Prepared in cooperation with the Cities of Auburn, Milton, Puyallup, Sumner, and Tacoma; Pierce Conservation District; Pierce County Public Works; Washington State Department of Health; Washington State Department of Ecology; Thurston County Public Utility District; Cascade Water Alliance; Lakehaven Utility District; Lakewood Water District; Firgrove Mutual Water Company; Fruitland Mutual Water Company; Spanaway Water Company; Summit Water & Supply Company; and Mt. View-Edgewood Water Company

Conceptual Hydrogeologic Framework and Groundwater Budget Near the Southeastern Part of Puget Sound, Washington

Chapters A–C of
Characterization of Groundwater Resources Near the Southeastern Part of Puget Sound, Washington, volume 1

Scientific Investigations Report 2024–5026–A–C

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

Cover. Port of Tacoma and southeastern Puget Sound with Mount Rainier in background, Washington, September 2, 2009. Photograph and copyrighted by Joseph E. Becker, Seldom Seen Photography; used with permission.

Conceptual Hydrogeologic Framework and Groundwater Budget Near the Southeastern Part of Puget Sound, Washington

Edited by Wendy B. Welch

Chapter A
Introduction and Background

By Wendy B. Welch and Sarah B. Dunn

Chapter B
Conceptual Hydrogeologic Framework

By Wendy B. Welch, Valerie A.L. Bright, Sarah B. Dunn, and Elisabeth T. Fasser

Chapter C
Groundwater Budget

By Andrew S. Gendaszek, Valerie A. L. Bright, and Alexander O. Headman

Prepared in cooperation with the Cities of Auburn, Milton, Puyallup, Sumner, and Tacoma; Pierce Conservation District; Pierce County Public Works; Washington State Department of Health; Washington State Department of Ecology; Thurston County Public Utility District; Cascade Water Alliance; Lakehaven Utility District; Lakewood Water District; Firgrove Mutual Water Company; Fruitland Mutual Water Company; Spanaway Water Company; Summit Water & Supply Company; and Mt. View-Edgewood Water Company

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Preface

This is the first of two reports in a multichapter volume characterizing groundwater resources near the southeastern part of Puget Sound, Washington. Chapters A, B, and C (this report) provide an overall introduction to the multichapter volume (Chapter A), the conceptual hydrogeologic framework (Chapter B), and the groundwater budget (Chapter C). Chapters D and E (Long and others, 2024) describe numerical groundwater-flow model construction and calibration (Chapter D) and the numerical groundwater-flow model results (Chapter E). Collectively, these two reports present a characterization and simulation tool for groundwater resources near the southeastern part of Puget Sound, Washington.

Acknowledgments

The conceptual hydrogeologic framework and groundwater budget described in this report were developed by the U.S. Geological Survey (USGS) with the assistance of a large team of technical experts and advisors from the hydrogeologic community. This technical team consisted of representatives of the following organizations: the cities of Auburn, Milton, Puyallup, Sumner, and Tacoma; Pierce Conservation District; Pierce County Public Works; Washington State Department of Health; Washington State Department of Ecology; Thurston County Public Utility District; Cascade Water Alliance; Lakehaven Utility District; Lakewood Water District; Firgrove Mutual Water Company; Fruitland Mutual Water Company; Spanaway Water Company; Summit Water & Supply Company; and Mt. View-Edgewood Water Company. Special appreciation is acknowledged to the following technical team members for providing in-depth courtesy reviews of the draft report manuscript and numerical groundwater model: Joe Becker, Burt Clothier, Shuhui Dun, Andy Dunn, and Peter Schwartzman. Furthermore, we thank USGS peer reviewers Stephen Hundt and Sue Kahle (emeritus) for their thorough reviews of the manuscript and model.

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
	Area	
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
cubic inch (in^3)	16.39	cubic centimeter (cm^3)
cubic inch (in^3)	0.01639	cubic decimeter (dm^3)
cubic inch (in^3)	0.01639	liter (L)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	0.001233	cubic hectometer (hm^3)
	Flow rate	
foot per day (ft/d)	0.3048	meter per day (m/d)
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)

Multiply	By	To obtain
acre-foot per year (acre-ft/yr)	0.001233	cubic hectometer per year (hm^3/yr)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)

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

°C = (°F – 32) / 1.8.

