 132 columns, and 11 layers. Each model cell has a horizontal dimension of 1,000 by 1,000 feet, and the model contains a total of 123,602 active cells. The thickness of model layers varies throughout the model area and ranges from 1.5 feet in the A3 aquifer unit to 1,567 feet in the G undifferentiated unit. Groundwater flow was simulated for both steady-state and transient conditions. Steady-state conditions were simulated using average recharge, discharge, and water levels for the 24-month period September 2006–August 2008. Transient conditions were simulated for the

period September 2006–August 2008 using 24 monthly stress periods. Resource managers and local stakeholders intend to use the model to evaluate a range of water resource issues under both steady-state and transient conditions. Initial conditions for the transient calibration were developed from a 3-year “lead-in” period that used recorded precipitation and river levels, and temporal extrapolations of other boundary conditions. During model calibration, variables were adjusted within probable ranges to minimize differences between measured and simulated groundwater levels and stream baseflows. The model as calibrated to steady-state conditions has a standard deviation for heads and flows of 28.42 feet and 2.12 cubic feet per second, respectively; the model as calibrated to transient conditions has a standard deviation for heads and flows of 23.01 feet and 2.67 cubic feet per second, respectively.

Simulated steady-state inflow to the model area from precipitation and secondary recharge was 477,266 acre-feet per year (acre-ft/yr) (79 percent of total simulated inflow), and simulated inflow from stream and lake leakage was 129,778 acre-ft/yr (21 percent of total simulated inflow). Simulated outflow from the model primarily was through discharge to streams, lakes, springs, seeps, and Puget Sound (559,192 acre-ft/yr; 92 percent of total simulated outflow), and withdrawals from wells (47,863 acre-ft/yr; 8 percent of total simulated outflow).

Six scenarios were formulated and simulated using the calibrated model to provide representative examples of how the model can be used to evaluate the effects on groundwater levels and stream baseflows of potential changes in groundwater withdrawals, in consumptive use, and in recharge.

Introduction

In 1998, the Washington State Legislature established the Washington State Watershed Management Act (codified under RCW 90.82) to address the diminishing availability and quality of water and the loss of critical habitat for fish and wildlife. Watershed studies under this Act were begun in 1998 in the Chambers–Clover Creek Watershed (CCCW) Water Resources Inventory Area (WRIA 12) by a group of Initiating Governments and local stakeholders (the Planning Unit). Upon completion of a technical assessment of the watershed, some members of the Planning Unit concluded that additional data, including development of a numerical groundwater-flow model, would contribute to an improved understanding of water resources in the CCCW.

In May 2006, the U.S. Geological Survey (USGS), in cooperation with Pierce Conservation District (serving as sponsoring agency for local public water suppliers and Pierce County Surface Water Management Division) and the Washington State Department of Ecology, began a project to characterize the groundwater-flow system in the CCCW and vicinity, and to integrate this information (Savoca and others, 2010) and other information into a numerical groundwater-flow model to contribute to an improved understanding of water resources in the CCCW.

Purpose and Scope

This report documents the development and calibration of a numerical model to simulate groundwater flow in the CCCW and vicinity. The model described in this report can be used to assess the impacts of groundwater withdrawals on groundwater levels and on streamflows during low-flow conditions. This report presents the information used to construct and calibrate the model, and provides assessments of numerical model performance in simulating measured hydrologic conditions, and a discussion of model limitations. Information used to construct and calibrate the numerical model was based on the work of Justin and others (2009), and Savoca and others (2010). Six scenarios were formulated and simulated using the calibrated model to provide representative examples of how the model can be used to evaluate the effects on groundwater levels and stream baseflows of potential changes in groundwater withdrawals, in consumptive use, and in recharge.

Description of Model Area

The model covers an area of about 491 square miles in western Pierce County, Washington ([fig. 1](#)), and includes major hydrologic features that could be used as hydrologic boundaries of the groundwater-flow model of the CCCW and vicinity. The model area is bounded to the northeast by the Puyallup River valley, to the southwest by the Nisqually River valley, and extends northwest to Puget Sound, and southeast to Tanwax Creek which approximates the southeastern extent of the majority of water-bearing hydrogeologic units (Savoca and others, 2010).

The model area is underlain by a northwest-thickening sequence of unconsolidated glacial (till and outwash) and interglacial (fluvial and lacustrine) deposits. Sedimentary and volcanic bedrock units underlie the unconsolidated deposits, and crop out in a few areas within deeply incised river valleys along the southern and southeastern margin of the model area.

The Puyallup and Nisqually Rivers occupy large, relatively flat alluvial valleys that are separated by a broad, poorly drained, upland area that covers most of the model area. The northwest-flowing Puyallup River receives streamflow from several north-flowing streams (Swan, Clear, and Clarks Creeks) that originate within the northern uplands. Chambers and Clover Creeks drain much of the central uplands and flow westward to Puget Sound. Muck and Lacamas Creeks, and several small tributaries to the northwest-flowing Nisqually River, drain the southern part of the model area. Many stream reaches flow year-round, however, intermittent and ephemeral flow conditions also are common in many stream reaches, especially during the summer months. Springs are present throughout the model area, and contribute to late-summer baseflow to streams and year-round groundwater discharge to Puget Sound along shoreline bluffs. Major lakes in the model area include Steilacoom, Gravelly, American, and Spanaway. These lakes are likely of glacial (kettle) origin and generally reflect water levels in the shallow groundwater-flow system. Many smaller lakes in the area are associated with poorly drained wetland areas that typically form on glacial till deposits.

The model area has a temperate marine climate with warm, dry summers, and cool, wet winters. Mean annual precipitation (average annual precipitation for 1971–2000) is 38.9 in. at Tacoma, and 43.1 in. at McMillin Reservoir (National Oceanic and Atmospheric Administration, 2007). Land-surface altitude in the model area ranges from sea level along the Puget Sound coast and the western extent of major river valleys to near 900 ft in hills along the southeastern and eastern margin of the model area.

Figure 1. Location of Chambers-Clover Creek watershed and vicinity, Washington.

Groundwater-Flow System

This section describes the hydrogeologic units that constitute the groundwater-flow system in the model area and includes discussions of recharge, flow direction, discharge, exchange of water between the aquifer system and creeks, temporal fluctuations in groundwater levels, and water budget. This information was used to construct and calibrate the numerical model and is based on the work of Justin and others (2009), and Savoca and others (2010).

Geologic Setting

The most recent advance and retreat of continental glaciers in the Pleistocene epoch of the Quaternary Period left behind more than 3,000 ft of unconsolidated deposits in the Puget Lowland and about 2,000 ft of deposits within the model area. The Puget Lobe of the Cordilleran ice sheet has advanced and retreated several times into the Puget Lowland from the mountains of British Columbia since the beginning of the Quaternary and has left behind a complex sequence of alternating glacial and interglacial sediments. The Vashon Stade of the Fraser Glaciation was the most recent and extensive of the major advances. Glacial sediment typically includes (in order of deposition) outwash sand and gravels deposited by the advancing ice; glacial till (hard and poorly sorted mixture of clay, silt, sand, and gravel) and ice-contact material deposited beneath and adjacent to the ice; and outwash sand and gravels at the top of the sequence deposited by the retreating ice.

Each major glacial interval was followed by an extended interglacial period during which fluvial, lacustrine, bog, and marsh deposition dominated. Interglacial deposits typically comprise clay, silt, or discontinuous lenses of sand and gravel or peat. Underlying the unconsolidated glacial and interglacial deposits are Tertiary bedrock units comprised mainly of sedimentary claystone, siltstone, sandstone, beds of coal, and volcanic rocks (Walters and Kimmel, 1968). Alpine glacial deposits are locally present within areas of exposed bedrock.

Hydrogeologic Units

Savoca and others (2010) delineated 11 hydrogeologic units in the model area ([table 1](#)). Geologic units were grouped into hydrogeologic units, comprising aquifers and confining units, on the basis of lithologic (depositional facies, grain size, and sorting) and hydrologic (hydraulic conductivity and unit geometry) characteristics. 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. Similarly, a confining layer composed predominantly of silt or clay may contain local lenses of coarse material. These 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 regional-scale groundwater-flow model constructed for this study. Local-scale variability in the distribution of glacial depositional facies often results in the formation of spatially discontinuous units of varying thickness. Therefore, some units are not spatially contiguous, and unit thickness may vary considerably over short distances throughout the model area (Savoca and others, 2010, figs. 3–12).

Within the study area, aquifers primarily comprise glacial outwash but also may include coarse-grained interglacial deposits. The confining units primarily comprise fine-grained interglacial deposits but also may include glacial till or glaciolacustrine deposits. Unconsolidated glacial and interglacial aquifer and confining units are underlain by low-permeability Tertiary bedrock units, which Jones (1999) described as the basement confining unit.

Unconfined and confined conditions are present in the groundwater-flow system and affect the movement and storage of groundwater. Unconfined conditions occur when the upper surface of the saturated zone (water table) is at atmospheric pressure and the water table is free to rise and decline, filling and draining pore space, respectively, in response to changes in groundwater recharge and discharge. Confined conditions occur when groundwater pressure exceeds atmospheric pressure due to the presence of a less permeable overlying unit that constrains the thickness of the saturated zone. Changes in fluid pressure or head under confined conditions in response to groundwater recharge and discharge are governed by the compressibilities of the fluid and the skeletal matrix of the unit and do not result in filling or draining pore space.

Hydraulic Conductivity

Horizontal hydraulic conductivity was estimated for the hydrogeologic units using specific-capacity data from drillers' logs and results of aquifer tests conducted by environmental consulting firms (Savoca and others, 2010). Specific-capacity data were compiled and analyzed for 160 wells that had a driller's log containing discharge rate, time of pumping, drawdown, static water level, well-construction data, and lithologic descriptions. Aquifer tests results were available for 43 public water supply wells. Median values of estimated hydraulic conductivity, from specific-capacity data, for the aquifers ([table 2](#)) are similar in magnitude to values compiled by Vaccaro and others (1998) for the Puget Sound lowlands, and to values reported by Freeze and Cherry (1979) for similar materials. Median values of estimated hydraulic conductivities for the confining units ([table 2](#)) probably are biased too high because the specific-capacity data were obtained from wells that are preferentially open to lenses of coarse material within finer grained material. These data therefore likely represent the more productive zones in these units and not the entire unit.

Table 1. Lithologic and hydrologic characteristics of hydrogeologic units, Chambers-Clover Creek watershed and vicinity, Washington.

[Abbreviations: ft, feet]

Hydrogeologic unit (Savoca and others, 2010)		Principal model layer	Lithologic and hydrologic characteristics [refer to Savoca and others (2010) for unit extent and thickness maps]
AL Alluvial valley aquifer		1–3	The aquifer consists of alluvial silt, sand, and gravel and mudflow deposits that closely follow Holocene river valleys. The unit generally is less than 100 ft thick along the Nisqually River, but exceeds 250 ft along the Puyallup River as it nears Commencement Bay. Groundwater in this aquifer generally is unconfined; however, confined conditions may occur locally beneath mudflow deposits.
A1 Aquifer		1	The aquifer primarily is composed of recessional outwash deposits consisting of stratified silt, sand and gravel deposited by large meltwater streams formed during the northward retreat of the Puget Lobe. Thickness typically ranges from a thin veneer (less than 35 ft) to approximately 150 ft, and locally exceeds 200 ft. Groundwater generally is unconfined in this aquifer.
A2 Confining unit		2	This low-permeability unit is composed of Vashon till and lesser amounts of ice-contact, moraine and fine-grained glaciolacustrine deposits. The unit consists of various proportions of clay, silt, sand, and gravel, with locally occurring sand and gravel lenses capable of providing water for domestic use. Thickness averages about 60 ft but varies spatially from a thin veneer to approximately 150 ft, and locally exceeds 200 ft.
A3 Aquifer		3	The aquifer is composed of Vashon advance outwash and lesser amounts of Pre-Fraser coarse-grained non-glacial deposits, and consists of well-sorted sand or sand and gravel, with lenses of silt and clay. Thickness averages about 75 ft, and locally exceeds 160 ft. Groundwater in this aquifer generally is confined by the overlying Vashon till, however, unconfined conditions may occur locally where the unit is not fully saturated or is exposed at land surface.
B Confining unit		4	This low-permeability unit primarily is composed of fine-grained silts and clays deposited during the Olympia interglacial and glaciolacustrine clays deposited during early Vashon. Thickness averages about 55 ft, but locally exceeds 200 ft.
C Aquifer		5	The aquifer is composed of pre-Olympia glacial drift deposits consisting of sand and gravel, with minor lenses of silt, clay, and till. Thickness averages about 105 ft, and locally exceeds 200 ft. Groundwater in this aquifer generally is confined by the overlying B confining unit. However, unconfined conditions may occur locally where no overlying confining unit is present, or in places where the aquifer is not fully saturated.
D Confining unit		6	This low-permeability unit consists of alluvial and lacustrine sand, silt and clay deposits, and occasional deposits of volcanic ash. Thickness averages about 100 ft, and locally exceeds 200 ft.
E Aquifer		7	The aquifer consists of silt, sand, and gravel, with discontinuous till and lacustrine deposits. Thickness typically ranges from a thin veneer to approximately 120 ft, and locally exceeds 200 ft. Groundwater in this aquifer is confined by the overlying D confining unit.
F Confining unit		8	This low-permeability unit consists of silt and clay, with minor lenses of sand and gravel. Limited well data indicate thickness typically ranges from 50 to 200 ft, and locally exceeds 300 ft.
G Undifferentiated deposits		9–11	Undifferentiated deposits assigned to unit G consist of stratified sand and gravel, with discontinuous layers of till. Few wells in the study area fully penetrate the unit, and little is known about the spatial distribution of water-bearing and non-water-bearing sediments in the deeper parts of the unconsolidated sequence. Several public water-supply systems in the study area withdraw water from the upper part of the unit.
Bedrock unit		–	This low-permeability unit consists primarily of sedimentary claystone, siltstone, sandstone, beds of coal, and volcanic rocks.

Table 2. Summary of hydraulic conductivity values estimated from specific-capacity data and aquifer tests, by hydrogeologic unit Chambers-Clover Creek watershed and vicinity, Washington.

Hydrogeologic unit	Number of wells	Horizontal hydraulic conductivity (feet per day)			
		Minimum	Median	Maximum	
From specific-capacity data					
AL Alluvial valley aquifer	10	36	328	3,779	
A1 Aquifer	4	62	933	5,065	
A2 Confining unit	5	1	18	144	
A3 Aquifer	34	1	122	15,137	
B Confining unit	5	4	21	120	
C Aquifer	59	3	96	12,753	
D Confining unit	3	18	29	32	
E Aquifer	22	11	57	1,317	
F Confining unit	1		131		
G Undifferentiated deposits	17	7	33	936	
From aquifer tests					
A3 Aquifer	9	229	588	3,228	
C Aquifer	13	21	198	1,337	
E Aquifer	15	12	214	1,519	
G Undifferentiated deposits	6	11	39	163	

Estimates of horizontal hydraulic conductivity compiled from aquifer tests (table 2) conducted by environmental consulting firms (Carr/Associates Inc., 1988; Robinson-Noble Inc., written commun., 2009) were available for public supply wells only, and are biased toward the major water-producing aquifers in the model area. Aquifer-test data were not available for the AL and A1 aquifers or for any of the confining units.

Recharge

Because precipitation is the dominant source of water that recharges groundwater in the model area, it is reasonable to expect the volume of recharge to vary with the volume of precipitation. However, other factors, such as the permeability of surficial hydrogeologic units and land-cover characteristics also determine the volume of recharge. The distribution of recharge from precipitation in the model area was estimated by applying precipitation–recharge relations (Savoca and others, 2010) based on four separate regression equations developed for areas in Washington State by Bidlake and Payne (2001). The four regression equations compute recharge to aquifers and confining units in areas with or without tree cover.

Recharge in areas where the percentage of impervious surfaces are greater than 50 percent was reduced by one-half according to the method of Bidlake and Payne (2001). The groundwater-flow system within the water-budget area (432 mi²) located within the slightly larger model area, receives about 455,000 acre-ft or about 20 in. of recharge from precipitation during an average year (Savoca and others, 2010). Groundwater recharge also occurs through return flows from septic systems, outdoor (irrigation) use, and leakage from public water-system distribution lines; return-flow estimates used in the groundwater-flow model are discussed later in this report.

Groundwater-Flow Directions

Groundwater flow in unconsolidated aquifers generally is towards the northwest in the direction of Puget Sound, and towards the north and northeast in the direction of the Puyallup River (Savoca and others, 2010, figs. 16–21). The potential for vertical flow between aquifers is difficult to determine because extents and thicknesses of hydrogeologic units vary considerably throughout the model area, the presence of low-permeability deposits within and between aquifers is highly variable, and the data available for comparing water levels between adjacent units are widely spaced. Water-level differences between the A3 and C aquifers show the potential for downward vertical flow in western (vicinity of American, Gravelly, and Steilacoom Lakes) and eastern (along the bluffs of the Puyallup River valley) parts of the model area. The potential for upward groundwater movement, indicated by the presence of flowing wells, was observed at several locations within aquifer units in the Puyallup River valley.

Discharge

Groundwater in the model area discharges to streams, lakes, springs, marshes, and along coastal and river valley bluffs; as evaporation and transpiration 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) in the model area. Groundwater discharge to streams in the model area was estimated to be 120.6 ft³/s (87,310 acre-ft/yr) in September 2007 and 127.4 ft³/s (92,230 acre-ft/yr) in July 2008 (Savoca and others, 2010). These estimates represent flow from contributing areas upstream of synoptic streamflow measurement sites (235.4 mi²) and do not include contributing areas in downstream portions of the subbasins (28.1 mi²). The averaged, area-weighted groundwater discharge was estimated to be 126.8 ft³/s (91,800 acre-ft/yr), not including discharge to the Puyallup and Nisqually Rivers, which were not measured. This value includes area-weighted estimates of groundwater

discharge for portions of stream reaches that were downstream of synoptic measurement sites. An estimate of groundwater discharge to the Puyallup and Nisqually Rivers, along with submarine seepage to Puget Sound, was computed as a residual component (“other natural discharge”) in the water budget presented later in this report.

Groundwater withdrawals from wells in the water-budget area in 2007 were estimated to be 58,500 acre-ft (Savoca and others, 2010). This quantity represents gross withdrawals and does not reflect return flows from septic systems, outdoor (irrigation) use, and leakage from public water-system distribution lines. Groundwater discharge also occurs at numerous springs in the model area, and spring locations and discharge have been previously reported in several studies. The total previously reported discharge of springs in the area is about 110 ft³/s (80,000 acre-ft/yr (Savoca and others, 2010).

Groundwater and Surface-Water Interactions

Stream reaches that either gained flow or lost flow from the shallow groundwater system were identified from synoptic measurements conducted during low-flow conditions in September 2007 and July 2008 (Savoca and others, 2010). Reaches upstream of the uppermost measurement sites on all streams, except at Swan Creek, gained flow from groundwater discharge. Intermediate reaches of most streams generally were losing or neutral (no substantial gain or loss), and the lowermost reaches were generally gaining. Substantial groundwater discharge to the lower reaches of Chambers, Clear, and Clarks Creeks also was measured and probably is due to significant incision of stream channels as they descend to Puget Sound or to the Puyallup River valley (Savoca and others, 2010).

Groundwater-Level Fluctuations

Seasonal changes in groundwater levels that follow a typical pattern for shallow wells in western Washington were observed in many wells in the model area (Justin and others, 2009). Water levels rose in autumn and winter when precipitation and river stage were high, and declined during spring and summer when precipitation and river stage were low. The peak groundwater levels lagged behind the peak streamflow by a few months, reflecting the storage characteristics of the groundwater system. Water levels in wells completed in the unconsolidated hydrogeologic units exhibited seasonal variations ranging from less than 1 to about 50 ft. The largest fluctuation in water level (78 ft) during the monitoring period (March 2007–September 2008) was measured in a well completed in the bedrock unit.

Water Budget

An approximate water budget for average precipitation during the study period (September 1, 2006–August 31, 2008) for the water-budget area (Savoca and others, 2010) is presented in [table 3](#). Precipitation during the study period averaged an estimated 45 in/yr in the area. About 44 percent of precipitation enters the groundwater system as recharge. Almost one-half of this recharge (49 percent) discharges to the Puyallup and Nisqually Rivers or leaves the groundwater system as submarine discharge to Puget Sound. The remaining groundwater recharge discharges to streams (20 percent) and springs (18 percent), or is withdrawn from wells (13 percent). The estimated magnitude of discharge to Puget Sound is highly uncertain because it incorporates all the inaccuracies in the other water-budget component estimates, and no attempts have been made to measure it directly. Submarine groundwater discharge is a potentially significant unknown because it represents a potential groundwater resource that could be withdrawn without impact to freshwater instream flows.

Table 3. Estimated annual water budget for the Chambers–Clover Creek watershed and vicinity, Washington, September 1, 2006–August 31, 2008.

Water budget component	Quantity		Percent of total
	Inches per year	Acre-feet per year	
Precipitation			
Fate of precipitation			
Surface runoff	3	65,700	7
Evapotranspiration	22	504,300	49
Groundwater recharge	20	455,000	44
Total precipitation	45	1,025,000	100
Fate of recharge			
Discharge to streams	4	91,800	20
Discharge to springs	3.5	80,000	18
Other natural discharge ¹	10	224,700	49
Withdrawals from wells	2.5	58,500	13
Total	20	455,000	100

¹ Discharge to the Puyallup and Nisqually Rivers or submarine seepage to Puget Sound.

Numerical Simulation of the Groundwater-Flow System

Groundwater flow in the Chambers–Clover Creek Watershed and vicinity was simulated using the U.S. Geological Survey modular three-dimensional finite-difference groundwater-flow model, MODFLOW-2000 (Harbaugh and others, 2000). MODFLOW-2000 is a computer program that numerically solves the three-dimensional groundwater-flow equation for a porous medium using the finite-difference method. The modular design of MODFLOW-2000 uses packages to represent groundwater-flow system processes, such as recharge, groundwater flow, discharge, and interactions between the aquifer and surface-water bodies. The model described in this report was developed to simulate steady-state and transient conditions. Steady-state groundwater flow represents a groundwater system that is in a state of equilibrium: inflows into and outflows from the system are constant and equal, resulting in no changes in groundwater storage. Transient groundwater flow represents a dynamic system, in which variable inflows, outflows, and groundwater storage change with time. The simulation of steady-state conditions incorporates average annual values for recharge, discharge, and other groundwater-flow system processes. The simulation of transient conditions incorporates monthly variations in recharge, discharge, and other groundwater-flow system processes. Resource managers and local stakeholders intend to use the model to evaluate a range of water resource issues under both long-term steady-state and short-term transient conditions.

Spatial and Temporal Discretization

The model area was subdivided, horizontally and vertically, into rectilinear blocks called cells. The hydraulic properties of the material in each cell are assumed to be homogeneous. A model grid of 146 rows, 132 columns, and 11 layers was used to represent the groundwater-flow system ([fig. 2](#)). The model grid is aligned 45° counterclockwise from the north to allow model boundaries to more closely approximate the locations of Puget Sound, and the Puyallup and Nisqually River valleys. Each cell in the model grid has a uniform dimension of 1,000 by 1,000 ft, and the model contains a total of 123,602 active cells. The thickness of model layers varies throughout the model area. All 11 model layers are active throughout the entire model area, except where regional features such as underlying bedrock units or Puget Sound truncate the lateral extents of hydrogeologic units. The

bottom of the model (typically the bottom of model layer 11) is an implicit no-flow boundary and coincides with the top of bedrock. The Layer Property Flow (LPF) package was used to assign hydraulic properties to model cells in each model layer based on the hydrogeologic unit present at that location within the model.

The model simulates both steady-state and transient conditions. The steady-state condition simulates average recharge, discharge, and water levels for the study period (September 2006–August 2008). The transient simulation period (September 2006–August 2008) was divided into 24 monthly stress periods to represent temporal variations in recharge, discharge, and other groundwater-flow system processes. Each stress period comprises one time step to coincide with the frequency of data collected in the field, and because smaller time steps were not necessary for stable operation of the model. Initial conditions for the transient calibration of the model were developed from a 3-year “lead-in” period (September 2003–August 2006) designed to isolate the transient calibration period from potential inaccuracies associated with initial transient calibration start-up. The lead-in period used recorded precipitation and river levels, and extrapolations of other boundary conditions.

Hydrogeologic Framework

The hydrogeologic units ([table 1](#)) delineated by Savoca and others (2010) were used to represent the three-dimensional hydrogeologic framework in the model. Most units are not spatially contiguous throughout the model area, and unit thicknesses vary considerably over short distances. Each hydrogeologic unit was assigned a principal model layer ([table 1](#)) that most closely corresponds to the unit’s stratigraphic position in the aquifer system based on the unit top and thickness ([fig. 21](#), at back of report). With the exception of the alluvial valley aquifer (AL) and undifferentiated deposits (G), most units are represented by a single model layer, although overlying or underlying units can occupy a model layer in areas where the primary hydrogeologic unit assigned to the layer is absent. The relation between hydrogeologic units and model layers is illustrated in a vertical section through the model ([fig. 3](#)) that corresponds with hydrogeologic section A–A’ in Savoca and others (2010, pl. 2). Tertiary sedimentary and volcanic bedrock units are assumed to be impermeable when compared to overlying unconsolidated units, and therefore, were not assigned a model layer. The top of the bedrock unit delineates the bottom of the model domain. A nearby groundwater-flow model by Drost and others (1999) characterized bedrock units in a similar manner.

Figure 2. Locations of model river, general head, spring and seep cells, domestic and public-supply wells, and irrigation wells, Chambers-Clover Creek watershed and vicinity, Washington.

Figure 3. Hydrogeologic units and numerical model layers, Chambers-Clover Creek watershed and vicinity, Washington.

Hydraulic Properties

The hydrogeologic units in the model area contain a variety of materials, and each unit likely exhibits a range in the spatial distribution of the values of hydraulic properties (hydraulic conductivity and specific storage) that is not well understood. Where available, initial estimates of values of hydraulic properties were obtained from previously published reports in and adjacent to the model area (Savoca and others, 2010), as well as from published values in a standard reference (Freeze and Cherry, 1979). A uniform distribution of hydraulic parameter values was initially specified in the numerical model for each hydrogeologic unit.

Hydraulic Conductivity

Initial values of horizontal hydraulic conductivity (K_h) for the hydrogeologic units (table 4) were based on analyses of specific-capacity data and results of aquifer tests (Savoca and others, 2010). Because there is no evidence to suggest that hydraulic conductivity varies with direction (no preferential flow), horizontal isotropy ($K_x = K_y$) was assumed. Initial values of horizontal hydraulic conductivity in aquifer units ranged from 198 ft/d in the C aquifer to 933 ft/d in the A1 aquifer. Initial values of horizontal hydraulic conductivity in confining units ranged from 18 ft/d in the A2 confining unit to 30 ft/d in the F confining unit. The G undifferentiated deposits were represented using an initial horizontal hydraulic conductivity value of 39 ft/d.

Initial values of vertical hydraulic conductivity (K_v) were assigned to each hydrogeologic unit (table 4) as the ratio of horizontal to vertical hydraulic conductivity (vertical anisotropy). Assignment of vertical anisotropy to hydrogeologic units was based on unit lithologic and hydraulic characteristics, and initial vertical anisotropy values used in a nearby groundwater-flow model by Drost and others (1999).

- Aquifers comprising primarily well-sorted sand and gravel (hydrogeologic units AL, A1, A3, C, and E) were assigned a vertical anisotropy of 10 (that is, $K_h = 10 \times K_v$);
- Confining units comprising primarily poorly sorted and fine-grained deposits (hydrogeologic units A2, B, D, and F) were assigned a vertical anisotropy of 100.
- The G undifferentiated deposits represent a composite of probable aquifers and intervening confining units and were assigned a vertical anisotropy of 30, which represents an intermediate value between an unconsolidated aquifer and a confining unit.

Table 4. Initial hydraulic property values of hydrogeologic units used in the steady-state calibration, Chambers-Clover Creek watershed and vicinity, Washington.

[Descriptions of hydrogeologic units from Savoca and others (2010). **Abbreviations:** ft, feet ft/d, feet per day;]

Hydrogeologic unit	Hydraulic conductivity (ft/d)		Vertical anisotropy (K_h/K_v)	Specific storage (s_t)
	Horizontal (K_h)	Vertical (K_v)		
AL Alluvial valley aquifer	328	33	10	1.0E-2
A1 Aquifer	933	93	10	1.0E-2
A2 Confining unit	18	0.2	100	1.0E-5
A3 Aquifer	588	59	10	1.0E-6
B Confining unit	21	0.2	100	1.0E-5
C Aquifer	198	20	10	1.0E-6
D Confining unit	29	0.3	100	1.0E-5
E Aquifer	214	21	10	1.0E-6
F Confining unit	¹ 30	0.3	100	1.0E-5
G Undifferentiated deposits	39	1.3	30	3.0E-6

¹ Estimated value assigned to more closely approximate horizontal hydraulic conductivity of confining unit; value derived from analyses of limited specific-capacity data (table 2) for unit F (131 ft/d) was not used.

Specific Storage

Specific storage values were assigned to model cells to represent the change in groundwater storage that results from changes in water levels in a confined aquifer. Both unconfined and confined conditions occur within the groundwater system, however, in order to prevent the drying of model cells, and resultant model instability, all model layers were simulated as confined and specific storage values were assigned to all model cells. Values of specific storage in confined aquifers commonly range from 1.0×10^{-5} to 1.0×10^{-6} ft⁻¹ (Riley, 1998), and values for clay-bearing confining units could be an order of magnitude larger, based on reported compressibility values (Freeze and Cherry, 1979). An initial specific storage value of 1.0×10^{-6} ft⁻¹ was assigned to aquifer units A3, C, and E, and a larger value of initial specific storage (1.0×10^{-2} ft⁻¹) comparable to specific yield of 1 percent was assigned to aquifer units AL and A1 to more closely represent the change in groundwater storage in unconfined aquifers (table 4). An initial specific storage value of 1.0×10^{-5} ft⁻¹ was assigned to all confining units, and an intermediate value of 3.0×10^{-6} ft⁻¹ was assigned to the G undifferentiated deposits (table 4).

Boundary Conditions and Implementation of MODFLOW Packages

Specified-flux and head-dependent flux boundaries were used to represent hydrologic boundaries in the model. Specified-flux boundaries represent recharge from precipitation and discharge through groundwater withdrawals. Head-dependent flux boundaries represent groundwater discharge to rivers, lakes, springs, seeps, and Puget Sound. Specified-flux and head-dependent flux boundaries are implemented in the model using various MODFLOW packages and are described in the following sections.

A no-flow boundary is inferred: (1) along the Puyallup and Nisqually River valleys; (2) along Tanwax Creek; and (3) along the top of the bedrock surface beneath unconsolidated deposits. No-flow boundaries are specified flux boundaries with flux equal to zero—no groundwater flow is simulated across these boundaries. Groundwater flow beneath the Puyallup River valley is towards the north and northwest in the down-valley direction of the river, and a northwest down-valley groundwater flow direction also is likely beneath the Nisqually River valley (Savoca and others, 2010). Model boundaries were aligned sub-parallel to the direction of groundwater flow in the Puyallup and Nisqually River valleys to approximate no-flow conditions across the model boundary.

Tanwax Creek approximates the southeastern extent of the majority of water bearing hydrogeologic units in the model area (Savoca and others, 2010). Relatively impermeable Tertiary sedimentary and volcanic bedrock units (Drost and others, 1999; Jones, 1999) are present near land surface southeast of Tanwax Creek and beneath unconsolidated water bearing units throughout the model area. It is assumed that the bedrock unit is impermeable when compared to the unconsolidated deposits overlying it; therefore, the contact between the top of the bedrock unit and overlying unconsolidated deposits is represented as a no-flow boundary. A nearby groundwater-flow model by Drost and others (1999) characterized the contact between bedrock and unconsolidated deposits in a similar manner.

Recharge Package

The Recharge Package was used to represent groundwater recharge from precipitation, and return flows from septic systems, outdoor (irrigation) use, and leakage from public water system distribution lines. Recharge (in units of feet per day) was applied as a specified flux to the uppermost model cell. The distribution of recharge from precipitation in the model area was estimated by applying precipitation–recharge relations (Savoca and others, 2010) based on regression equations developed for areas in Puget Sound, Washington (Bidlake and Payne, 2001). Recharge

from precipitation was reduced by 50 percent in the Puyallup and Nisqually River valleys to account for losses due to evapotranspiration of shallow groundwater, and the likely rejection of some amount of precipitation recharge due to high water levels and periodic saturated conditions within the river valleys (Robinson-Noble Inc., oral commun., 2011).

Residential return flows were represented as a percentage of the water used at residences with septic systems. A total residential return-flow rate (indoor and outdoor use) of 76 percent was used in the steady-state calibration, and closely correlates with total return-flow rates used in other groundwater studies in western Washington (Sapik and others, 1989; Drost and others, 1999; van Heeswijk and Smith, 2002; Geoengineers, 2003). The steady-state residential return-flow estimate (228 gal/d per connection) is based on a typical per connection water-use rate in these same references. Residential return-flow estimates used in the transient calibration were adjusted to account for temporal variations in outdoor use. During the winter months (October through April), outdoor use (lawn and garden irrigation) is assumed to be zero. Therefore, water use during the winter is entirely for indoor use, and an indoor return-flow rate of 87 percent was used to represent septic-system return flows during the winter. This indoor (winter) return-flow rate is similar to the winter rate used in a groundwater study in western Washington (Geoengineers, 2003). The indoor return-flow estimate (151 gal/d per connection) used in the transient calibration is based on a per connection indoor water-use rate estimate of 173 gal/d that was derived from an analysis (Ron Lane, U.S. Geological Survey, written commun., 2009) of reported public water system pumpage data for Pierce County, Washington.

An outdoor use residential return-flow rate of about 40 percent was used in the transient calibration to represent lawn and garden irrigation return flows during the summer months (May–September). A similar outdoor residential use return-flow rate was recently used in a groundwater study in eastern Washington (Hsieh and others, 2007), and a quantitative field study of consumptive use associated with lawn watering by Oad and others (1997) estimates an efficiency of 60 percent and deep percolation of 40 percent of applied lawn water. Several methods have been used to determine return-flow rates associated with lawn and garden irrigation resulting in a wide range of published return-flow rate values (Oad and DiSpigno, 1997). These return-flow rates are based on studies representing conditions that may not be descriptive of conditions in the model area. Lawn and garden irrigation return-flow rates may vary spatially in the model area, and the return-flow rate used in the model is only an approximation based on limited data. Residential return flows were spatially distributed to cells according to the number of residences in each cell that had septic systems. Locations of residences were based on a mapping of known septic systems that was developed by the Tacoma Pierce County Health Department.

Return flows associated with public water system conveyance losses were represented as a percentage of the water pumped to public water system-service areas. An estimated conveyance loss return-flow rate of 10 percent was used in the steady-state and transient calibrations to simulate delivery losses that occur along water lines within service areas. This estimate of return-flow rate is based on an average of reported values for conveyance loss that several public water supply systems in the model area provided. The total estimated conveyance loss return-flow for each public water supply service area was uniformly distributed among all the model cells that had significant residential development (based on more than four improved parcels per cell) within the combined service areas.

The distribution of recharge is shown in [figure 4](#) in terms of average annual total recharge (precipitation and return flows), and the amount of total recharge that is attributed to return flows (septic, outdoor use, and conveyance loss) is shown in [figure 5](#). The temporal distribution of residential and public water system return flows in the transient calibration was based on an analysis of monthly public water system pumpage data for Pierce County, Washington, conducted by the USGS (Ron Lane, written commun., 2009). The temporal discretization of monthly recharge (precipitation recharge, residential return flow, and conveyance loss) used in the transient calibration is shown in [figure 6](#) as relative stress level factors that increase or decrease the values used in the steady-state calibration. During the winter (October–April), a constant return flow rate (151 gal/d per rural connection) was used to reflect primarily indoor water use during the winter months. In the summer (May–September) precipitation recharge decreases proportionally to the precipitation during each month, and increased residential and public supply withdrawals (due to increased outdoor water use) result in increased rural residential return flows that peak (378 gal/d per connection) in July.