Datums and Coordinate System

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

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

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

Following is the reference coordinate system used for the development of the hydrogeologic framework:

Category	Description
Coordinate system	NAD_1983_StatePlane_Washington_South_FIPS_4602_Feet
Study Projection	Lambert Conformal Conic
Linear unit	Feet, US
False easting	1640416.667
False northing	0
Central meridian	–120.5
Standard parallel 1	45.83333333
Standard parallel 2	47.33333333
Latitude of origin	45.33333333

Well-Numbering System

Wells in the State of Washington are assigned a local well number that identifies each well based on its location in a township, range, section, and 40-acre tract. For example, local well number 20N/04E-14B01 indicates that the well is in township 20 north of the Willamette Base Line, and range 4 east of the Willamette Meridian. The numbers immediately following the hyphen indicate the section (14) in the township. Most range-townships in Washington are divided into 36 equal sections of 1 square mile (640 acres) numbered from 1 to 36. However, the Washington Territory Donation Land Claims of 1852–55 predate the Public Lands Survey and appear on maps as irregularly sized and shaped sections with assigned section numbers greater than 36. The letter following the section (B) gives the 40-acre tract of the section. The two-digit sequence number (01) following the letter is used to distinguish individual wells in the same 40-acre tract. A "D" following the sequence number indicates a well that has been deepened. In the plates of this report, wells are identified using only the section and 40-acre tract, such as 14B01; the township and range are shown on the map borders.

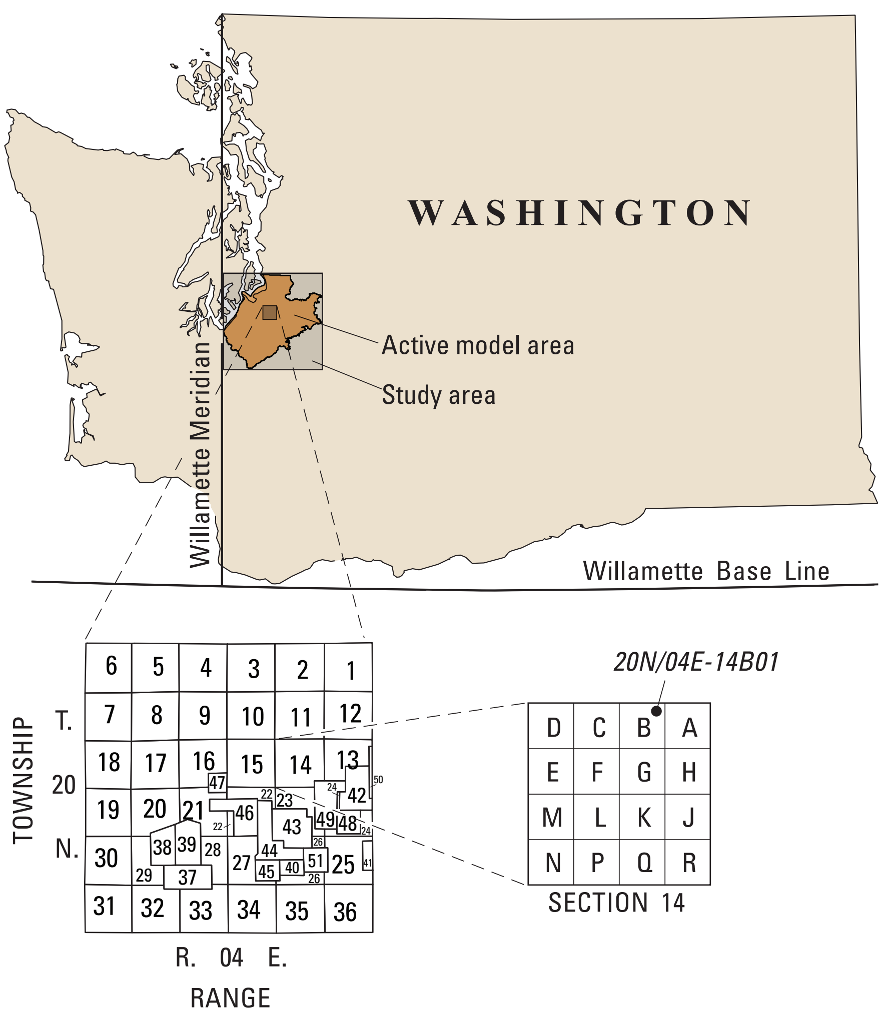


Diagram showing well-numbering system used in Washington.

Abbreviations

ΔS	change in groundwater storage
A1	A1 aquifer
A2	A2 confining unit
A3	A3 aquifer
AL1	AL1 upper alluvial aquifer
AL2	AL2 lower alluvial aquifer (only in subsurface)
AMA	active model area
AWC	available water capacity
B	B confining unit
C	C aquifer
D	D confining unit
E	E aquifer
Ecology	Washington State Department of Ecology
F	F confining unit
G	G undifferentiated deposits
GW_{in}	groundwater inflow
GW_{out}	groundwater outflow
HGU	hydrogeologic unit
HYSEP	hydrograph separation program
Kh	horizontal hydraulic conductivity, in dimensions of foot per day
LOSS	large on-site sewage systems
MFLU	upland mudflow confining unit
MFLV	valley mudflow confining unit
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
NRCS	Natural Resources Conservation Service
NWIS	U.S. Geological Survey National Water Information System
PLSS	Public Land Survey System

R_{GWR}	groundwater-return flow recharge
R_P	precipitation recharge
SF_{in}	infiltration of surface-water features
SF_{out}	outflow of surface-water features
SSURGO	Soil Survey Geographic Database
STATSGO	State Soil Geographic Database
SWB	Soil-Water-Balance (model)
USGS	U.S. Geological Survey
WADOH	Washington State Department of Health

Conceptual Hydrogeologic Framework and Groundwater Budget Near the Southeastern Part of Puget Sound, Washington

Edited by Wendy B. Welch

Executive Summary

More than 1 million people live within the active model area (AMA) in the southeastern part of the lowlands surrounding Puget Sound, or Puget Lowland, Washington, and groundwater is the source for approximately one-half of their public, domestic, and irrigation water demands. The 887-square-mile AMA, located in King and Pierce Counties, represents the area of analysis for the conceptual hydrogeologic framework and numerical groundwater-flow models within the study area and includes the Puyallup River and Chambers-Clover Creek watersheds. To assess the potential hydrologic and anthropogenic impacts to groundwater and the connected surface-water resources, conceptual and numerical groundwater-flow models of groundwater flow were developed by the U.S. Geological Survey Washington Water Science Center in close cooperation with 18 water-resource agencies and stakeholders.

This report presents information used to characterize the groundwater-flow system and the development of a numerical model in the AMA. Included are descriptions of the geology and conceptual hydrogeologic framework, groundwater levels and flow directions, groundwater recharge and discharge, numerical groundwater-flow model construction and results, and model limitations. The study area encompasses the western part of Pierce County and the southwestern part of King County, Washington. The study area extends south to the Nisqually River, southwest to Tanwax Creek, northeast to the Green River, and north through the valley near Auburn and adjacent uplands. It is bounded on the east by foothills of the Cascade Range, and on the northwest by Puget Sound.

Geologic Setting

The study area consists of a thick sequence of unconsolidated Quaternary glacial and interglacial sediments (unconsolidated sediments) unconformably deposited over Tertiary volcanic and sedimentary bedrock units. The unconsolidated sediments were largely derived from Pleistocene continental glaciations, with minor contributions from alpine glaciations, alluvial processes, and mudflows or lahars. The sediments taper from a thin veneer (5–10 feet [ft]) over bedrock in the Cascade Range foothills in the east to more than 2,000 ft in the northwestern part of the study area. Tectonic, glacial, and post-glacial processes resulted in the present topography, stratigraphy, and hydrogeology of the study area.

Hydrogeology

Geologic units were grouped into 14 hydrogeologic units, consisting of aquifers, confining units, and an underlying bedrock unit. The units were grouped based on similarities in lithology (grain size and sorting), hydrologic characteristics, and relative stratigraphic position. An aquifer is saturated geologic material with high permeability capable of yielding water in substantial quantities to wells or springs, whereas lower permeability geologic materials that limit the movement of groundwater are confining units. Geologic units, composed of coarse-grained sediments, generally have higher permeabilities than fine-grained or poorly sorted sediments. In the Puget Lowland, saturated glacial outwash or coarse-grained interglacial sediments form primary aquifers, whereas till and glaciolacustrine sediments form confining units. A high degree of heterogeneity exists in the unconsolidated sediments, resulting in localized areas of high permeability within confining units, or low permeability within aquifers. The Tertiary bedrock units typically have low permeabilities and form the basal unit of the study.

Potentiometric Surfaces and Flow Directions

Within the AMA, potentiometric surfaces for each hydrogeologic unit were developed from water levels that were measured in wells as part of an earlier Chambers-Clover Creek watershed study and a Puyallup River watershed study, and that were supplemented by previously collected water levels in the U.S. Geological Survey National Water Information System database. Groundwater generally moves

from areas of recharge to areas of discharge in the direction of decreasing water-level altitudes, and the flow direction is perpendicular to water-level altitude contours. In the AMA, horizontal groundwater flow is generally toward the northwest with localized flow in shallower units toward major river valleys and Puget Sound and radially from groundwater highs in upland areas.