Well Package

The Well Package was used to represent groundwater withdrawals (in units of cubic feet per day) from pumping wells. The spatial distribution of public-supply, domestic, and irrigation withdrawals is shown in [figure 2](#). The Well Package imposes a specified-flux boundary condition in each model cell to which a well is assigned based on the withdrawal rate for each well or group of pumping wells located in the cell. Average annual withdrawals were used for

steady-state conditions. Withdrawals for transient conditions were specified for each monthly stress period and are shown in [figure 6](#) as relative stress-level factors that increase or decrease the values used in the steady-state conditions. The distribution of withdrawal among model layers was based on the reported depths of public-supply and domestic wells, the estimated depths of irrigation wells, and the hydrogeologic framework, as reported in from Savoca and others (2010). Public-supply withdrawals were assigned to model layers using well construction records (depth of open interval) from the Sentry system maintained by the Washington State Department of Health (accessed January, 2010, at <https://fortress.wa.gov/doh/eh/portal/odw/si/Intro.aspx>) to identify the corresponding hydrogeologic unit and model layer ([table 1](#)). Model layer assignments for public water supply wells were confirmed, when possible, by hydrogeologic interpretations of drillers' logs, or by personal communications with the purveyor. Domestic well withdrawals were assigned to model layers using well construction records (depth of open interval) obtained from the Tacoma–Pierce County Health Department (Brad Costello, written commun., 2010).

Locations of irrigation wells were obtained from a 2008 crop distribution database for Pierce County as compiled by the Washington State Department of Agriculture (accessed April, 2009 at <http://www.agr.wa.gov/PestFert/natresources/AgLandUse.aspx>), and withdrawals were assigned to model layers based on the assumption that most irrigation wells in the model area withdraw water from the first reliable source of water encountered during well drilling, typically the advance outwash aquifer (A3 aquifer) where it is present, or the alluvial valley aquifer (AL aquifer), in the Puyallup Valley where many of the irrigation wells are located. This assumption is supported by the inventory of well records compiled by Savoca and others (2010), in which most of the wells in the model area were open to the A3 aquifer. Therefore, irrigation well withdrawals were assigned to the A3 or AL aquifers, if present (generally using the middle layer of the AL aquifer, which normally spanned three model layers). In a few cases in which an aquifer was not present, irrigation well withdrawals were assigned to the A2 confining unit.

Groundwater withdrawals in 2007 are estimated to be about 48,000 acre-ft from wells in the 491 mi² model area, a value which is less than the 58,500 acre-ft estimated by Savoca and others (2010) for their 432 mi² water-budget area. Refinements in public-water withdrawal estimates and the exclusion of withdrawals from wells in bedrock units resulted in a decrease in total estimated groundwater withdrawals from the model area.

Figure 4. Distribution of average annual groundwater recharge from precipitation and return flow, Chambers-Clover Creek watershed and vicinity, Washington.

Figure 5. Distribution of average annual groundwater recharge from return flow (septic, outdoor use, and conveyance loss), Chambers-Clover Creek watershed and vicinity, Washington.

Figure 6. Temporal discretization of selected model values, Chambers-Clover Creek watershed and vicinity, Washington.

Groundwater withdrawals for Group A (15 or more connections, or at least 25 residents) and for Group B (fewer than 15 connections or less than 25 residents) public water-supply systems (43,540 acre-ft) were estimated using typical per capita water-use rates of 138 and 109 gal/d, respectively. These typical use rates were based on reported withdrawals from several public water purveyors in the area, and groundwater withdrawal and use data collected by the USGS (Ron Lane, written commun., 2009). Well withdrawals for transient conditions were calculated by multiplying steady-state withdrawals by a monthly factor derived from reported monthly withdrawals from public water purveyors in the area (Ron Lane, written commun., 2009) to account for year-round indoor use of about 173 gal/d per connection, and summertime outdoor water use that reaches a maximum of about 205 gal/d per connection in July (fig. 6). Public water-supply system service populations were obtained from the Washington State Department of Health SENTRY public water system database (accessed January 2010, at <https://fortress.wa.gov/doh/eh/portal/odw/si/Intro.aspx>). Self-supplied domestic groundwater withdrawals (305 acre-ft/yr) were estimated using a typical per capita water use rate of 228 gal/d per connection, and a database of the individual wells in the area (Brad Costello, Tacoma–Pierce County Health Department, oral. commun., 2010).

Groundwater withdrawals for the irrigation of golf courses, cemeteries, and agricultural crops (4,018 acre-ft/yr) were estimated using crop irrigation requirement (CIR) rates based on crop type and irrigation method from the Washington State Department of Agriculture (accessed April 2009, at <http://www.agr.wa.gov/pestfert/natresources/giscropdata.aspx>). Monthly variations in crop irrigation were based on the irrigation needs for turf obtained from the Washington State Department of Agriculture Irrigation Guide: Appendix A (accessed April 2009, at http://www.wa.nrcs.usda.gov/technical/ENG/irrigation_guide/index.html) since many of the reported irrigation wells were for golf courses.

River Package

The River Package was used to represent the exchange of water between rivers and lakes and the aquifer system. Model cells used in the River Package are shown in figure 2. In the River Package, a river reach refers to the section of a river within a model cell. For a river reach, the volumetric flow rate across the riverbed to the underlying model cell is computed as

$$Q_{rb} = C_{rb} (h_r - h_a), \quad (1)$$

where

Q_{rb} is the flow rate across the riverbed (ft³/day),
 C_{rb} is the conductance of the riverbed (ft²/day),
 h_r is the river stage (ft), and
 h_a is the hydraulic head (ft) in the cell underlying the riverbed when the bottom of the riverbed is below the water table in the cell; h_a is the altitude of the bottom of the riverbed (ft) when the bottom of the riverbed is above the hydraulic head in the cell.

The conductance of the riverbed is given by

$$C_{rb} = K_v w L / m, \quad (2)$$

where

K_v is the vertical hydraulic conductivity of the riverbed sediment (ft/day),
 w is the width of the river reach (ft),
 L is the length of the river reach (ft), and
 m is the thickness of the riverbed sediment (ft).
 Conductance of the riverbed, C_{rb} , is specified in the model.

River stage was estimated using Light Detection and Ranging (LiDAR) derived altitudes along river channels (accessed January 2010 at <http://pugetsoundlidar.ess.washington.edu/>). Riverbed conductance was computed from the channel area and estimates of the riverbed thickness and vertical hydraulic conductivity. The channel area within a model cell was calculated by summing area calculations for the short line segments in that cell. The width of the river channel at any point was based on the National Hydrography Dataset (accessed January 2010 at <http://nhd.usgs.gov/index.html> and NHD Plus, <http://www.horizon-systems.com/nhdplus/>) and those widths were confirmed by river cross-section measurements at stream gages and at stream base-flow measurement sites (Savoca and others, 2010). The thickness of the riverbed at any point was estimated as a function of the depth of the river at the point, based on depth measurements at gage and baseflow sites (Savoca and others, 2010). The vertical hydraulic conductivity of the riverbed was based on the vertical hydraulic conductivity of the hydrogeologic unit underlying each river reach (Savoca and others, 2010).

The riverbed conductances of all river channels in a model cell were summed to get the total riverbed conductance for that cell; river stage in the cell was based on the average of LiDAR- derived altitudes for the river points in the cell. In the transient calibration, the widths of rivers (except the Puyallup and Nisqually River) were estimated to vary seasonally according to variations in streamflows measured at several stream-gage sites in the model area, and riverbed conductance values were adjusted during model calibration by a monthly river stage factor (fig. 6) to reflect temporal changes in river width. Temporal changes in river depth also were adjusted, by the same factor for changes in stage.

An average steady-state river stage was assigned to each model cell along the Puyallup and Nisqually Rivers for the steady-state period, based on LiDAR measurements, as had been done for all the other river cells. These river stage values for the Puyallup and Nisqually Rivers were then modified in the transient calibration, using a linear interpolation of variations of the monthly river stages between USGS monthly gage data, including an unchanging sea-level stage at the mouths of the rivers. (Tidal levels in Puget Sound were considered to change too rapidly to include in the monthly time-step data.) The width and depth of the Puyallup and Nisqually Rivers were estimated based on the National Hydrography Dataset and confirmed by surveyed cross-section data by Czuba and others (2010). Widths of these major rivers were not changed in the transient calibration, but the stages were adjusted from gage data, as discussed above.

The River Package also was used to represent the exchange of water between the aquifer system and lakes that receive inflow from and (or) provide outflow to streams (Spanaway, Steilacoom, American, and Sequim Lakes, and several smaller lakes). Transient variations in lake stage were based on water levels recorded by the Pierce Conservation District Stream Team and Lakewood Water District (Robinson Noble Inc., written commun., 2009) and were adjusted in accordance with the stages of the streams flowing into or out of them. The vertical hydraulic conductivity of lakebed sediments was based on the vertical hydraulic conductivity of the underlying hydrogeologic units. Lake depths reported by the Washington State Departments of Ecology (accessed April, 2009 at http://www.ecy.wa.gov/programs/eap/wsb/pdfs/WSB_43a_Book.pdf and http://www.ecy.wa.gov/programs/eap/wsb/pdfs/WSB_43c_Book.pdf) were used to identify hydrogeologic units beneath lakes.

Drain Package

The Drain Package is used to represent groundwater discharge to springs, and groundwater seepage along bluffs adjacent to the Puyallup and Nisqually River valleys and

bluffs along Puget Sound (fig. 2). The simulated volume of groundwater discharge at a drain cell is equal to the product of a drain conductance and the difference between the simulated water level in the drain cell and the drain altitude. The conductance of a drain cell is a function of the hydraulic conductivity of the surrounding hydrogeologic material and the cell geometry. Spring locations and discharge were compiled from previous investigations (Blair, 1929; Sceva and others, 1955; Walters and Kimmel, 1968; Jones and others, 1999). Drain altitudes were estimated using LiDAR-derived elevation values and information about the hydrogeologic unit that was most probably discharging water to the spring at that location.

General-Head Boundary Package

The General-Head Boundary Package is used to represent the exchange of water between the aquifer system and Puget Sound (fig. 2). An unquantified amount of groundwater flow out of the model occurs along the western extent of the model as submarine seepage to Puget Sound along part of the western extent of model layers 1, 4, 5, 6, 7, and 8 (hydrogeologic units AL, B, C, D, E, and F).

Groundwater flow into or out of each cell (Q_b) is computed as

$$Q_b = C_b (h_b - h_a), \quad (3)$$

where

- C_b is the boundary conductance (ft² per day),
- h_b is the hydraulic head on the outside of the model boundary (ft), and
- h_a is the hydraulic head in the model cell (ft).

The hydraulic head on the outside (h_b) of the model boundary for each cell was specified as sea level, adjusted according to the depth of Puget Sound at that location and the unit weight of sea water. The value of conductance (C_b) at general head boundary cells was based on the conductivity of the surrounding hydrogeologic material. The largest conductance values were assigned to cells representing aquifers in contact with Puget Sound (5,075,089 ft²/d in the AL aquifer unit); the lowest conductance values were assigned to cells representing confining units in contact with Puget Sound (33,026 ft²/d in the B confining unit).

Model Calibration

Model calibration is the adjustment of model parameters so that the differences (residuals) between measured and simulated groundwater levels and stream baseflows are minimized with respect to an objective function. This section of the report describes the method used for calibration, the calibration data, and the calibration results. The calibration is assessed by examining how well the simulated quantities fit the measured quantities from previous investigations (Justin and others, 2009; Savoca and others, 2010). Values of horizontal and vertical hydraulic conductivity and conductance values for the specified-flux boundary conditions were estimated through steady-state calibration, and values of specific storage were estimated through transient calibration.

Calibration Procedure

The parameter estimation program PEST (Doherty, 2005, 2006), enhanced with Pilot-Point Parameterization (Doherty, 2003; Doherty and others, 2010), Tikhonov Regularization (Doherty, 2003; Fienen and others, 2009) and Singular Value Decomposition (Doherty and Hunt, 2010), was used to calibrate the groundwater-flow model. PEST automatically adjusted model parameters (horizontal and vertical hydraulic conductivity, specific storage, and river, drain, seep, and general head boundary conductance) through a series of model runs. After each run, simulated groundwater levels and stream baseflows were compared to measured values. Model runs continued until the differences (residuals) between simulated and observed values were minimized. PEST implements a nonlinear least-squares regression method (Gauss-Marquardt-Levenberg) to estimate model parameters by minimizing the sum of squared weighted residuals (objective function):

$$\Phi = \sum_{i=1}^N (w_i r_i)^2, \quad (4)$$

where

- N is the number of measurements,
- w_i is the weight for the i^{th} measured quantity, and
- r_i is the i^{th} residual, defined as the i^{th} measured quantity minus the corresponding i^{th} simulated quantity.

Details of this method are given in the PEST user's manual (Doherty, 2005, 2006). The weight, w_i , reflects the uncertainty in a measurement and affects the importance of the i^{th} measured quantity in the regression. A measurement with a small uncertainty (large w_i) asserts a larger influence on the regression than does a measurement with a large uncertainty (small w_i).

Pilot-point parameterization was used to represent spatial heterogeneity in horizontal and vertical hydraulic conductivity and specific storage. Pilot points were evenly distributed over the entire model domain by hydrogeologic unit at 140 locations and were used as surrogate parameters at which values for horizontal and vertical hydraulic conductivity were estimated during steady-state calibration. These pilot points were supplemented with 42 additional pilot points at the locations of aquifer tests, and were assigned initial values of horizontal hydraulic conductivity based on the reported transmissivity and the estimated aquifer thickness at the aquifer test location. During transient calibration all 182 pilot point locations were used to estimate specific storage. Estimated values of horizontal and vertical hydraulic conductivity and specific storage at pilot points were interpolated to the entire model domain using kriging (a geostatistical algorithm) procedures in PEST in such a way that the heterogeneity in hydraulic conductivity and specific storage could be represented at a much lower computational cost than trying to estimate parameter values at every model cell.

Groundwater-flow models with many parameters are commonly affected by parameter insensitivity and correlation, which in turn lead to solution non-uniqueness and an ill-posed inverse problem. The Preferred-Homogeneity condition of Tikhonov regularization was used to mitigate these problems in the CCCW model. This approach facilitates geologic continuity where it is believed to exist but still allows heterogeneity to be expressed within hydrogeologic units as informed by groundwater-level and stream baseflow measurement values. Regularization using the preferred homogeneity condition attempts to minimize variation between values at pilot points within each hydrogeologic unit by penalizing deviations from "smoothness." Finally, the compromise between model fit and the preferred condition was initially weighted in favor of model fit and later weighted to favor the preferred condition (PEST variable PHIMLIM).

The Singular Value Decomposition-Assist (SVDA) method was used to reduce the number of estimated parameters, thereby speeding up the calibration process. For steady-state calibration the SVDA method identified 100 "super parameters" that are linear combinations of the original parameters and contribute most to changes (reductions) in the objective function; 30 super parameters were used for transient calibration because of the longer execution time for transient runs. The SVDA process calibrates to the best solution in terms of super parameters, and then assigns calibrated values to the original parameters. The advantage of SVDA is that fewer parameters (100 rather than 1,855 for the steady-state calibration) are required during model calibration so fewer model runs are needed, and the objective function converges more quickly.

The model was calibrated for steady-state and transient conditions separately. The steady-state calibration resulted in estimates of parameter values for

- Both horizontal and vertical hydraulic conductivity for each of the 10 hydrogeologic units at each of the pilot points, and estimates of parameter values for each active model cell;
- River conductance in each of eight surface-water subbasins: Puyallup River; tributaries to Puyallup River; north Tacoma; Chambers–Clover Creek; American Lake–Murray Creek; Sequelitchew Creek; Nisqually River; tributaries to Nisqually River;
- General Head Boundary conductance for each of the six hydrogeologic units that are in contact with Puget Sound (AL, B, C, D, E, and F);
- Drain conductance for springs and seeps.

The aquifer properties were allowed to vary during model calibration within two orders of magnitude above the initial specified value and within one order of magnitude below the initial specified value. The steady-state calibration used as observations (“calibration targets”) both the measured water-level altitudes from synoptic and monthly monitoring wells ([table 13](#), at end of report), as well as the estimated stream baseflow measurements (Savoca and others, 2010). Parameter value distributions from the steady-state PEST calibration were then used in the transient PEST calibration. The transient calibration allowed specific storage to vary within one order of magnitude above the initial specified value and within one order of magnitude below the initial specified value. After the transient calibration using PEST, the model was run again in the steady-state mode to generate subsequent steady-state model results.

Calibration Data

The groundwater-flow model was calibrated to groundwater-level and stream baseflow measurements. The steady-state calibration used the average values for these measurements, and the transient calibration used each of the monthly water-level and baseflow measurements. Water-level measurements within the model domain from Savoca and others (2010) were used for calibration and include: (1) monthly water-level measurements for 124 monitoring wells (monthly wells) from March 2007–August 2008, and (2) synoptic water-level measurements for 99 wells measured during September–December 2006. Pierce County Surface Water Management Division provided monthly water-level measurements (January 2007–August 2008) for 4 monitoring wells (Rodney Gratzner, written commun., 2009) that also were used for calibration.

A total of 2,355 groundwater-level measurements were used in the model calibration, including water levels that

were influenced by conditions at the time of measurement (pumping, recovering, nearby pumping, nearby recovering, or flowing). Water-level measurements for each monthly well were averaged to determine the steady-state calibration target value for that well. Groundwater levels, as depth below land surface, were converted to a water level altitude, according to the North American Vertical Datum of 1988, based on the LiDAR-derived land surface altitude at the location of the well. The average water levels for monthly wells and the single water-level measurements for synoptic wells used during model calibration for each hydrogeologic unit are reported in [table 13](#). Wells used to measure water levels were located within a model cell at a location given by the measured latitude and longitude of the well. The reported depth of the well screen and the well log were used to determine the model layer that represented the hydrogeologic unit screened by the well.

Stream baseflow at 51 locations was measured during two synoptic streamflow measurements (September 2007 and July 2008) to identify gaining and losing reaches along segments of major streams in the model area. Stream baseflow measurement locations and discharge values used during calibration are given in Savoca and others (2010, pl. 1 and table 5, respectively). Stream baseflow measurements and estimates of stream gains and losses were used in the calibration process to assess whether the simulated pattern of gains and losses matched measured gains and losses. The estimates of stream gains and losses derived from stream baseflow measurements were compared with model-derived gains and losses for each stream reach.