Generalized Groundwater and Surface-Water Interactions

Groundwater movement and interaction with surface-water features occur within the physical domain described by the conceptual hydrogeologic framework and are influenced by the characteristics of the aquifer system. Groundwater in the study area discharges as seepage to streams, lakes, springs, marshes, and coastal bluffs. Surface water interacts with groundwater in aquifers, resulting in exchange or seepage, which can recharge aquifers or maintain streamflow depending on the hydraulic gradient. Groundwater is discharged to streams where the altitude of the water table is higher than the altitude of the stream surface (gaining reach/stream). Conversely, if the altitude of the stream surface is higher than the altitude of the water table, streamflow will seep into the underlying groundwater system (losing reach/stream). Additionally, groundwater pumping in nearby wells can reduce the amount of water available to maintain streamflow and can draw streamflow into the underlying groundwater system. Within the study area, many rivers receive a substantial part of their flow from groundwater; however, contributions from melting snow and glacial ice are also important.

Groundwater Budget

Inflow components of the estimated groundwater budget for the AMA consist of precipitation recharge, recharge from anthropogenic sources, and seepage to groundwater from Lake Tapps. Outflow components consist of well withdrawals and natural groundwater discharge to streams, springs, lakes, and Puget Sound. Estimates of groundwater-budget components were averaged over the entire 11-year period from January 2005 to December 2015 and monthly during the same period.

Forty-three percent of mean annual precipitation, which averaged 50.5 inches per year (in/yr) for the 11-year period, percolated below the root zone as precipitation recharge to groundwater (21.9 in/yr). The remainder of the precipitation was removed by evapotranspiration (30 percent; 15.3 in/yr) and surface runoff (20 percent; 10 in/yr) and was intercepted by vegetation (6 percent; 3.3 in/yr).

Precipitation recharge to groundwater (21.9 in/yr) accounted for 98 percent of total inflow to the groundwater system within the AMA for the 11-year period. For comparison to precipitation recharge, other groundwater budget components also are given in inches per year, as if uniformly distributed over the AMA. The remaining groundwater inflows were supplied by groundwater return flow from anthropogenic sources (1 percent; 0.3 in/yr) and seepage from Lake Tapps (1 percent; 0.2 in/yr). Groundwater recharge and other groundwater-budget components varied seasonally and between years because of seasonal and inter-annual changes in precipitation and temperature. Additionally, differences in the properties of soils, land cover, and other variables that affected the infiltration of water into aquifers affected the spatial distribution of recharge.

Withdrawals from wells for domestic, agricultural, and commercial water use collectively accounted for 1.6 in/yr, which represented 7 percent of total groundwater discharge. An additional 14.8 in/yr (66 percent) of groundwater was estimated to discharge to streams, with the balance of groundwater discharge inferred to result from flow to unmeasured streams or other surface-water features including springs, lakes, wetlands, and Puget Sound (6.0 in/yr; 27 percent).

Glossary

active model area (AMA) The part (887 square miles) of the study area that includes the conceptual hydrogeologic framework, estimated groundwater-budget, and numerical groundwater-flow model.

base flow The component of streamflow that results from groundwater inflow to the stream.

conceptual hydrogeologic framework (framework) A spatially continuous, three-dimensional representation of hydrogeologic units, maps of the extents and thicknesses of major water-bearing units, groundwater levels, potentiometric surfaces, groundwater flow directions and generalized groundwater/surface-water interactions.

glacial terminus End of the glacier.

Holocene Epoch representing the most recent interglacial interval of the Quaternary Period.

hydraulic conductivity Rate of groundwater flow per unit area under a unit hydraulic gradient (unit: length/time).

isostatic rebound Also known as post-glacial rebound, is the rise of the land masses that occurs when the huge weight of ice sheets and glaciers is removed through melting.

lahar A volcanic mudflow, a flowing slurry or volcanic debris mixed with water from melted snow, ice, or rain.

large spring A spring that has been identified and generally named and has larger discharge than a seep.

mean monthly The average for a given month of the year; for example, the average streamflow for all months of March for the period of record.

potentiometric surface A surface representing the static head of groundwater in tightly cased wells that tap a water-bearing rock unit (aquifer) or, in the case of unconfined aquifers, the water table (see https://doi.org/10.3133/wsp1988).

precipitation recharge Groundwater recharge from precipitation on the land surface.

reach Defined for numerical modeling as the stream segment within one model cell.

sedimentary facies Succession of sedimentary facies or distinct, adjacent bodies of sediment that result from different depositional environments.

seep Small spring located along the bluffs of river valleys and Puget Sound with less discharge than a large spring.

stream Rivers, their tributaries, and other streams and creeks.

streamgage Station at which hydrologic data are collected.

subduction zone A tectonic zone where a plate with oceanic crust is going downward beneath the margin of an adjacent plate.

Chapter A. Introduction and Background

By Wendy B. Welch and Sarah B. Dunn

Introduction

In the lowlands between the southeastern part of Puget Sound and the Cascade Range, Washington (figs. A1, A2), public supply, domestic supply, and agricultural water use is met through a combination of groundwater and surface-water withdrawals. In addition to helping meet human water use needs, groundwater discharge sustains streamflows that support aquatic ecosystems, particularly during the summer dry season when surface runoff is minimal. To effectively manage groundwater use without endangering aquatic ecosystems, natural resource managers have looked to conceptual and numerical models of the groundwater-flow system to better understand how the groundwater system might respond to changes in climatic conditions and groundwater withdrawals.

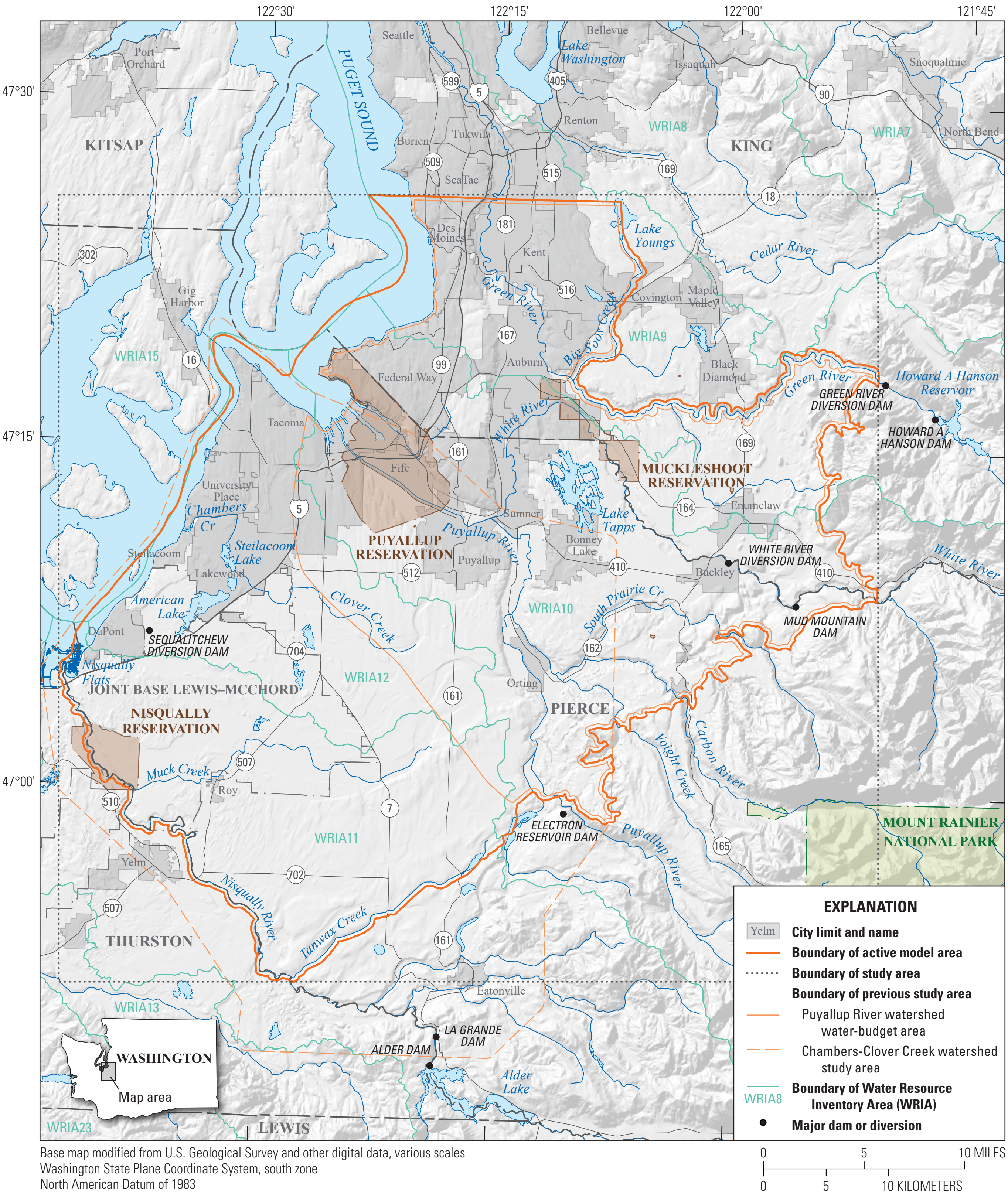
In 2006, the U.S. Geological Survey (USGS), in cooperation with State and local study-funding partners, began collecting hydrologic and hydrogeologic data within the area to support the development of a conceptual hydrogeologic framework (hereinafter referred to as framework) and construction of a numerical groundwater-flow model (hereinafter referred to numerical model) for the Chambers-Clover Creek watershed (Savoca and others, 2010) and Puyallup River watershed (Welch and others, 2015) (fig. A1). In 2018, these frameworks were merged, and one spatially continuous framework was developed that included maps of the extents and thicknesses of major water-bearing units, groundwater-flow directions, and estimates of groundwater/surface-water interactions. This merged framework was used to construct a numerical model to simulate the effects of future groundwater withdrawals and climatic conditions on the groundwater-flow system.