Weights for Measured Quantities

In PEST, weights are assumed to be proportional to the inverse of the standard deviation of measurement error (Doherty 2005; Hill and Tiedeman, 2007). Because measurement error was not well defined weights were assigned to calibration data (groundwater-level and stream baseflow) to reflect the approximate accuracy of each of the measurements. The weights ([table 13](#)) were assigned according to a relative scale from 1 to 10. For the steady-state calibration the most accurate monthly measurements were assigned a weight of 10. Weights were reduced for less accurate measurements that were affected by conditions at the time of measurement (pumping, recovering, nearby pumping, nearby recovering, or flowing). Most wells with monthly data had between 17 and 20 measurements; if the number of “most accurate” measurements associated with a well was between 10 and 15, the weight assigned to the average measurement was reduced to 9, if the number of “most accurate” measurements was less than 10, the weighting of the average was reduced to 8. Synoptic wells, with only one or two measurements, were assigned a default weight of 3, which was in some cases reduced to 2 or 1 if the measurement (s) were “less accurate”.

For the transient calibration, each monthly water-level measurement was included as a separate observation, with the most accurate monthly measurements assigned a weight of 10. The weights were reduced for less accurate measurements that were impacted by conditions at the time of measurement as follows: 5 for flowing, 4 for nearby pumping or nearby recovering, and 3 for pumping or recovering. Transient calibration weights also were assigned to differences between monthly water-level measurements used to represent seasonal water-level fluctuations in the model, and weighted according to the accuracy of the measurements. Estimates of stream baseflow were included in both steady-state and transient calibrations. The average of the two baseflow measurements (September 2007 and July 2008) at each baseflow location was used in the steady-state calibration; each of the two baseflow measurements was included as a separate observation for the transient calibration. These measurements were weighted according to the rankings assigned to each baseflow measurement (Savoca and others, 2010), and weighted with an additional factor of 0.0005 to account for (1) different measurement units (cubic feet per day rather than feet used for the altitude of water-level measurements), and (2) the greater uncertainty (standard deviation) associated with baseflow measurements. The different weighting factors used for water-level, water-level difference, and baseflow measurements also served to balance the contribution of each type of observation to the overall objective function, so that each would be considered in the calibration process (for example, the magnitude of the weighted residuals were similar for each type of observation).

[Table 13](#) shows the wells that were used for the calibration and their assigned steady state calibration weighting factors, the total number of transient observations, and the number of observations that were reduced on the basis of the status of the water-level reading. For the wells that were used for the transient calibration, the table shows the number of observations and the mean weighting factor for the observations in that well. The locations of the wells (as identified by the well map numbers in [table 13](#)) are shown in [figure 7](#).

Initial Conditions

Initial conditions refer to the distribution of water levels in the groundwater system at the beginning of the transient calibration period (September 2006–August 2008). Initial conditions were established through transient simulation of a 3-year “lead-in” period (September 2003–August 2006). The lead-in period simulation is designed to isolate the transient calibration from potential inaccuracies associated with initial transient calibration start-up. Temporal discretization of the lead-in period comprised 36 monthly transient stress periods in which specified recharge was based on measured precipitation. Well withdrawals (and return flows) were represented by adjusting withdrawal rates to reflect population change during

the lead-in period. Temporal fluctuations in Puyallup and Nisqually River stage were obtained from USGS records, and temporal fluctuations in other model boundary conditions (other streams and lakes) were patterned after fluctuations delineated for the calibration period. Starting heads for the beginning of the lead-in period (September 1, 2003) were derived from early calibration transient output for September 1, 2008 to provide representative transient water-level conditions.

Parameter Sensitivity

Sensitivity is the relative effect that changes in an individual parameter value has on the overall objective function. Because SVDA and “super parameters” were used for both steady-state and transient calibration, sensitivities for the original PEST parameters were not determined during the calibration process itself. However, an additional PEST run was conducted after completion of the steady-state and transient calibration to determine sensitivities for all original PEST parameters. The composite sensitivities of the parameters to the overall objective function including head (water level), head difference, and stream-baseflow target values, are shown in [figure 8](#). Horizontal and vertical hydraulic conductivity (K_h and K_v), and specific storage (and equivalent specific yield) parameter sensitivities were determined at 182 pilot point locations distributed throughout the model domain; [figure 8](#) contains the median value of pilot point sensitivities for each conductivity and storage parameter by hydrogeologic unit. The wide range of sensitivities dictated that a logarithmic scale be used to represent sensitivity values. Because the objective function is nominally scaled by the weighting factors (as inverse standard deviations) and because the parameter changes are produced on a logarithmic (multiplicative factor) basis, the sensitivity can be considered non-dimensional. The values of insensitive parameters (such as vertical hydraulic conductivity in the A1 aquifer unit) remain largely unchanged during the PEST calibration process. Therefore, the insensitivity of these parameters places greater importance on the initial values assigned to them.

Results from the steady-state sensitivity analysis ([fig. 8A](#)) indicate that the model is most sensitive to river conductance parameters Rv4 (conductance in Swan, Clear, and Clarks Creeks) and Rv6 (conductance in Chambers–Clover Creek), and slightly less sensitive to Rv0 (American Lake–Murray Creek) and Rv2 (tributaries to Nisqually River). The least sensitive river conductance parameters (Rv3, Puyallup River and Rv7, North Tacoma) coincide with model areas containing fewer groundwater level and streamflow measurements. The model also is sensitive to values of horizontal hydraulic conductivity (K_h), particularly in aquifer units AL, A1, A3, and C. Sensitivities to vertical hydraulic conductivity (K_v) generally are much lower than corresponding horizontal hydraulic conductivity values, but are most significant in confining units A2 and B. The steady-state calibration is

Figure 7. Locations of wells used in model calibration, Chambers-Clover Creek watershed and vicinity, Washington.

Figure 8.—Continued

relatively less sensitive to general head (ghc) and drain (dr) conductance parameters.

Results from the transient sensitivity analysis (fig. 8B) indicate that the model is most sensitive to river conductance parameters Rv4 (conductance in Swan, Clear, and Clarks Creeks), and Rv6 (conductance in Chambers–Clover Creek), and least sensitive to river conductance parameters Rv3 (Puyallup River), and Rv7 (North Tacoma). The model also is sensitive to values of: (1) horizontal hydraulic conductivity (K_h), particularly in aquifer units AL, A1, and C, and the undifferentiated deposit (unit G); (2) vertical hydraulic conductivity (K_v), particularly in confining units A2 and D; and (3) spring (dr1) and seep (dr2) drain conductance values. The transient calibration is less sensitive to storage parameters and general head boundary conductances (ghc).

Final Parameter Values

Final parameter value distributions were determined from the steady-state and transient PEST calibration process for each model parameter. Final value distributions of horizontal conductivity (figs. 22A–J, at back of report), vertical hydraulic conductivity (figs. 22K–T, at back of report) and specific storage (figs. 22U–DD, at back of report) are summarized in table 5. Median calibrated horizontal hydraulic conductivity values in aquifer units (table 5) ranged from 21 ft/d in aquifer unit E to 153 ft/d in the A1 aquifer unit. Median calibrated horizontal hydraulic conductivity values in confining units ranged from 1.9 ft/d in the A2 and B units to 2.9 ft/d in the D and F confining units. The median calibrated horizontal hydraulic conductivity value of the undifferentiated deposit (unit G) was 4.0 ft/d. Median calibrated horizontal hydraulic conductivity values are lower than initial estimates (table 4), but follow a similar pattern of higher conductivity values for aquifers and lower values for confining units (Savoca and others, 2010).

Median calibrated vertical hydraulic conductivity values in aquifer units (table 5) ranged from 2.0 ft/d in aquifer units C and E to 10 ft/d in the A1 aquifer unit. Median calibrated vertical hydraulic conductivity values in confining units ranged from 0.017 ft/d in the B unit to 0.031 ft/d in confining unit D. The median calibrated vertical hydraulic conductivity value of the undifferentiated deposit (unit G) was 0.099 ft/d. Median calibrated vertical hydraulic conductivity values are lower than initial estimates (table 4), but follow a similar pattern of higher conductivity values for aquifers and lower values for confining units (Savoca and others, 2010).

Median calibrated specific-storage values for aquifer units (table 6) ranged from 1.44×10^{-6} ft⁻¹ in aquifer unit E to 5.53×10^{-3} ft⁻¹ in aquifer unit A1. Median calibrated specific storage values for confining units ranged from 5.52×10^{-6} ft⁻¹

in the F unit to 2.74×10^{-5} ft⁻¹ in confining unit B. The median calibrated specific storage value of the undifferentiated deposit (unit G) was 3.0×10^{-7} ft⁻¹. Median calibrated specific storage values are lower than initial estimates (table 4) for units AL, A1, D, F, and G, and higher than initial estimates for units A2, A3, B, C, and E.

Calibrated General Head Boundary conductance values (table 5) for each of the six hydrogeologic units that surface under Puget Sound (AL, B, C, D, E, and F) ranged from 3.30×10^{-4} ft²/d in unit B to 5.08×10^{-6} ft²/d in the AL aquifer unit. Calibrated General Head Boundary conductance values are lower than initial estimates (table 4).

The final calibrated distribution of riverbed conductance is shown in figure 9, and is summarized in table 5 for eight surface-water subbasins delineated in the model area. Median calibrated riverbed conductance values ranged from 1.9 ft²/d (Rv3) to 2.04×10^6 ft²/d (Rv0). Median calibrated riverbed conductance values are lower than initial estimates for subbasins Rv0, Rv2, Rv3, Rv5, and Rv7, and higher than initial estimates for subbasins Rv1, Rv4, and Rv6.

The median calibrated drain conductance value for springs (Dr1) and seeps (Dr2) was 0.17 and 0.20 ft²/d, respectively (table 5). Median calibrated drain conductance values are lower than initial estimates for both springs and seeps.

Assessment of Steady-State Calibration

The results of the steady-state calibration were assessed by comparing measured and simulated quantities (groundwater levels and stream baseflows) and by examining the mean and standard deviation of residuals (un-weighted), objective function, and root mean-square error (RMSE) of weighted residuals for average monthly and individual synoptic groundwater levels, and average baseflow gains or losses. The mean of residuals represents the average difference between all measured and simulated values (residuals), and the sign of the mean of residuals (bias) indicates whether the model is over- or under-predicting values (negative and positive mean of residuals, respectively). The standard deviation of residuals is a measure of how much variation there is in residual values above and below the mean residual value. A low standard deviation indicates that the residuals tend to be very close to the mean, whereas high standard deviation indicates that residuals are spread out over a large range of values around the mean. The objective function represents the weighted total of all squared residuals, and the magnitude of the objective function is a measure of the cumulative difference between all measured and simulated values. The RMSE of weighted residuals provides a measure of variation that considers measurement accuracy.

Table 5. Final parameter values and factors used in the steady-state and transient calibrations, Chambers-Clover Creek watershed and vicinity, Washington.

[Abbreviations: K_h , horizontal hydraulic conductivity; K_v , vertical hydraulic conductivity; HGU, hydrogeologic unit; GHB, general head boundary; ft, feet; ft/d, feet per day; 1/ft, per foot; ft²/d, square feet per day]

Hydro-geologic unit	K _h (ft/d)			K _v (ft/d)			Specific storage (1/ft)			GHB conductance (ft ² /d)		
	Median	Mini-mum	Maxi-mum	Change from initial estimate	Median	Mini-mum	Maxi-mum	Change from initial estimate	Median	Mini-mum	Maxi-mum	Change from initial estimate
AL	42	3.28	3,280	× 0.13	3.1	0.328	328	× 0.093	1.90E-03	1.00E-03	1.00E-01	× 0.190
A1	153	9.33	9,330	× 0.16	10	8.33	54	× 0.108	5.53E-03	1.00E-03	1.00E-01	× 0.553
A2	1.9	0.18	180	× 0.10	0.022	0.002	1.8	× 0.110	1.40E-05	1.00E-06	1.00E-04	× 1.40
A3	85	5.88	5,880	× 0.15	6.0	0.588	19	× 0.102	2.48E-06	1.00E-07	1.00E-05	× 2.48
B	1.9	0.21	12	× 0.09	0.017	0.002	2.1	× 0.083	2.74E-05	1.00E-06	1.00E-04	× 2.74
C	32	0.60	9,913	× 0.16	2.0	0.198	198	× 0.102	1.74E-06	1.00E-07	1.00E-05	× 1.74
D	2.9	0.29	107	× 0.10	0.031	0.003	2.9	× 0.103	6.09E-06	1.00E-06	1.00E-04	× 0.609
E	21	2.14	2,140	× 0.10	2.0	0.393	3.5	× 0.095	1.44E-06	1.00E-07	1.00E-05	× 1.44
F	2.9	1.31	14	× 0.10	0.030	0.013	0.136	× 0.099	5.52E-06	1.00E-06	1.00E-04	× 0.552
G	4.0	0.39	450	× 0.10	0.099	0.013	0.587	× 0.076	3.00E-07	3.00E-07	3.00E-05	× 0.100

River conductance				
River parameter group	Sub-basin	Median cell value (ft ² /d)	Minimum cell value (ft ² /d)	Maximum cell value (ft ² /d)
Rv0	American Lake-Murray Creek	2.04E6	2,392	5.36E6
Rv1	Nisqually River	2.96E5	555	1.29E6
Rv2	Tributaries to Nisqually River	22	0.021	16,603
Rv3	Puyallup River	1.9	0.009	3.6
Rv4	Tributaries to Puyallup River	4.10E5	1,540	2.29E8
Rv5	Sequalitchew Creek	917	115	4.48E5
Rv6	Chambers-Clover Creek	8.05E4	86	5.72E7
Rv7	North Tacoma	30	0.043	44

Drain conductance				
Drain parameter group	Drain feature	Median cell value (ft ² /d)	Mini-mum cell value (ft ² /d)	Maxi-mum cell value (ft ² /d)
Dr1	Springs	0.17	0.003	10
Dr2	Seeps	0.20	0.038	1.4

Change from initial estimate		
× 0.53	× 25.2	× 1.60E ⁻³
× 1.70E ⁻⁴	× 73.4	× 0.051
× 5.04	× 3.10E ⁻³	

Change from initial estimate		
× 0.153	× 0.166	× 0.103
× 0.137	× 0.103	× 0.121

Figure 9. Final parameter value distribution of river conductance (Puyallup River; tributaries to Puyallup River; north Tacoma; Chambers-Clover Creek; Murray Creek-American Lake; Sequalichew Creek; Nisqually River; tributaries to Nisqually River), Chambers-Clover Creek watershed and vicinity, Washington.

Table 6 shows the steady-state calibration statistics for groundwater-levels (by hydrogeologic unit) and stream baseflow gains or losses. Calibration statistics were used to evaluate how well the model simulates measured values (fit). The best fit for simulated and measured groundwater-level values based on RMSE occurred in hydrogeologic units D, AL, and G; the worst fit occurred in hydrogeologic units A3, E, and A2. Hydrogeologic units A3, A1, and G had the lowest absolute value of mean residuals, indicating simulated groundwater-levels in these units had the lowest model bias. The final steady-state calibration has an RMSE for all groundwater levels and stream baseflows of 24.29 ft and 1.82 ft³/s, respectively. Given that the total range of average measured groundwater levels is about 843 ft (853.61 ft in well #154 – 10.95 ft in well #4) an RMSE of 24.29 ft is about 3 percent of the total range. Similarly, the range of average stream baseflow measurements is 63.5 ft³/s (55 ft³/s gaining at seepage run location 12102010 – losing 8.5 ft³/s at gage 12102075) and an RMSE of 1.82 is about 3 percent of the total range.

A plot of measured versus simulated groundwater-level altitudes by hydrogeologic unit (fig. 10) provides a useful graphical assessment of model calibration. Measured versus simulated values should plot close to a line with a slope equal to 1.0 and an intercept of zero. This diagonal line represents perfect agreement between measured and simulated values (the line of equal measured and simulated values), and the magnitude of the residual (difference between measured and simulated values) is reflected in the distance of the value above or below the line. Positive residuals (measured value is greater than simulated) and negative residuals (measured value is less than simulated) plot below and above the line, respectively. Measured versus simulated values shown in figure 10 generally fall along the line of equal measured and simulated values. The magnitude and sign of residuals for selected hydrogeologic units is discussed later in this section of the report.

Table 6. Calibration statistics for the steady-state calibration by hydrogeologic unit and baseflow, Chambers-Clover Creek watershed and vicinity, Washington.

[Root mean-square error of weighted residuals is calculated by dividing the sum of squared weighted residuals by the sum of squared weighting factors, then taking the square root. **Abbreviations:** ft, feet; ft², square feet; NA, not applicable]

Hydrogeologic unit observation group	Count of observations	Mean of unweighted residuals (ft)	Standard deviation of unweighted residuals (ft)	Sum of squared weighting factors	Objective function (sum of squared weighted residuals) (ft ²)	Root mean- square error of weighted residuals (ft)
Heads in AL	26	-5.66	9.71	793	89,174	10.60
Heads in A1	26	-3.84	19.92	1,778	263,500	12.17
Heads in A2	14	7.40	26.17	909	628,905	26.30
Heads in A3	84	0.80	38.09	4,471	5,075,077	33.69
Heads in B	3	16.19	13.70	281	114,667	20.20
Heads in C	61	-9.20	20.85	3,847	850,320	14.87
Heads in D	1	-6.43	NA	100	4,130	6.43
Heads in E	9	5.17	29.83	655	681,665	32.26
Heads in G	3	-4.44	13.72	300	43,534	12.05
Total: All heads	227	-2.48	28.42	13,134	7,750,974	24.29
Baseflow gain or loss observation group	50	0.23 (ft ³ /s)	2.12 (ft ³ /s)	6.53×10 ⁻⁴	16,137,000 (ft ³ /d) ² or 2.16 × 10 ⁻³ (ft ³ /s) ²	1.82 (ft ³ /s)

Figure 10. Simulated and average measured water-level altitudes for the steady-state calibration, Chambers-Clover Creek watershed and vicinity, Washington.

The results of the steady-state calibration also were evaluated by displaying the simulated water levels (heads) in each model cell for aquifer units and G undifferentiated deposits ([figs. 23A–F](#), at back of report). The residuals (measured target value minus model-simulated value in that well) for each of the monthly and synoptic wells screened in the hydrogeologic unit are posted at well locations. Simulated steady-state groundwater-level altitudes and flow directions ([figs. 23A–F](#)) agree generally with groundwater conditions observed by Savoca and others (2010, figs. 16–21).

Simulated steady-state groundwater-level altitudes in the AL alluvial valley aquifer beneath the Puyallup River valley ([fig. 23A](#)) indicate flow generally moving in a northwesterly down-valley direction towards Puget Sound. Maximum positive and negative groundwater-level altitude residuals in the AL alluvial valley aquifer beneath the Puyallup River valley are 18 and -26 ft, respectively. Simulated groundwater-level altitudes in the AL alluvial valley aquifer beneath the Nisqually River valley ([fig. 23A](#)) also indicate flow generally moving in a northwesterly down-valley direction towards Puget Sound. No data were collected from the aquifer in this area (Savoca and others 2010), therefore residuals were not computed.

Simulated groundwater-level altitudes in the A1 and A3 aquifers ([figs. 23B](#) and [23C](#), respectively) indicate flow generally moving in a northwesterly direction towards Puget Sound. Simulated groundwater-level altitudes also indicate northeast and westward flows toward the Puyallup and Nisqually River valleys, respectively. Maximum positive and negative groundwater-level altitude residuals in the A1 aquifer are 64 and -37 ft, respectively, and in the A3 aquifer are 180 and -111 ft, respectively.

Simulated groundwater-level altitudes in the C and E aquifers ([figs. 23D](#) and [23E](#), respectively) indicate flow generally moving in a northwesterly direction towards Puget Sound. Simulated groundwater-level altitudes also indicate northeast and westward flows toward the Puyallup and Nisqually River valleys, respectively. Maximum positive and negative groundwater-level altitude residuals in the C aquifer are 61 and -87 ft, respectively, and in the E aquifer are 72 and -28 ft, respectively.

Simulated groundwater-level altitudes in the G undifferentiated deposits ([fig. 23F](#)) indicate flow generally moving in a northwesterly direction towards Puget Sound. Simulated groundwater-level altitudes also indicate northeast and westward flows toward the Puyallup and Nisqually River valleys, respectively. Maximum positive and negative groundwater-level altitude residuals in the G undifferentiated deposits are 11 and -15 ft, respectively.

The steady-state calibration also was evaluated for how well it simulated flow out of the model through boundary conditions. A water budget for the steady-state calibration is presented in section, “[Model-Derived Groundwater Budget](#),” as calculated by the MODFLOW utility Zonebudget (Harbaugh, 2000). Groundwater recharge and well withdrawals were determined outside the model and were assigned fixed values as model input; groundwater discharge to rivers, lakes, and springs, and flow out of the model to Puget Sound were simulated in the model according to head-dependent boundary conditions.

A comparison of the measured and simulated groundwater discharge to streams (baseflow) in the model area was based on synoptic stream baseflow measurements conducted in September 2007 and July 2008 (Savoca and others, 2010). Time-averaged stream gain and loss values derived from baseflow measurements from 51 measurement sites (Savoca and others, 2010, pl. 1 and table 5) were compared to simulated stream gain and loss values derived from simulated groundwater discharge to streams at the same locations ([fig. 11](#)). Stream gains and losses are reasonably well simulated by the steady-state calibration, however, there are a few locations in the Chambers-Clover Creek Watershed (WRIA12) where the model simulates a net loss of streamflow but small net gains in streamflow were measured during synoptic stream baseflow measurements (Savoca and others, 2010). There also is one location in the Puyallup River Watershed (WRIA 10) where the model simulates a net gain of streamflow but a small net loss in streamflow was measured during synoptic stream baseflow measurements (Savoca and others, 2010).

Figure 11. Simulated and average measured stream baseflows for the calibrated model for steady-state conditions, Chambers–Clover Creek watershed and vicinity, Washington.

Assessment of Transient Calibration

The results of the transient calibration were assessed by comparing measured and simulated quantities (groundwater levels and stream baseflows) and by examining the mean and standard deviation of residuals (un-weighted), objective function, and RMSE of weighted residuals for: (1) all individual synoptic and monthly groundwater-level measurements; (2) groundwater-level differences to represent seasonal water-level fluctuations above and below the initial groundwater-level measurement for each monthly well; and (3) baseflow gains or losses for September 2007 and July 2008 (table 7).

The best fit between simulated and measured groundwater-level head values based on RMSE occurred in hydrogeologic units D, AL, and A1; the worst fit occurred in hydrogeologic units E, A3, and A2. These same units were among the best and worst fit, respectively, for simulated and measured groundwater-level head difference values based on RMSE. Hydrogeologic units AL, A1, A3, and E had the lowest absolute value of mean head and head difference residuals, indicating simulated groundwater-levels in these units had the lowest model bias. The final transient calibration has an RMSE for all groundwater-level head, head difference, and stream baseflows of 22.59 ft, 5.82 ft, and -2.51 ft³/s, respectively. Given the total range of measured values for these observation groups (851.5 ft, 135.5 ft, and 68.4 ft³/s), the RMSE for head, head difference, and stream baseflows are 2.7, 4.3, and 3.7 percent of the total range.

Table 7. Calibration statistics for the transient calibration by hydrogeologic unit and baseflow, Chambers-Clover Creek watershed and vicinity, Washington.

[Root mean-square error of weighted residuals is calculated by dividing the sum of squared weighted residuals by the sum of squared weighting factors, then taking the square root. **Abbreviations:** ft, feet; ft², square feet; ft³/s, cubic feet per second]

Hydrogeologic unit observation group	Count of observations	Mean of unweighted residuals (ft)	Standard deviation of unweighted residuals (ft)	Sum of squared weighting factors	Objective function (sum of squared weighted residuals) (ft ²)	Root mean-squared error of weighted residuals (ft)
Heads in AL	138	-2.34	10.13	12,134	1,065,153	9.37
Heads in A1	323	0.44	11.15	31,663	3,983,952	11.22
Heads in A2	169	10.96	25.09	12,872	10,043,721	27.93
Heads in A3	787	1.60	31.22	72,787	66,633,173	30.26
Heads in B	50	16.56	11.86	4,545	2,038,732	21.18
Heads in C	705	-4.36	13.32	64,206	12,671,574	14.05
Heads in D	18	-5.97	1.85	1,800	69,977	6.24
Heads in E	112	14.95	30.97	10,745	12,998,208	34.78
Heads in G	53	-2.76	12.04	5,300	794,085	12.24
Total: All heads	2,355	0.90	23.01	216,052	110,298,574	22.59
Head differences in AL	112	-0.37	1.23	1,200,925	2,224,021	1.36
Head differences in A1	297	0.23	2.84	3,507,313	23,194,476	2.57
Head differences in A2	155	0.81	6.88	1,420,850	74,552,544	7.24
Head differences in A3	703	-2.01	7.85	7,902,253	333,801,660	6.50
Head differences in B	47	-1.56	5.34	516,200	5,571,155	3.29
Head differences in C	644	0.82	6.77	7,058,931	296,428,333	6.48
Head differences in D	17	-0.71	1.89	205,700	797,886	1.97
Head differences in E	103	-0.47	6.44	1,204,300	51,526,875	6.54
Head differences in G	50	0.50	4.31	605,000	11,183,625	4.30
Total: All head differences	2,128	-0.39	6.59	23,621,472	799,280,575	5.82
Baseflow gain or loss observation group	96	-0.36 (ft ³ /s)	2.67 (ft ³ /s)	1.16 × 10 ⁻³	54,297,883 (ft ³ /s) or 7.27 × 10 ⁻³ (ft ³ /s)	-2.51 (ft ³ /s)

A plot of average measured versus average simulated groundwater-level altitudes values for the transient simulation period (September 2006–August 2008) by hydrogeologic unit ([figure 12](#)) generally fall along the line of equal measured and simulated values (slope equal to 1.0, intercept of zero). The magnitude of the residual (difference between measured and simulated values) is reflected in the distance of the value above or below the line. Positive residuals (measured value is greater than simulated value) and negative residuals (measured value is less than simulated) plot below and above the line, respectively.

The results of the transient calibration were evaluated by comparing measured and simulated groundwater-level hydrographs for selected wells ([fig. 13](#)). Measured water levels generally fluctuate in response to seasonal changes in recharge. Simulated water levels also fluctuate in response to seasonal variation in recharge and, in most cases, the magnitude and timing of these fluctuations are similar to the changes in measured water levels.

The transient calibration also was evaluated for how well it simulated groundwater discharge to streams during baseflow conditions. Stream gain and loss values derived from baseflow measurements conducted in September 2007 and July 2008 at 51 measurements sites (Savoca and others, 2010, pl. 1 and table 5) were compared to simulated stream gain and loss values derived from simulated groundwater discharge to streams at the same locations and times of year ([fig. 14](#)). Stream gains and losses are reasonably well simulated by the transient calibration, however, there are a few instances where the model simulates a net loss of streamflow but small net gains in streamflow were measured during synoptic stream baseflow measurements (Savoca and others, 2010). There also are a few instances where the model simulates a net gain of streamflow but small to moderate net losses in streamflow were measured during synoptic stream baseflow measurements (Savoca and others, 2010).

Model Limitations

The model presented in this report is a simplified mathematical representation of the complex natural groundwater-flow system in the CCCW and vicinity. Intrinsic to the model is the error and uncertainty associated with the approximations, assumptions, and simplifications that must be made. Although the model provides a relatively good fit between simulated and measured quantities, indicating that the overall simulated groundwater flow is a reasonable

representation of groundwater flow in the CCCW and vicinity, the model is subject to limitations. In general, because of model scale and level of detail, the model is most applicable to analysis of groundwater issues at the subbasin scale (see [fig. 9](#)). Local-scale heterogeneity in hydrologic properties, recharge, and discharge that occur at a scale of one model cell or less (1,000 ft or less) are not adequately represented by the regional-scale groundwater-flow model constructed for this study.

The data used to construct and calibrate the model reflect short-term conditions (September 2006–August 2008) and probably do not represent the full range of hydrologic and anthropogenic variability within the system. Boundary conditions and the representation of various components of the flow system that were appropriate for the calibrated range of conditions may be inappropriate for model simulations when conditions in the groundwater system are beyond the range used during calibration. There is no long-term ambient groundwater monitoring network in the model area, and data from the short-term (March 2007–September 2008) monthly monitoring network established for this study (Justin and others, 2009) are insufficient to evaluate water-level trends relating to long-term changes in groundwater storage, or for testing the assumption of steady-state conditions.

Measurement-based estimates of recharge were not available for the model area. The distribution of recharge from precipitation in the model area was estimated by applying regional precipitation–recharge relations based on regression equations for unconsolidated glacial deposits in other areas of Puget Sound. The lack of available Group B public supply, residential, and crop irrigation well withdrawal data (few wells have flow gages installed or read) required the use of per-capita and crop irrigation requirement water-use estimates. Uncertainty also exists regarding estimates of residential return flows to the aquifer through septic system drain fields, and through outdoor (irrigation) use.

Model Applications

The calibrated model was used to derive components of the groundwater budget and to estimate the response of the regional system to new stresses, such as increased groundwater withdrawals. Water-resource managers can use this information to make informed decisions when planning for future groundwater development. The uncertainty associated with inaccuracies in the groundwater-flow model is carried forward to the model applications.

Figure 12. Average simulated and average measured water-level altitudes for the calibrated model for transient conditions, Chambers-Clover Creek watershed and vicinity, Washington.

Figure 13. Simulated and measured groundwater levels for the calibrated model for transient conditions, Chambers–Clover Creek watershed and vicinity, Washington.

Figure 13.—Continued.

Figure 13.—Continued.

Figure 13.—Continued.

Figure 14. Simulated and measured stream baseflows for the transient calibration, Chambers–Clover Creek watershed and vicinity, Washington.

Model-Derived Groundwater Budget

A groundwater budget for average conditions during the study period (September 1, 2006–August 31, 2008) in the model area is expressed by the following equation:

$$GW_{in} + R = GW_{out} + D + \Delta S, \quad (5)$$

where

GW_{in} is groundwater inflow to the model area,

GW_{out} is groundwater outflow from the model area,

R is recharge,

D is discharge, and

ΔS is change in groundwater storage.

Recharge to the groundwater system occurs primarily as precipitation and seepage from streams and lakes. Secondary recharge (return flow) occurs as seepage from septic systems, deep percolation of irrigation water, and public water system conveyance losses. Discharge from the groundwater system occurs as seepage to streams and lakes, and groundwater seepage along bluffs adjacent to the Puyallup and Nisqually River valleys and bluffs along Puget Sound, as evaporation of groundwater from soils and transpiration from plants, as submarine seepage to Puget Sound, and as withdrawals from wells. A more detailed representation of the groundwater budget of the model area is provided by the equation:

$$GW_{in} + R_{ppt} + R_{sw} + R_{sec} = GW_{out} + D_{sw} + D_{et} + D_{ppg} + \Delta S, \quad (6)$$

where

R_{ppt} is recharge from precipitation,

R_{sw} is recharge from streams, lakes, and Puget Sound,

R_{sec} is secondary recharge,

D_{sw} is groundwater discharge to streams, lakes, springs, seeps, and Puget Sound,

D_{et} is groundwater discharge by evapotranspiration, and

D_{ppg} is groundwater withdrawal from wells.

All water-budget components can be quantified on the basis of the steady-state calibration except discharge by evapotranspiration and change in groundwater storage.

Net recharge was used; therefore, water lost to the system through direct evapotranspiration of groundwater is largely taken into account, and D_{et} is not calculated in the model. Inflow to the system is assumed to be equal to outflow from the system under steady-state conditions, resulting in no change in the volume of water stored within the system ($\Delta S = 0$). Substituting the calibrated-model values and above assumptions into equation 6 yields the following:

In	Rate (acre-ft/yr)	Out	Rate (acre-ft/yr)
GW_{in}	0	GW_{out}	0
R_{ppt}	465,567	D_{sw}	559,192
R_{sw}	129,778	D_{et}	Not calculated in model
R_{sec}	11,699	D_{ppg}	47,863
Total In	607,044	Total Out	607,055

The calibrated steady-state groundwater model budget can be used to make general observations about the flow system. Total flow through the groundwater system was about 607,050 acre-ft/yr in the model area. Precipitation was the primary source of water recharging the groundwater system (77 percent); recharge from streams and lakes (and a minor amount from Puget Sound) was 21 percent of the total recharge. Groundwater discharge to streams, lakes, springs, seeps, and Puget Sound was 559,192 acre-ft/yr, or 92 percent of the total discharge from the groundwater system. Withdrawals from wells were about 8 percent of discharge. The model-derived groundwater budget indicates no groundwater inflow to (GW_{in}) or outflow from (GW_{out}) the model area. This is due to the presence of regional-scale boundary conditions for the model, such as Puget Sound, the Puyallup and Nisqually River valleys, and an implicit no-flow boundary that coincides with the top of bedrock. These boundary conditions simulate the exchange of groundwater with surface-water features (R_{sw} and D_{sw}), and preclude the exchange of groundwater (no-flow boundary). Boundary conditions are approximate descriptions of complex natural systems, and it is likely that in places, groundwater flow occurs across major river valleys and bedrock contacts.

Savoca and others (2010) reported an estimated total groundwater discharge from the water-budget area of 455,000 acre-ft/yr. About one-half of this discharge (49 percent) was estimated to flow out of the CCCW and vicinity as submarine seepage to Puget Sound and as groundwater discharge to the Puyallup and Nisqually Rivers (224,700 acre-ft/yr), and 38 percent (171,800 acre-ft/yr) was estimated to flow to streams and springs. Model-derived groundwater flows for the CCCW and vicinity ([table 8](#)) indicate a total groundwater discharge of 476,777 acre-ft/yr. More than one-half of this simulated groundwater discharge (69 percent) flows out of the CCCW and vicinity as submarine seepage to Puget Sound and as groundwater discharge to the Puyallup and Nisqually Rivers (330,573 acre-ft/yr), and 21 percent (98,341 acre-ft/yr) flows to streams, lakes, and springs. Model-derived groundwater flows are considered reasonable when compared to estimates from Savoca and others (2010).

The water budget for the transient simulation period (September 2006–August 2008) is presented in section, “[Model Simulations for Six Scenarios](#).” The budget indicates a change in groundwater storage of 11,392 acre-ft/yr during the transient simulation period, or about 2 percent of the precipitation recharge. This change in storage suggests that “true” steady-state conditions may not have been reached during steady-state calibration. However, there is no long-term ambient groundwater monitoring network in the model area, and data from the short-term (March 2007–September 2008) monthly monitoring network established for this study ([fig. 13](#)) are insufficient to evaluate water-level trends relating to long-term changes in groundwater storage.

Table 8. Model-derived groundwater flow, Chambers-Clover Creek watershed and vicinity, Washington.

[Net flows equal inflow minus outflow; negative flows are out of the groundwater system or out of the WRIA. Column entries may not add exactly due to rounding. **Abbreviation:** acre-ft/yr, acre-feet per year; WRIA, water resources inventory area; NA, not applicable]

	Net flows (acre-ft/yr)			
	WRIA 12	WRIA 10	WRIA 11	All WRIsAs
Recharge (precipitation and return flows)	178,080	82,451	216,240	476,772
Withdrawals from wells	-32,909	-10,840	-4,114	-47,863
Puyallup and Nisqually Rivers	0	-127	-149,032	-149,159
Streams and Lakes	-17,281	-75,708	-5,307	-98,296
Springs and Seeps	-27	-11	-7	-45
Puget Sound	-108,460	-50,463	-22,491	-181,414
Flow between WRIsAs	-19,389	54,681	-35,292	NA
To WRIA 12	NA	56,546	-37,157	NA
To WRIA 10	-56,546	NA	1,865	NA
To WRIA 11	37,157	-1,865	NA	NA

Model Simulations for Six Scenarios

The groundwater-flow model was used to simulate possible effects on water levels and groundwater discharge caused by potential changes in well withdrawals and recharge. Six scenarios were formulated and simulated using the calibrated model to demonstrate how the model could be used to investigate water-resource issues under steady-state or transient conditions. Model results were compared to “base simulation” results that represent calibrated steady-state or transient conditions prior to modification for simulations. Resultant change in flow components (such as stream and lake, or spring and seep flows) are evaluated as a percent of the simulated change in recharge ([table 9](#)), and as a percent of the simulated change in consumptive use ([tables 10–12](#)). Simulated increases in withdrawals were not applied to crop irrigation wells or to springs that supply public water. Model simulations were made to evaluate the following conditions:

Simulation 1. Decrease recharge from precipitation by 20 percent throughout the model area to simulate drier conditions while maintaining all other “base simulation” steady-state conditions. Compare simulation results to “base simulation” ([table 9](#) and [fig. 15](#)).

Table 9. Comparison of selected water budget components for the “base simulation” steady-state condition and simulation 1.