Purpose and Scope

The purpose of this multichapter volume is to describe the (1) framework, (2) the groundwater budget, and (3) the numerical model results for 10 climate and water-use scenarios in the lowland area between the southeastern part of Puget Sound and the Cascade Range (figs. A1, A2). This multichapter volume includes descriptions of the geology and framework, groundwater levels and flow directions, groundwater recharge and discharge, numerical model construction and results, and model limitations. Also described in this report are hydrologic and hydrogeologic data collection methods and how these data were used to construct and inform the framework and numerical model. The numerical model documentation includes explanations of boundary conditions, model input parameters, calibration approach, groundwater budget calculations, and sensitivity analysis. Results from this study can assist resource managers in evaluating the response of groundwater water levels and stream base flows to potential changes in water use and drought conditions.

Previous USGS Investigations

Prior to this study, the USGS was conducting independent yet geographically overlapping groundwater studies for the Puyallup River and Chambers-Clover Creek watersheds (fig. A1). In 2018, the USGS and 18 cooperators merged the Puyallup River and Chambers-Clover Creek watershed studies and created a single comprehensive framework and numerical model that includes the Puyallup River and Chambers-Clover Creek watershed study areas. The following paragraphs summarize the products and timelines of the Puyallup River and Chambers-Clover Creek watershed studies prior to consolidation.



Base map modified from U.S. Geological Survey and other digital data, various scales
Washington State Plane Coordinate System, south zone
North American Datum of 1983

Figure A1. Location of the study area and active model area near the southeastern part of Puget Sound, Washington.

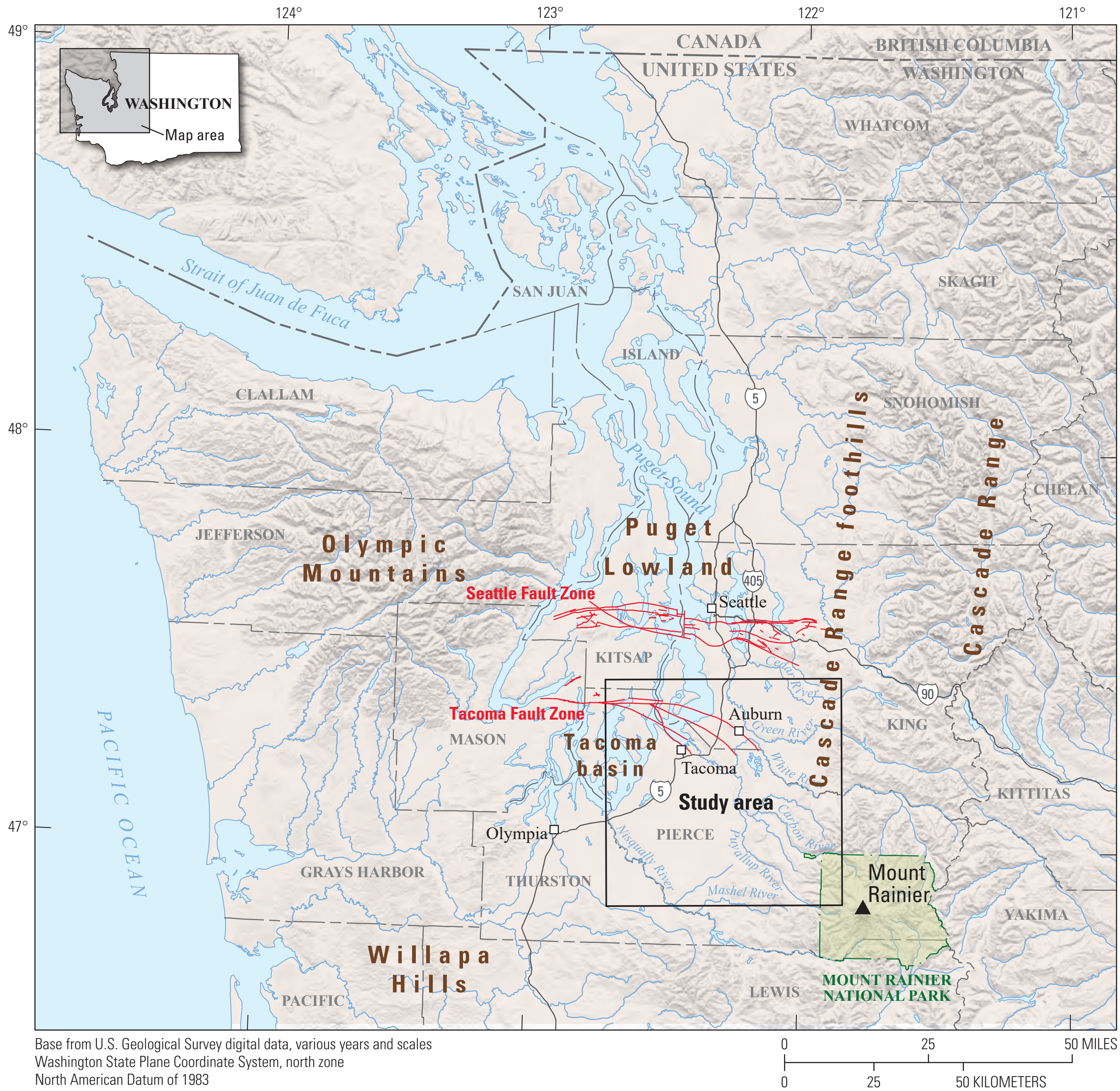


Figure A2. Location of the study area in the Puget Lowland region with prominent physiographic features, northwestern Washington State.

Chambers-Clover Creek Watershed

In 2006, the USGS, in cooperation with the 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 study to characterize the groundwater-flow system in the Chambers-Clover Creek watershed and vicinity. The framework and groundwater budget (Savoca and others, 2010) and the numerical model (Johnson and others, 2011) were published prior to the current study. Monthly water-level altitude measurements (water levels) from a groundwater monitoring well network (Justin and others, 2009) and streamflow measurements from 2007 to 2008 were incorporated in the Johnson and others (2011) numerical model. Understanding the benefit of long-term groundwater monitoring, local stakeholders supported continued monthly measurements from the monitoring well network that extended the period of record through 2015 and provided additional data for potential future refinement of the numerical model. In 2015, multiple water-resource agencies and stakeholders requested that the USGS update and refine the 2011 groundwater model, incorporate the water-level measurements from the reactivated network, and make other model improvements.

Puyallup Watershed

In 2011, the USGS, in cooperation with multiple State and local study-funding partners (some of whom were also members of the Chambers-Clover Creek watershed stakeholder group), began studying the groundwater-flow system in the Puyallup River watershed and vicinity. Soon after Welch and others (2015) published the framework, development began on the numerical model using data from a monthly groundwater monitoring network (Lane and others, 2013) and streamflow measurements from 2011 to 2012. Because of the large area of overlap, shared model boundaries, and the desire for a single regional model with consistent input data and results, in 2018 the Puyallup River and Chambers-Clover Creek watershed studies were combined.

Description of the Study Area

The study area encompasses the western part of Pierce County and the southwestern part of King County, Washington (fig. A1). It includes the entirety of the Puyallup and Muckleshoot Reservations, and most of the Nisqually Reservation. The study area extends south to the Nisqually River, southwest to Tanwax Creek, northeast to the Green River, and north through the valley near Auburn. It is bounded on the east by foothills of the Cascade Range and on the northwest by Puget Sound. These hydrologic and physiographic features were used in the conceptual and numerical model and constrained the groundwater and surface-water data collection.

Physiography, Drainage Features, and Land Use

The study area is in the southeastern part of the Puget Lowland, a broad, low-lying region situated between the Cascade Range to the east and the Olympic Mountains and Willapa Hills to the west (fig. A2). The Puget Lowland is characterized by glacial landforms including the north-south trending glacial troughs of Puget Sound, fluted till uplands, kettles, drumlins, and outwash terraces. Land-surface altitude in the study area ranges from approximately 2,380 ft in the Cascade Range foothills, to sea level near Puget Sound. The topography consists of a series of poorly drained, fluted upland plains divided by northwest-trending rivers and ravines incised by small streams tributary to the major rivers.