[Net flows equal inflow minus outflow; negative flows are out of the groundwater system or out of the WRIA. Column entries may not add exactly due to rounding. **Abbreviations:** acre-ft/yr, acre-feet per year; WRIA, water resources inventory area; NA, not applicable]

Chambers-Clover Creek (WRIA12)	Base simulation (acre-ft/yr)	Simulation 1 (acre-ft/yr)	Change (acre-ft/yr)	Percent of change in recharge
Recharge from precipitation	171,976	137,581	-34,395	NA
Return flows	6,100	6,100	0	NA
Withdrawals from wells	-32,909	-32,909	0	NA
Consumptive use	-26,809	-26,809	0	NA
Change in recharge	NA	NA	-34,395	100
Streams and Lakes	-17,281	+23,009	+40,290	+117
Springs and Seeps	-27	-22	+5	0
Puget Sound	-108,460	-104,397	+4,063	+12
Flow between WRIAs	-19,389	-29,361	-9,972	-29
To WRIA 10	-56,546	-55,027	+1,519	+4
To WRIA 11	+37,157	+25,666	-11,491	-33

Figure 15. Simulated groundwater-level altitude change between the steady-state “base-simulation” and simulation 1, Chambers-Clover Creek watershed and vicinity, Washington.

Simulation 2. Increase current withdrawals in all public supply and residential wells by 15 percent (with corresponding increases in return flows) under steady-state conditions. Compare simulation results to “base simulation” (table 10 and fig. 16).

Simulation 3. Increase current withdrawals in all public supply and residential wells by the same total amount in simulation 2 (with corresponding increases in return flows), but distribute that amount only in deeper wells under steady-state conditions. Deeper wells were simulated by assigning the additional Group A public-supply withdrawal amounts to the E aquifer and G undifferentiated deposits, and assigning the additional Group B public-supply and residential withdrawal amounts to the next lowest aquifer. Wells already located in the lowest hydrogeologic unit (G undifferentiated deposits) were not “deepened”. Compare simulation results to “base simulation” and Simulation 2 (table 10, fig. 17).

Table 10. Comparison of selected water budget components for the “base simulation” steady-state condition and simulations 2 and 3, Chambers-Clover Creek watershed and vicinity, Washington.

[Flows equal inflow minus outflow; negative flows are out of the groundwater system or out of the WRIA. Column entries may not add exactly due to rounding. **Abbreviations:** acre-ft/yr, acre-feet per year; WRIA, water resources inventory area; NA, not applicable]

Chambers-Clover Creek (WRIA12)	Base simulation (acre-ft/yr)	Simulation 2 (acre-ft/yr)	Change from base simulation (acre-ft/yr)	Percent of change in consumptive use	Simulation 3 (acre-ft/yr)	Change from base simulation (acre-ft/yr)	Percent of change in consumptive use
Recharge from precipitation	171,976	171,976	0	NA	171,976	0	NA
Return flows	6,100	6,648	548	NA	6,648	548	NA
Withdrawals from wells	-32,909	-36,964	-4,055	NA	-36,957	-4,047	NA
Consumptive use	-26,809	-30,315	-3,507	100	-30,308	-3,499	100
Streams and Lakes	-17,281	-14,583	2,697	77	-14,805	2,476	71
Springs and seeps	-27	-27	0	0	-27	0	0
Puget Sound	-108,460	-107,961	499	14	-107,800	660	19
Flow between WRIAs	-19,389	-19,084	304	9	-19,024	365	10
To WRIA 10	-56,546	-56,379	167	5	-56,340	206	6
To WRIA 11	37,157	37,295	138	4	37,316	158	4

Figure 16. Simulated groundwater-level altitude change between the steady-state “base-simulation” and simulation 2, Chambers-Clover Creek watershed and vicinity, Washington.

Figure 17. Simulated groundwater-level altitude change between the steady-state "base-simulation" and simulation 3, Chambers-Clover Creek watershed and vicinity, Washington.

Simulation 4. Increase current withdrawals in all public supply and residential wells by the same total amount in simulation 3 (with corresponding increases in return flows) and distribute that amount in Group A public-supply wells that have been deepened, and group B public-supply and residential wells that have not been deepened, under steady-state conditions. Compare simulation results to “base simulation” and Simulation 3 ([table 11](#) and [fig. 18](#)).

Table 11. Comparison of selected water budget components for the “base simulation” steady-state condition and simulations 3 and 4, Chambers-Clover Creek watershed and vicinity, Washington.

[Flows equal inflow minus outflow; negative flows are out of the groundwater system or out of the WRIA. Column entries may not add exactly due to rounding. **Abbreviation:** acre-ft/yr, acre-feet per year; WRIA, water resources inventory area; NA, not applicable]

Chambers-Clover Creek (WRIA12)	Base simulation (acre-ft/yr)	Simulation 3 (acre-ft/yr)	Change from base simulation (acre-ft/yr)	Percent of change in consumptive use	Simulation 4 (acre-ft/yr)	Change from base simulation (acre-ft/yr)	Percent of change in consumptive use
Recharge from precipitation	171,976	171,976	0	NA	171,976	0	NA
Return flows	6,100	6,648	548	NA	6,648	548	NA
Withdrawals from wells	-32,909	-36,957	-4,047	NA	-36,957	-4,047	NA
Consumptive use	-26,809	-30,308	-3,499	100	-30,308	-3,499	100
Streams and Lakes	-17,281	-14,805	2,476	71	-14,805	2,476	71
Springs and seeps	-27	-27	0	0	-27	0	0
Puget Sound	-108,460	-107,800	660	19	-107,800	660	19
Flow between WRIAs	-19,389	-19,024	365	10	-19,025	364	10
To WRIA 10	-56,546	-56,340	206	6	-56,340	206	6
To WRIA 11	37,157	37,316	158	4	37,315	158	4

Figure 18. Simulated groundwater-level altitude change between the steady-state "base-simulation" and simulation 4, Chambers-Clover Creek watershed and vicinity, Washington.

Simulation 5. Increase current monthly withdrawals under transient conditions in all public supply and residential wells by 15 percent (with corresponding increases in return flows) for the transient simulation period (September 2006–August 2008). Compare simulation results to “base simulation” ([table 12](#) and [fig. 19](#)).

Simulation 6. Increase current monthly withdrawals under transient conditions in all public supply and residential wells by the same total amount in simulation 5 (with corresponding increases in return flows) for the transient simulation period (September 2006–August 2008). Distribute the increase in withdrawals during summer months (April–September) in deeper Group A public-supply wells, and Group B public supply and residential wells that have not been deepened. Distribute the increase in withdrawals during winter months (October–March) in Group A and Group B public supply wells and residential wells that have not been deepened. Compare simulation results to “base simulation” and to simulation 5 ([table 12](#) and [fig. 20](#)).

Table 12. Comparison of selected water budget components for the “base simulation” transient condition and simulations 5 and 6, Chambers-Clover Creek watershed and vicinity, Washington.

[Flows equal inflow minus outflow averaged over 24 monthly time steps during the transient simulation period, September 2006 – August 2008; negative flows are out of the groundwater system or out of the WRIA. Column entries may not add exactly due to rounding. **Abbreviations:** acre-ft/yr, acre-feet per year; WRIA, water resources inventory area; NA, not applicable]

Chambers-Clover Creek (WRIA12)	Base simulation (acre-ft/yr)	Simulation 5 (acre-ft/yr)	Change from base simulation (acre-ft/yr)	Percent of change in consumptive use	Simulation 6 (acre-ft/yr)	Change from base simulation (acre-ft/yr)	Percent of change in consumptive use
Recharge from precipitation	171,980	171,980	0	NA	171,980	0	NA
Return flows	6,103	6,652	549	NA	6,652	549	NA
Withdrawals from wells	-32,908	-36,956	-4,047	NA	-36,956	-4,047	NA
Consumptive use	-26,806	-30,304	-3,498	100	-30,304	-3,498	100
From groundwater storage	-2,513	-1,185	1,328	38	-1,222	1,290	37
Streams and Lakes	-14,724	-13,300	1,424	41	-13,411	1,312	38
Springs and seeps	-27	-27	0	0	-27	0	0
Puget Sound	-108,105	-107,685	421	12	-107,586	519	15
Flow between WRIAs	-19,823	-19,499	324	9	-19,447	376	11
To WRIA 10	-56,619	-56,531	88	3	-56,498	121	4
To WRIA 11	36,796	37,032	236	7	37,052	255	7

Figure 19. Simulated groundwater levels for transient “base-simulation” and simulation 5 and difference, Chambers-Clover Creek watershed and vicinity, Washington.

Figure 20. Simulated groundwater levels for transient “base-simulation” and simulation 6 and difference, Chambers-Clover Creek watershed and vicinity, Washington.

Model simulations are briefly summarized below:

Model Simulation	Recharge (precipitation and return flows)	Withdrawal amount (public and residential)	Withdrawal location
Simulation 1 Steady-State	Decrease precipitation recharge by 20 percent	No change	No change
Simulation 2 Steady-State	Increase return flows by 15 percent	Increase public and residential withdrawals by 15 percent	No change
Simulation 3 Steady-State	Increase return flows by 15 percent	Increase public and residential withdrawals by 15 percent	Deepen all public and residential withdrawals
Simulation 4 Steady-State	Increase return flows by 15 percent	Increase public and residential withdrawals by 15 percent	Deepen only group A public withdrawals
Simulation 5 Transient	Increase monthly return flows by 15 percent	Increase monthly public and residential withdrawals by 15 percent	No change
Simulation 6 Transient	Increase monthly return flows by 15 percent	Increase monthly public and residential withdrawals by 15 percent	Deepen only group A public withdrawals during summer months

Simulation 1 reduces the amount of groundwater recharge from precipitation to simulate drier climatic conditions. The resulting change in flow components for simulation 1 ([table 9](#)) indicate that a 34,395 acre-ft/yr reduction in groundwater recharge from precipitation produces a reversal in the net exchange of groundwater and surface-water in WRIA12 from a loss of 17,281 acre-ft/yr of groundwater to streams and lakes, to a gain of 23,009 acre-ft/yr of groundwater from streams and lakes, and a reduction or loss of spring flows from 27 acre-ft/yr to 22 acre-ft/yr. Groundwater discharge to Puget Sound is reduced by 4,063 acre-ft/yr, and groundwater flow from WRIA12 to WRIA10 and WRIA11 is increased by 9,972 acre-ft/yr. Simulated water level declines in the A3 aquifer typically ranged from about 30 ft to less than 1 ft, with a maximum decline of 64 ft ([fig. 15](#)).

The change in flow components for simulation 2 ([table 10](#)) indicate that of the 3,507 acre-ft/yr of increased consumptive withdrawals (pumpage in wells minus return flows), a majority (2,697 acre-ft/yr or 77 percent) comes from decreased groundwater discharge to streams and lakes; that 499 acre-ft/yr (14 percent) comes from decreased groundwater discharge to Puget Sound; and that 304 acre-ft/yr (9 percent) comes from decreased flow from WRIA12 to WRIA10 and WRIA11. Simulated water level declines in the A3 aquifer resulting from increased withdrawals typically ranged from about 0.6 ft to less than 0.1 ft with a maximum decline of about 3.3 ft ([fig. 16](#)). Water-level declines are greatest in areas of higher well density.

The change in flow components for simulation 3 ([table 10](#)) indicate a slight reduction in the amount of consumptive withdrawal derived from streams and lakes (2,476 acre-ft/yr, or 71 percent) resulting from the distribution of withdrawals among deeper wells. Slight increases in the amount of consumptive withdrawal derived from groundwater discharge to Puget Sound (660 acre-ft/yr or 19 percent) and flow from WRIA12 to WRIA10 and WRIA11 (365 acre-ft/yr or 10 percent) result from the distribution of withdrawals among deeper wells. The relatively minor influence of withdrawals from deeper wells on the amount of consumptive withdrawal derived from streams and lakes may be due to increased groundwater discharge to streams through enhanced shallow groundwater recharge from increased return flows from deeper withdrawals. Simulated water level declines in the A3 aquifer resulting from increased withdrawals from deeper wells typically ranged from about 0.6 ft to less than 0.1 ft with a maximum decline of about 1.7 ft ([fig. 17](#)). Water-level declines are greatest in areas of higher well density. A comparison of the simulated change in groundwater level between simulations 2 and 3 ([figs. 16](#) and [17](#), respectively) suggests that withdrawals from deeper wells reduced simulated groundwater level lowering in the A3 aquifer in areas of higher well density.

Simulation 4 applies the same increase in withdrawal as simulation 3, but distributes that amount in Group A public-supply wells that have been deepened, and Group B public-supply and residential wells that have not been deepened. Results from this simulation are compared with results from simulation 3 to evaluate the relative impact of potential future increases in withdrawals from deeper Group A public-supply wells compared with the present-day depth distribution of Group B public supply and residential withdrawals. The change in flow components for simulation 4 ([table 11](#)) indicate that the effect of the present-day depth distribution of Group B public-supply and residential well withdrawals was not of sufficient magnitude to produce a response in water budget components in WRIA12. A comparison of the simulated change in groundwater level between simulations 3 and 4 ([figs. 17](#) and [18](#), respectively) suggests that the effect of the present-day depth distribution of Group B public-supply and residential well withdrawals was not of sufficient magnitude to produce a response in simulated groundwater levels in the A3 aquifer. This lack of response may be the result of the relatively small amount of additional consumptive use associated with Group B public-supply and residential withdrawals compared with the amount of recharge from precipitation.

Simulations 5 and 6 were made using the model for transient conditions. Simulation 5 increases monthly withdrawals in all public-supply and residential wells. The resulting change in flow components for simulation 5 ([table 12](#)) indicate that, of the 3,498 acre-ft/yr of increased consumptive withdrawals over the 2-year transient simulation period, the majority (79 percent) comes from decreased groundwater discharge to streams and lakes (1,424 acre-ft/yr, or 41 percent) and from decreased groundwater storage (1,328 acre-ft/yr or 38 percent), 421 acre-ft/yr (12 percent) comes from decreased groundwater discharge to Puget Sound and 324 acre-ft/yr (9 percent) comes from flow from WRIA12 to WRIA10 and WRIA11. Representative hydrographs of groundwater levels for the transient simulation period illustrate differences of less than 2 ft between the “base simulation” and Simulation 5 ([fig. 19](#)). Continually increasing water-level differences suggest that the effects of withdrawals at mid and deep levels of the aquifer system did not stabilize during the simulation period, and that a continued loss of groundwater storage is likely.

Simulation 6 increases monthly withdrawals in all public-supply and residential wells by the same total amount in simulation 5, but distributes the increase in withdrawals during summer months (April–September) to Group A public-supply wells that have been deepened, and Group B public supply and residential wells that have not been deepened. Results from this simulation are compared to results from simulation 5 to evaluate the potential mitigation of adverse impacts on water levels and stream baseflows by deepening Group A public-supply withdrawals during summer months. The resulting

change in flow components for simulation 6 ([table 12](#)) indicate a decrease in the amount of consumptive withdrawal derived from streams and lakes (1,312 acre-ft/yr, or 38 percent) and from groundwater storage (1,290 acre-ft/yr, or 37 percent), and an increase in both the amount of consumptive withdrawal derived from groundwater discharge to Puget Sound (519 acre-ft/yr, or 15 percent), and flow from WRIA12 to WRIA10 and WRIA11 (376 acre-ft/yr, or 11 percent). A comparison of groundwater-difference hydrographs between simulations 5 and 6 ([figs. 19](#) and [20](#)) indicate that deepening Group A public-supply during the summer delayed by several months the timing of the greatest simulated impact of withdrawals in a well (map index no. 102) completed in the C aquifer and located within an area containing several nearby Group A public-supply wells. A similar delay in groundwater-level response was not observed for other wells (map index no. 72 and 223) completed in the C aquifer that are located within areas containing fewer nearby Group A public wells. The deepening of Group A public-supply withdrawals during the summer decreased simulated groundwater-level declines during the summer months in two wells (map index no. 72 and 102) completed in the C aquifer, and increased simulated groundwater-level declines in a well (map index no. 75) completed in the E aquifer.

Summary

In 1998, the Washington State Legislature established the Washington State Watershed Management Act (codified under RCW 90.82) to address the diminishing availability and quality of water and the loss of critical habitat for fish and wildlife. Watershed studies under this Act were begun in 1998 in the Chambers–Clover Creek Watershed (CCCW) Water Resources Inventory Area (WRIA 12) by a group of Initiating Governments and local stakeholders (the Planning Unit). Upon completion of a technical assessment of the watershed, some members of the Planning Unit concluded that additional data, including development of a numerical groundwater-flow model, would contribute to an improved understanding of water resources in the CCCW. A groundwater-flow model was constructed by the U.S. Geological Survey to assist stakeholders in developing an improved understanding of water resources in the CCCW and vicinity.

The model covers an area of about 491 mi² in western Pierce County, Washington ([fig. 1](#)), and was selected to include major hydrologic features that could be used as regional model boundaries during development of the numerical flow model of the CCCW and vicinity. The model area is bounded to the northeast by the Puyallup River valley, to the southwest by the Nisqually River valley, and extends northwest to Puget Sound, and southeast to Tanwax Creek which approximates the southeastern extent of the majority of water-bearing hydrogeologic units. The model

area is underlain by a northwest-thickening sequence of unconsolidated glacial (till and outwash) and interglacial (fluvial and lacustrine) deposits. Sedimentary and volcanic bedrock units underlie the unconsolidated deposits, and crop out in a few areas within deeply incised river valleys along the southern and southeastern margin of the model area.

Groundwater flow in the CCCW and vicinity was simulated using the groundwater-flow model, MODFLOW-2000. The finite-difference model grid comprises 146 rows, 132 columns, and 11 layers. Each model cell has a horizontal dimension of 1,000 by 1,000 ft, and the model contains a total of 123,602 active cells. The thickness of model layers varies throughout the model area. Boundary conditions representing inflow and outflow components were implemented using packages in MODFLOW-2000. The Recharge Package was used to represent recharge from precipitation and water returned to the groundwater system through seepage from septic systems, deep percolation of irrigation water, and public water-system conveyance losses. The Well Package was used to represent withdrawals from wells. The River Package was used to represent the exchange of water between streams, lakes, and the aquifer system. The Drain Package was used to represent groundwater discharge to springs and seeps, and the General-Head Boundary Package was used to represent groundwater discharge to Puget Sound.

Groundwater flow was simulated in unconsolidated glacial (till and outwash) and interglacial (fluvial and lacustrine) deposits in the CCCW and vicinity. The hydrogeologic framework presented in Savoca and others (2010) was used to delineate 10 hydrogeologic units comprising aquifers and confining units within the model domain that are represented using 11 model layers. Initial estimates and probable ranges of values for hydraulic properties used during model calibration were defined from data collected during previous studies in and adjacent to the model area.

Groundwater flow was simulated for both steady-state and transient conditions. Steady-state conditions were simulated using average recharge, discharge, and water levels for the period, September 2006–August 2008. Transient conditions were simulated for the period, September 2006–August 2008 using 24 monthly stress periods. Initial conditions for the transient calibrations were developed from a 3-year “lead-in” period that used recorded precipitation and river levels, and extrapolations of other boundary conditions. During model calibration, variables were adjusted within probable ranges to minimize differences between measured and simulated groundwater levels and stream baseflows. The model as calibrated to steady-state conditions has a standard deviation for heads and flows of 28.42 ft and 2.12 cubic feet per second, respectively; the model as calibrated to transient conditions has a standard deviation for heads and flows of 23.01 ft and 2.67 cubic feet per second, respectively.

Simulated steady-state inflow to the model area from precipitation and secondary recharge was 477,266 acre-feet per year (acre-ft/yr) (79 percent of total simulated inflow), and simulated inflow from stream and lake leakage was 129,778 acre-ft/yr (21 percent of total simulated inflow). Simulated outflow from the model primarily was through discharge to streams, lakes, springs, seeps, and Puget Sound (559,192 acre-ft/yr; 92 percent of total simulated outflow), and withdrawals from wells (47,863 acre-ft/yr; 8 percent of total simulated outflow).

Six scenarios were formulated and simulated using the calibrated model to demonstrate model performance and to provide representative examples of how the model can be used to evaluate the effects of potential changes in groundwater withdrawals, consumptive use, and recharge on groundwater levels and stream baseflows.

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Figure 21. Extent and thickness of hydrogeologic units simulated with the Layer-Property Flow package, Chambers-Clover Creek watershed and vicinity, Washington.

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Figure 22. Final parameter value distributions of horizontal (A–J) and vertical hydraulic conductivity (K–T), and specific storage coefficients (U–DD), Chambers–Clover Creek watershed and vicinity, Washington.

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Figure 23. Simulated water-level altitudes and residuals for the steady-state calibration, Chambers–Clover Creek watershed and vicinity, Washington.

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Table 13. Wells used in model calibration, Chambers-Clover Creek watershed, Washington.

[**Weighting factor:** Applied according to a relative scale from 1 to 10. **Measurements with status:** Number of measurements affected by pumping, recovering, or flowing conditions. **Abbreviations:** HGU, Hydrogeologic-Unit; S, synoptic measurement; M, monthly measurements; NA, not applicable]

Map No. (fig. 7)	Site identification No.	Local well No.	HGU	Weight- ing factor	Type	Measured groundwater altitude	Simulated steady state water level	Steady state residual	Total measure- ments	Measure- ments with status	Transient target measure- ments	Mean of transient weighting factors	Mean of transient residuals	Standard deviation of transient residuals
1	471546122265601	21N/03E-32K01	A3	10	M	226.90	205.49	21.41	18	0	17	10	22.25	3.73
2	471515122322801	20N/02E-03E01	A3	3	S	154.20	148.86	5.34	1	0	1	10	6.59	NA
4	471402122232501	20N/03E-11L01	AL	10	M	10.95	13.49	-2.54	19	0	18	10	-2.44	0.90
5	471459122314601	20N/02E-03J01	B	9	M	181.41	172.66	8.75	19	5	18	8.1	10.25	6.65
6	471338122221701	20N/03E-13C02	AL	2	S	16.94	17.81	-0.87	1	1	1	5	-0.84	NA
7	471415122283201	20N/03E-07F01	A3	3	S	223.75	207.26	16.49	1	0	1	10	12.87	NA
8	471321122224601	20N/03E-14H01	C	3	S	84.13	23.03	61.10	1	0	1	10	61.20	NA
9	471351122281001	20N/03E-07Q02	A3	10	M	224.82	212.53	12.29	17	0	17	10	12.89	2.57
10	471312122225801	20N/03E-14K01	A3	10	M	72.53	79.40	-6.87	17	0	16	10	-5.13	4.37
11	471408122312801	20N/02E-11E01	C	3	S	205.53	186.57	18.96	1	0	1	10	20.86	NA
12	471258122222501	20N/03E-13N01	D	10	M	58.74	65.17	-6.43	19	0	18	10	-5.97	1.85
13	471356122312601	20N/02E-11M01	E	10	M	209.75	182.58	27.17	20	0	19	10	29.16	5.12
14	471345122302601	20N/02E-11R03	A3	10	M	223.30	205.50	17.80	19	2	18	9.2	18.73	2.64
15	471236122200901	20N/04E-20D06	E	1	S	17.22	26.98	-9.76	1	1	1	3	-9.60	NA
16	471243122200001	20N/04E-20D01	C	2	S	30.08	22.67	7.41	1	1	1	5	7.51	NA
17	471235122205101	20N/04E-19F03	AL	2	S	24.01	22.66	1.35	1	1	1	5	1.45	NA
18	471230122195601	20N/04E-20E06	AL	1	S	28.05	22.48	5.57	1	1	1	3	5.56	NA
19	471344122311601	20N/02E-11N01	A2	10	M	218.59	192.59	26.00	19	0	18	10	27.60	2.36
20	471220122203001	20N/04E-19K04	AL	3	S	25.05	22.70	2.35	1	0	1	10	2.43	NA
21	471350122334101	20N/02E-09P02	A3	10	M	36.28	125.85	-89.57	19	1	18	9.6	-87.78	5.08
22	471148122165401	20N/04E-27B01	AL	3	S	43.83	45.48	-1.65	1	0	1	10	-1.57	NA
23	471130122145401	20N/04E-51J01	AL	10	M	63.43	62.50	0.93	19	0	18	10	1.03	1.08
24	471203122203401	20N/04E-19Q01	AL	2	S	28.81	27.17	1.64	1	1	1	5	1.76	NA
25	471125122144901	20N/04E-25M01	AL	3	S	69.28	66.04	3.24	1	0	1	10	3.29	NA
26	471115122164501	20N/04E-27J01	AL	8	M	55.72	38.18	17.54	18	18	18	5	17.51	0.01
27	471246122285101	20N/03E-19D01	C	9	M	211.20	213.41	-2.21	20	5	19	8.3	-2.11	8.38
28	471102122130501	20N/05E-31C01	AL	3	S	75.73	81.40	-5.67	1	0	1	10	-5.55	NA
29	471252122301501	20N/02E-14R01	A3	3	S	214.43	208.70	5.73	1	0	1	10	11.15	NA
30	471044122134501	20N/04E-36H03	AL	3	S	76.47	78.81	-2.34	1	0	1	10	-2.34	NA
31	471103122151401	20N/04E-35A03	AL	3	S	67.27	75.54	-8.27	1	0	1	10	-8.08	NA
32	471137122205301	20N/04E-30F01	C	10	M	85.23	98.79	-13.56	19	1	18	9.6	-13.25	0.90
33	471030122122201	20N/05E-38K01	AL	3	S	79.92	90.77	-10.85	1	0	1	10	-10.45	NA
34	471239122303901	20N/02E-23B02	A3	2	S	182.92	195.08	-12.16	1	1	1	5	-12.26	NA
35	471046122213201	20N/04E-36H04	AL	3	S	77.50	81.46	-3.96	1	0	1	10	-3.93	NA
36	471028122122901	20N/05E-38P01	AL	3	S	74.28	90.77	-16.49	1	0	1	10	-16.11	NA
37	471117122195201	20N/04E-29P03	C	2	S	55.96	88.69	-32.73	1	1	1	5	-34.16	NA

Table 13. Wells used in model calibration, Chambers-Clover Creek watershed, Washington.—Continued

[**Weighting factor:** Applied according to a relative scale from 1 to 10. **Measurements with status:** Number of measurements affected by pumping, recovering, or flowing conditions. **Abbreviations:** HGU, Hydrogeologic-Unit; S, synoptic measurement; M, monthly measurements; NA, not applicable]

Map No. (fig. 7)	Site identification No.	Local well No.	HGU	Weight- ing factor	Type	Measured groundwater altitude	Simulated steady state water level	Steady state residual	Total measure- ments	Measure- ments with status	Transient target measure- ments	Mean of transient weighting factors	Mean of transient residuals	Standard deviation of transient residuals
38	471230122302101	20N/02E-23H08	A3	3	S	203.61	204.97	-1.36	1	0	1	10	-4.00	NA
39	471032122213001	20N/04E-35H04	E	3	S	98.04	111.39	-13.35	1	0	1	10	-12.68	NA
40	471227122302801	20N/02E-23H03	A3	10	M	200.36	202.65	-2.29	19	0	18	10	-1.65	2.17
41	471125122231001	20N/03E-26K01	A2	10	M	399.56	382.45	17.11	19	0	18	10	17.39	11.40
42	471019122213201	20N/04E-36R02	AL	10	M	77.88	83.30	-5.42	18	0	18	10	-5.42	1.26
43	471058122193901	20N/04E-32C01	C	3	S	72.71	107.30	-34.59	1	0	1	10	-34.51	NA
44	471031122160401	20N/04E-35M02	E	8	M	92.43	120.36	-27.93	9	2	8	8.3	-27.32	0.40
45	470958122124401	19N/03E-06A02	AL	3	S	78.56	95.05	-16.49	1	0	1	10	-15.65	NA
46	471009122134701	19N/04E-01A02	AL	3	S	78.93	94.56	-15.63	1	0	1	10	-15.40	NA
47	471018122150801	20N/04E-35R02	C	9	M	119.16	139.78	-20.62	14	4	13	8.4	-19.33	4.52
48	471024122151201	20N/04E-35R03	A1	10	M	275.11	261.84	13.27	20	0	19	10	15.48	0.64
49	471056122203601	20N/04E-31B01	A2	10	M	337.00	284.17	52.83	19	0	18	10	55.20	2.58
50	471009122152001	19N/04E-02B01	A3	3	S	349.25	290.86	58.39	1	0	1	10	64.43	NA
51	471051122213501	20N/03E-36H01	A3	3	S	336.67	259.43	77.24	1	0	1	10	79.82	NA
52	471203122323801	20N/02E-22N04	A3	10	M	205.23	183.17	22.06	19	0	18	10	24.81	3.42
53	471030122170301	20N/04E-34N01	C	3	S	94.74	181.29	-86.55	1	0	1	10	-83.98	NA
54	470939122132901	19N/03E-06M04	AL	3	S	83.94	100.01	-16.07	1	0	1	10	-15.92	NA
55	471148122305501	20N/02E-26C02	C	9	M	213.41	201.69	11.72	20	6	19	7.8	12.01	13.63
56	471137122304701	20N/02E-26C01	C	10	M	219.36	202.19	17.17	21	0	20	10	17.67	6.44
57	471138122300601	20N/02E-38L01	C	10	M	219.07	213.34	5.73	20	1	19	9.6	6.37	5.20
58	470937122135001	19N/04E-01J04	AL	3	S	86.20	112.56	-26.36	1	0	1	10	-25.81	NA
59	471149122325701	20N/02E-28A01	E	10	M	83.65	89.63	-5.98	20	1	19	9.6	-5.48	0.73
60	4711161222292701	20N/02E-37B03	A1	3	S	226.13	216.37	9.76	1	0	1	10	12.18	NA
61	4710201222229901	20N/03E-36N01	C	3	S	260.12	258.84	1.28	1	0	1	10	3.39	NA
62	471124122320901	20N/02E-41G01	E	9	M	126.51	121.51	5.00	13	1	13	9.5	4.51	1.46
63	471012122220601	19N/03E-01C02	C	10	M	270.66	262.37	8.29	17	0	16	10	9.58	1.92
64	471022122250901	20N/03E-41K01	C	10	M	243.00	254.16	-11.16	19	2	18	9.2	-10.39	2.35
65	471134122315901	20N/02E-41Q02	G	10	M	120.34	130.22	-9.88	19	0	18	10	-9.27	4.33
66	471134122320001	20N/02E-41Q01	C	10	M	152.40	168.10	-15.70	19	0	18	10	-15.18	2.83
67	470910122160401	19N/04E-11D01	A3	3	S	362.45	318.22	44.23	1	0	1	10	51.60	NA
68	471048122293501	20N/02E-37K01	C	10	M	237.06	218.60	18.46	19	0	18	10	18.77	1.40
69	471007122222702	19N/03E-01E01	A2	10	M	249.92	274.79	-24.87	17	1	16	9.6	-24.23	3.97
70	470910122160301	19N/04E-11D02	E	10	M	359.77	287.36	72.41	19	0	18	10	74.37	1.13
71	471032122292701	20N/02E-36K01	A1	10	M	236.13	235.35	0.78	22	0	21	10	1.41	0.70
72	471058122334801	20N/02E-33C01	C	10	M	98.56	131.89	-33.33	19	0	18	10	-32.53	5.67
73	471335122141501	19N/04E-13B01	AL	9	M	105.84	125.76	-19.92	12	0	11	10	-19.35	0.44

Table 13. Wells used in model calibration, Chambers-Clover Creek watershed, Washington.—Continued

[**Weighting factor:** Applied according to a relative scale from 1 to 10. **Measurements with status:** Number of measurements affected by pumping, recovering, or flowing conditions. **Abbreviations:** HGU, Hydrogeologic-Unit; S, synoptic measurement; M, monthly measurements; NA, not applicable]

Map No. (fig. 7)	Site identification No.	Local well No.	HGU	Weight- ing factor	Type	Measured groundwater altitude	Simulated steady state water level	Steady state residual	Total measure- ments	Measure- ments with status	Transient target measure- ments	Mean of transient weighting factors	Mean of transient residuals	Standard deviation of transient residuals
74	471018122305701	20N/02E-35P01	G	10	M	188.93	177.77	11.16	20	0	19	10	12.23	3.78
75	471011122332101	19N/02E-04B03	E	10	M	149.93	139.00	10.93	19	0	18	10	12.67	14.44
76	470928122281501	19N/03E-06Q01	C	3	S	240.84	263.80	-22.96	1	0	1	10	-16.86	NA
77	470845122230601	19N/03E-11Q01	C	10	M	261.78	276.71	-14.93	19	0	18	10	-13.58	1.85
78	470913122293101	19N/02E-12 LT05	A1	10	M	259.94	259.78	0.16	18	0	17	10	1.32	1.34
79	470812122230301	19N/03E-14G01	C	3	S	269.01	280.48	-11.47	1	0	1	10	-5.28	NA
80	470817122235101	19N/03E-14D01	A3	3	S	283.06	283.93	-0.87	1	0	1	10	6.48	NA
81	470941122350101	19N/02E-06L01	A1	10	M	154.81	142.48	12.33	19	2	18	9.6	14.91	5.82
82	470731122181001	19N/04E-21C01	A3	10	M	255.41	295.36	-39.95	19	0	18	10	-38.36	1.70
83	470654122143601	19N/04E-24L01	A3	3	S	163.19	195.75	-32.56	1	0	1	10	-30.34	NA
84	470759122233101	19N/03E-14L02	A3	10	M	304.98	288.06	16.92	19	0	18	10	18.66	2.29
85	470840122292902	19N/02E-12 CW32C	G	10	M	234.22	248.82	-14.60	17	0	16	10	-13.25	3.31
86	470839122293401	19N/02E-12 CW32A	A3	10	M	263.31	266.26	-2.95	17	0	16	10	-1.59	0.72
87	470744122224001	19N/03E-14R01	C	10	M	261.51	284.82	-23.31	20	0	19	10	-21.73	6.31
88	470723122201802	19N/04E-19A01D1	A3	3	S	279.85	292.28	-12.43	1	0	1	10	-5.55	NA
89	470842122300801	19N/02E-48L01	A3	9	M	260.84	266.74	-5.90	15	0	14	10	-4.06	0.74
90	470857122333501	19N/02E-09F01	B	10	M	218.27	186.28	31.99	16	0	15	10	33.41	1.29
91	470822122275001	19N/03E-42N01	A1	9	M	280.96	284.04	-3.08	18	3	17	8.8	-2.49	0.81
92	470713122193601	19N/04E-20F02	C	10	M	282.19	287.73	-5.54	19	0	18	10	-3.94	1.70
93	470717122195801	19N/04E-20E03	C	10	M	283.23	288.74	-5.51	18	0	17	10	-3.74	1.18
94	470705122180601	19N/04E-21K01	A1	3	S	473.81	409.89	63.92	1	0	1	10	66.52	NA
95	470700122193601	19N/04E-20M01	C	3	S	292.40	292.62	-0.22	2	0	2	10	1.52	2.84
96	470813122292601	19N/02E-13 CW15D	E	10	M	258.62	270.61	-11.99	16	0	15	10	-10.67	1.76
97	470813122292602	19N/02E-13 CW15C	A3	10	M	265.04	273.88	-8.84	18	2	17	9.3	-7.94	3.55
98	470812122293001	19N/02E-13 CW15	A1	10	M	278.20	274.40	3.80	18	0	17	10	4.69	1.61
99	470629122163101	19N/04E-27A01	A3	10	M	392.98	365.45	27.53	20	0	18	10	30.36	3.12
100	470613122141701	19N/04E-25G02	AL	3	S	156.19	156.28	-0.09	1	0	1	10	0.30	NA
101	470730122251301	19N/03E-47Q01	C	3	S	293.23	305.84	-12.61	1	0	1	10	-9.55	NA
102	470649122192701	19N/04E-20Q02	C	10	M	294.95	303.28	-8.33	18	1	17	9.6	-6.52	2.80
103	470726122252201	19N/03E-22D05	A3	10	M	309.34	307.37	1.97	19	1	18	9.6	3.08	1.92
104	470827122273701	19N/03E-45R01	A3	10	M	283.14	298.87	-15.73	19	0	18	10	-15.01	2.51
105	470638122193701	19N/04E-29C01	A3	3	S	306.86	322.81	-15.95	1	0	1	10	-8.24	NA
106	470659122244201	19N/03E-22L01	A3	10	M	337.07	310.71	26.36	19	0	18	10	27.55	0.67
107	470543122135601	19N/04E-36A01	AL	10	M	167.63	179.02	-11.39	19	0	18	10	-11.15	0.63
108	470744122311301	19N/02E-14 DA13A	A1	10	M	261.39	268.87	-7.48	18	0	17	10	-6.00	1.55
109	470721122275101	19N/03E-19 IH1C	A3	10	M	297.60	302.44	-4.84	18	0	17	10	-4.21	0.28

Table 13. Wells used in model calibration, Chambers-Clover Creek watershed, Washington.—Continued

[**Weighting factor:** Applied according to a relative scale from 1 to 10. **Measurements with status:** Number of measurements affected by pumping, recovering, or flowing conditions. **Abbreviations:** HGU, Hydrogeologic-Unit; S, synoptic measurement; M, monthly measurements; NA, not applicable]

Map No. (fig. 7)	Site identification No.	Local well No.	HGU	Weight- ing factor	Type	Measured groundwater altitude	Simulated steady state water level	Steady state residual	Total measure- ments	Measure- ments with status	Transient target measure- ments	Mean of transient weighting factors	Mean of transient residuals	Standard deviation of transient residuals
110	470620122195401	19N/04E-29E02	A3	10	M	332.17	334.47	-2.30	18	0	17	10	-0.41	2.48
111	470537122134601	19N/04E-36A02	AL	3	S	171.15	187.95	-16.80	1	0	1	10	-15.38	NA
112	470635122221502	19N/03E-25C02D1	A3	9	M	262.30	324.39	-62.09	19	4	18	8.4	-61.31	28.80
113	470620122215101	19N/03E-25C04	A3	3	S	270.19	324.99	-54.80	1	0	1	10	-48.76	NA
114	470607122193501	19N/04E-29E11	C	3	S	342.67	340.74	1.93	1	0	1	10	9.27	NA
115	470737122310802	19N/02E-14 DA12D	C	10	M	246.12	248.34	-2.22	18	0	17	10	-1.11	1.62
116	470725122295702	19N/02E-24 DA2D	C	10	M	264.48	291.95	-27.47	18	0	17	10	-26.54	0.55
117	470725122295801	19N/02E-24 DA2A	A1	10	M	265.97	286.53	-20.56	18	0	17	10	-19.38	0.74
118	470721122292002	19N/02E-24 CW34D	A1	10	M	264.69	288.53	-23.84	18	0	17	10	-22.94	1.05
119	470721122292001	19N/02E-24 CW34C	C	10	M	282.75	300.09	-17.34	18	2	17	9.3	-16.53	0.68
120	470555122195601	19N/04E-29L03	A3	3	S	349.10	350.81	-1.71	1	0	1	10	6.39	NA
121	470556122234801	19N/03E-26D01	C	10	M	336.08	325.53	10.55	20	1	19	9.6	12.02	1.31
122	470731122311801	19N/02E-42A02	A3	3	S	261.52	261.00	0.52	1	0	1	10	0.53	NA
123	470622122215001	19N/03E-25G06	C	3	S	312.47	331.15	-18.68	1	0	1	10	-14.95	NA
124	470729122314801	19N/02E-42G02	A3	10	M	254.88	251.41	3.47	19	0	18	10	6.98	1.19
125	470506122131801	19N/03E-31P03	AL	10	M	191.85	190.85	1.00	19	0	18	10	1.14	1.02
126	470531122273501	19N/04E-32A06	A3	10	M	365.61	382.61	-17.00	19	0	18	10	-14.38	5.02
127	470633122205201	19N/04E-31C03	A3	3	S	344.99	361.36	-16.37	1	0	1	10	-7.53	NA
128	470529122230701	19N/04E-32G04	A3	10	M	374.29	388.11	-13.82	19	0	18	10	-11.27	3.67
129	470711122333801	19N/02E-21 LC80DP1	C	10	M	170.51	171.07	-0.56	18	0	17	10	-0.04	1.36
130	470512122170701	19N/04E-34L03	A3	9	M	440.51	427.98	12.53	19	5	18	8.4	16.09	13.87
131	470515122170401	19N/04E-34L01	C	10	M	378.34	396.53	-18.19	19	1	18	9.6	-16.18	9.10
132	470550122222401	19N/03E-51N01	A3	10	M	341.34	357.57	-16.23	19	3	18	8.8	-14.83	7.24
133	470659122325003	19N/02E-21 LC40C	B	10	M	229.76	221.95	7.81	18	0	17	10	8.37	0.52
134	470659122325102	19N/02E-21 LC40D	C	10	M	182.37	198.98	-16.61	17	0	16	10	-15.82	1.08
135	470540122221901	19N/03E-36C01	A1	3	S	352.24	369.28	-17.04	1	0	1	10	-5.76	NA
136	470707122361101	19N/02E-19 LF4MW13A	A1	10	M	214.41	218.03	-3.62	18	0	17	10	-3.40	0.48
137	470706122361101	19N/02E-19 LF4MW13B	A3	10	M	212.33	214.69	-2.36	18	0	17	10	-2.26	0.42
138	470702122353201	19N/02E-19 LF4MW02C	C	10	M	124.95	127.58	-2.63	30	0	28	10	-2.11	0.58
139	470701122353601	19N/02E-19 LF4MW02A	A1	10	M	225.29	219.17	6.12	30	0	28	10	6.37	0.72
140	470701122353501	19N/02E-19 LF4MW02B	A3	10	M	230.06	222.78	7.28	19	0	15	10	7.54	0.36
141	470423122170502	18N/04E-03A04D1	C	3	S	451.15	452.14	-0.99	1	0	1	10	2.71	NA
142	470525122225201	19N/03E-35H02	A1	3	S	365.12	371.88	-6.76	1	0	1	10	4.27	NA
143	470705122380501	19N/01E-23 93LF54SS	C	10	M	81.31	77.97	3.34	18	0	17	10	3.69	0.47
144	470429122162002	18N/04E-03H03D1	C	3	S	453.30	480.20	-26.90	1	0	1	10	-23.07	NA
145	470620122312003	19N/02E-21 LC21C	C	10	M	269.82	279.27	-9.45	18	0	17	10	-8.66	0.55

Table 13. Wells used in model calibration, Chambers-Clover Creek watershed, Washington.—Continued

[**Weighting factor:** Applied according to a relative scale from 1 to 10. **Measurements with status:** Number of measurements affected by pumping, recovering, or flowing conditions. **Abbreviations:** HGU, Hydrogeologic-Unit; S, synoptic measurement; M, monthly measurements; NA, not applicable]

Map No. (fig. 7)	Site identification No.	Local well No.	HGU	Weight- ing factor	Type	Measured groundwater altitude	Simulated steady state water level	Steady state residual	Total measure- ments	Measure- ments with status	Transient target measure- ments	Mean of transient weighting factors	Mean of transient residuals	Standard deviation of transient residuals
146	470413122145301	18N/04E-01N03	A1	10	M	563.84	555.41	8.43	19	3	18	8.8	8.90	1.47
147	470619122330301	19N/02E-28 LC75D	C	10	M	239.79	243.79	-4.00	18	0	17	10	-3.35	1.98
148	470605122315901	19N/02E-44 9700MW1	A1	10	M	270.34	269.47	0.87	18	0	17	10	1.64	1.27
149	470603122305101	19N/02E-26 LC149C	A3	10	M	275.85	293.90	-18.05	20	0	18	10	-16.96	0.91
150	470519122241001	19N/03E-34L02	A3	3	S	366.63	360.23	6.40	1	0	1	10	12.75	NA
151	470503122240501	19N/03E-34R02	A3	10	M	372.88	366.45	6.43	19	0	18	10	8.56	1.20
152	470339122125601	18N/03E-07G04	C	3	S	644.67	696.25	-51.58	1	0	1	10	-30.22	NA
153	470343122131801	18N/03E-07F08D1	C	9	M	656.08	659.23	-3.15	11	0	11	10	-0.74	2.04
154	470343122131801	18N/03E-07F08D1	A3	8	M	853.61	673.75	179.86	6	1	6	8.8	180.07	3.45
155	470425122193001	18N/04E-05L02	A1	5	S	395.63	431.02	-35.39	3	0	4	10	-20.96	2.83
156	470416122182701	18N/04E-04P05	C	10	M ¹	445.41	437.52	7.89	19	19	22	5	10.51	3.67
157	470437122234702	18N/03E-02D01D1	A3	3	S	374.30	369.48	4.82	1	0	1	10	12.55	NA
158	470608122354401	19N/02E-30 LC89D1	C	10	M	131.65	129.37	2.28	18	0	17	10	2.29	0.87
159	470635122393401	19N/01E-27B01	C	3	S	60.97	55.05	5.92	1	0	1	10	4.76	NA
160	470330122133902	18N/03E-07P03D1	A3	10	M	652.72	706.49	-53.77	19	1	18	9.6	-52.24	4.32
161	470309122130701	18N/03E-18B02	C	3	S	636.84	698.58	-61.74	1	0	1	10	-50.38	NA
162	470411122213501	18N/03E-01R01	A3	1	S	363.34	401.66	-38.32	1	1	1	3	-30.40	NA
163	470304122133101	18N/03E-18D03	C	3	S	645.28	688.04	-42.76	1	0	1	10	-33.45	NA
164	470234122185901	18N/04E-17J03	A2	10	M ¹	477.80	499.83	-22.03	19	19	22	5	-19.82	1.52
165	470303122140901	18N/04E-13B06	A3	1	S	685.69	690.45	-4.76	1	1	1	3	9.42	NA
166	470403122224001	18N/03E-12D03	A3	3	S	383.35	382.29	1.06	1	0	1	10	7.79	NA
167	470343122203301	18N/04E-07G01	A2	10	M	409.70	422.15	-12.45	19	3	18	8.8	-9.97	3.40
168	470327122182901	18N/04E-09P03	A2	10	M ¹	487.47	458.76	28.71	19	19	22	5	31.26	4.42
169	470416122254101	18N/03E-04Q02	A3	10	M	381.09	362.73	18.36	19	0	18	10	19.68	1.36
170	470251122145401	18N/04E-13E04	A3	10	M	688.42	681.17	7.25	19	0	18	10	9.71	4.62
171	470249122143501	18N/04E-13F06	A3	3	S	731.84	684.79	47.05	1	0	1	10	61.28	NA
172	470221122134601	18N/03E-18N04	A3	10	M	695.92	688.46	7.46	19	3	18	8.8	9.68	3.81
173	470221122135201	18N/04E-13R03	A3	1	S	699.74	687.18	12.56	1	1	1	3	25.86	NA
174	470204122132301	18N/03E-19C05	A2	3	S	673.80	711.62	-37.82	1	0	1	10	-19.96	NA
175	470317122234101	18N/03E-11N04	A1	10	M	395.47	388.26	7.21	18	0	17	10	9.25	1.52
176	470225122165102	18N/04E-15R02D1	A3	3	S	641.44	665.10	-23.66	1	0	1	10	-9.84	NA
177	470217122163901	18N/04E-22A01	C	10	M	647.78	660.01	-12.23	20	0	19	10	-11.20	2.10
178	470337122171901	18N/04E-10F03	A3	10	M ¹	523.42	528.66	-5.24	19	19	21	5	-2.71	2.70
179	470501122405001	19N/01E-33Q01	C	10	M	57.66	60.11	-2.45	19	3	18	8.8	-1.91	1.08
180	470210122180701	18N/04E-21B02	A3	10	M	630.91	628.49	2.42	19	3	18	8.8	4.76	4.16
181	470208122175001	18N/04E-21A03	C	3	S	618.31	626.61	-8.30	1	0	1	10	-0.65	NA

Table 13. Wells used in model calibration, Chambers-Clover Creek watershed, Washington.—Continued

[**Weighting factor:** Applied according to a relative scale from 1 to 10. **Measurements with status:** Number of measurements affected by pumping, recovering, or flowing conditions. **Abbreviations:** HGU, Hydrogeologic-Unit; S, synoptic measurement; M, monthly measurements; NA, not applicable]

Map No. (fig. 7)	Site identification No.	Local well No.	HGU	Weight- ing factor	Type	Measured groundwater altitude	Simulated steady state water level	Steady state residual	Total measure- ments	Measure- ments with status	Transient target measure- ments	Mean of transient weighting factors	Mean of transient residuals	Standard deviation of transient residuals
182	47024012224301	18N/03E-14J02	A3	10	M	402.14	391.65	10.49	19	0	18	10	12.38	3.02
183	470218122204601	18N/04E-19B02	A3	1	S	475.87	449.73	26.14	1	1	1	3	34.54	NA
184	470133122182801	18N/04E-21M02	A3	3	S	693.83	609.83	84.00	1	0	1	10	98.71	NA
185	470148122175201	18N/04E-21J01	C	3	S	626.71	641.70	-14.99	1	0	1	10	-7.53	NA
186	470148122205301	18N/04E-19L04	C	10	M	457.47	459.96	-2.49	19	0	18	10	-0.41	2.25
187	470418122423101	18N/01E-38R01	C	3	S	13.74	29.84	-16.10	1	0	1	10	-15.69	NA
188	470150122215301	18N/03E-24K01	A3	8	M	467.81	438.85	28.96	19	10	18	6.1	30.62	1.46
189	470146122214501	18N/03E-24K02	A3	1	S	443.43	445.33	-1.90	1	1	1	3	4.24	NA
190	47011122173601	18N/04E-27E03	A3	10	M	692.33	673.62	18.71	18	0	17	10	20.38	4.15
191	470054122162701	18N/04E-27J03	A2	3	S	707.46	684.62	22.84	1	0	1	10	37.96	NA
192	470134122215001	18N/03E-24Q03	A3	3	S	469.21	451.52	17.69	1	0	1	10	23.08	NA
193	470133122215101	18N/03E-24Q02	A3	3	S	442.67	451.50	-8.83	1	0	1	10	-3.49	NA
194	470056122190101	18N/04E-29J05	C	10	M	629.74	627.23	2.51	20	0	19	10	3.85	1.77
195	470104122251201	18N/03E-27E05	A3	1	S	388.61	393.42	-4.81	1	1	1	3	-1.49	NA
196	470114122244501	18N/03E-27L04	A1	10	M	402.80	406.39	-3.59	19	0	18	10	-2.15	5.19
197	465928122154401	17N/04E-02B01	A3	3	S	662.65	681.70	-19.05	1	0	1	10	-14.04	NA
198	465948122232801	18N/03E-35P03	C	3	S	456.81	460.68	-3.87	1	0	1	10	-0.03	NA
199	470204122401701	18N/01E-22P01	C	9	M	44.40	58.40	-14.00	18	5	17	8.5	-13.28	2.47
200	465931122224701	17N/03E-02A02	A1	3	S	460.74	486.75	-26.01	1	0	1	10	-25.32	NA
201	470033122312101	18N/02E-35D01	C	8	M	317.10	318.84	-1.74	20	12	19	5.6	-0.56	2.49
202	470013122301801	18N/02E-38 01IAMW14	A2	8	M	368.20	361.23	6.97	15	0	14	10	8.21	1.45
203	470027122324401	18N/02E-34D02	A1	10	M	303.17	299.59	3.58	19	0	18	10	4.20	1.27
204	465933122242801	17N/03E-03B02	C	10	M	451.84	445.29	6.55	19	2	18	9.2	8.57	2.71
205	465819122152301	17N/04E-11J01	A3	10	M	662.84	661.97	0.87	16	0	16	10	2.79	2.30
206	470020122312001	18N/02E-35K01	A3	3	S	326.71	344.85	-18.14	1	0	1	10	-15.18	NA
207	465923122251701	17N/03E-04H01	A1	3	S	402.50	439.71	-37.21	1	0	1	10	-31.21	NA
208	465946122293301	17N/02E-01B02	A1	3	S	374.24	386.14	-11.90	1	0	1	10	-3.93	NA
209	465956122314201	18N/02E-34R03	A2	3	S	317.83	334.05	-16.22	1	0	1	10	-13.52	NA
210	465813122190401	17N/04E-08J01	A3	3	S	532.84	644.07	-111.23	1	0	1	10	-105.53	NA
211	465903122262701	17N/03E-04N03	A3	10	M	410.31	413.88	-3.57	19	1	18	9.6	-0.86	2.73
212	465920122300501	17N/02E-01M04	C	9	M	333.12	349.89	-16.77	19	7	18	7.7	-14.98	2.48
213	465833122304001	17N/02E-11G01	A3	3	S	314.83	350.88	-36.05	1	0	1	10	-28.04	NA
214	465702122232601	17N/03E-23C02	A2	3	S	487.44	465.96	21.48	1	0	1	10	32.31	NA
215	465628122185301	17N/04E-21M01	A2	3	S	654.16	622.20	31.96	1	1	1	3	39.59	NA
216	465632122215202	17N/03E-24K08D1	A1	3	S	518.33	544.35	-26.02	1	0	1	10	-17.76	NA
217	465639122230901	17N/03E-23K01	A1	10	M	492.61	500.25	-7.64	19	0	18	10	-5.93	1.83
218	465612122183801	17N/04E-28D02	A2	10	M	606.07	596.99	9.08	19	3	18	8.8	9.61	3.47

Table 13. Wells used in model calibration, Chambers-Clover Creek watershed, Washington.—Continued

[**Weighting factor:** Applied according to a relative scale from 1 to 10. **Measurements with status:** Number of measurements affected by pumping, recovering, or flowing conditions. **Abbreviations:** HGU, Hydrogeologic-Unit; S, synoptic measurement; M, monthly measurements; NA, not applicable]

Map No. (fig. 7)	Site identification No.	Local well No.	HGU	Weight- ing factor	Type	Measured groundwater altitude	Simulated steady state water level	Steady state residual	Total measure- ments	Measure- ments with status	Transient target measure- ments	Mean of transient weighting factors	Mean of transient residuals	Standard deviation of transient residuals
219	465617122213002	17N/03E-24R07D1	A3	3	S	498.39	548.22	-49.83	1	0	1	10	-39.64	NA
220	465649122324301	17N/02E-22E01	A3	10	M	330.89	319.53	11.36	19	3	18	8.8	12.99	2.46
221	465625122292301	17N/02E-24Q04	A3	3	S	428.46	384.09	44.37	1	0	1	10	55.30	NA
222	465635122311001	17N/02E-23L03	A3	3	S	383.13	348.68	34.45	1	0	1	10	43.66	NA
223	465631122322201	17N/02E-22L01	A3	1	S	345.20	325.62	19.58	1	1	1	3	26.41	NA
224	465425122265801	16N/03E-05B01	A3	10	M	586.62	541.72	44.90	19	0	18	10	49.94	12.45
225	465416122270701	16N/03E-05G03	A3	1	S	583.27	538.82	44.45	1	1	1	3	69.28	NA
226	465353122272001	16N/03E-05L01	A3	3	S	492.93	521.56	-28.63	1	0	1	10	-8.72	NA
227	465350122282601	16N/03E-06Q01	A3	3	S	344.10	443.42	-99.32	2	0	2	10	-87.61	0.56
228	465319122261801	16N/03E-09E01	A3	10	M	464.92	490.51	-25.59	19	0	18	10	-24.54	1.15

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