Major perennial rivers occupy large, relatively flat valley floors and are fed by several underfit streams occupying relict glacial outwash channels. The White, Puyallup, and Nisqually Rivers originate from glaciers on Mount Rainier, an active stratovolcano to the southeast of the study area (fig. A1; plate). The Carbon and White Rivers feed the Puyallup River, which also receives flow from tributary streams Swan, Clear, and Clarks Creeks. Wapato and Hylebos Creeks enter Commencement Bay parallel to the mouth of the Puyallup River. South Prairie, Wilkeson, and Voight Creeks contribute to the Carbon River, and Boise Creek contributes to the White River in the study area. The White River historically flowed to the north as a tributary to the Green River, until it was modified in the early 20th century to flow south to the Puyallup River through a small distributary channel referred to as the Stuck River. The Green River originates in the Cascade Range (fig. A2), flowing west before turning to the north upon entering the valley near Auburn, where it is joined by Big Soos Creek. Tanwax, Muck, and Lacamas Creeks, and other small tributaries to the Nisqually River drain the southern part of the study area. Small streams flow from upland areas directly into Puget Sound. Des Moines, Massey, McSorley, Lakota, and Cold Creeks drain the northwestern uplands; Chambers and Clover Creeks drain much of the central-southwestern uplands. Many stream reaches flow year-round; however, intermittent and ephemeral flow conditions are also common in many reaches, especially during summer months. Numerous springs are present throughout the study area and contribute to late summer base flow to streams and year-round groundwater discharge to Puget Sound along shoreline bluffs.

Plate. Surficial hydrogeology, hydrogeologic sections, locations of selected wells, and surface-water measurement sites in the study area, near the southeastern part of Puget Sound, King and Pierce Counties, Washington. The plate is an Adobe Acrobat .pdf file available for download at https://doi.org/10.3133/sir20245026v1.

The White River is regulated at the Mud Mountain Dam, the Green River is regulated at the Howard Hanson Dam, the Puyallup River has a hydroelectric diversion at Electron Reservoir, and the Cascade Water Alliance diverts water from the White River into Lake Tapps (through the White River Diversion Dam) (fig. A1). Other major lakes in the study area include American, Youngs, Kapowsin, Steilacoom, Spanaway, Tanwax, Meridian, Gravelly, Harts, Chambers, and Angle Lakes (plate). These lakes formed under a variety of processes including glaciation (kettle), mudflow deposition (dam), and man-made reservoirs. Several lakes in the area reflect water levels in the shallow groundwater-flow system. Many small lakes in the area are associated with poorly drained wetland areas typically formed on glacial till deposits.

The land-cover types in the study area are simplified from 20 categories in the 2006 National Land Cover Database (NLCD) (Fry and others, 2011) and provide an understanding of general land uses in the study area. Approximately 43 percent of the study area is classified as “developed, including industrial, urban, suburban, and rural residential land-use categories. The developed areas are concentrated in the northwestern part of the study area and coincide with areas of high population density. The Port of Tacoma and the valley near Auburn constitute major industrial centers with large areas covered by impervious surfaces. Approximately 29 percent of the study area is categorized as “forest.” Forest areas are mainly in the Cascade Range foothills to the southeast and in the southwest part of the study area where several thousand acres are covered by Joint Base Lewis-McChord. Approximately 8 percent of land in the study area is categorized as planted or cultivated for agricultural use, mostly in the eastern part of the study area, with a cluster around the small city of Enumclaw. The remainder of the land cover is classified as shrublands (5 percent), grasslands (5 percent), wetlands (4 percent), barren lands (less than 1 percent), and open water (6 percent), including lakes and the part of Puget Sound within the study area boundary.

Climate

The study area has a temperate marine climate with warm, dry summers, and cool, wet winters. The Pacific Ocean and Puget Sound moderate temperatures and supply an abundance of moisture from winter storms that typically approach from the southwest. The following climate data are derived from the 1981–2010 monthly and annual normals provided by the National Oceanic and Atmospheric Administration (NOAA, 2022) for Tacoma #1 (USC00458278) and Buckley 1 NE (USC00450945) (plate). Mean annual precipitation was 39.2 inches (in.) at Tacoma and 47.8 in. at Buckley. The distribution of precipitation varies throughout the year; July and August are the driest months, with a mean total precipitation of 1.5 in. at Tacoma and 2.7 in. at Buckley. November, December, and January are the wettest months, with a mean total precipitation of 18.1 in. at Tacoma and 18.7 in. at Buckley. Mean monthly temperature at these locations ranges from about 40–41 degrees Fahrenheit (°F) in December to about 65–66 °F in August.

Population

The 2010 U.S. Census counted approximately 1,108,000 people residing in the active model area (AMA) (Washington State Office of Financial Management, 2022a). The 2000 U.S. Census counted 994,182 people residing in the AMA, indicating a 11-percent rate of growth during the10-year period. The 2010 population of the study area was mainly urban and suburban; the five most populous cities within the study area were Tacoma (198,397), Kent (92,411), Federal Way (89,306), Auburn (70,180), and Lakewood (58,163), accounting for nearly one-half of the total population (Washington State Office of Financial Management, 2022b). In addition, 32 incorporated but smaller cities are within or partially within the study area.

Geologic Setting

The Puget Lowland was shaped by a diverse and dynamic collection of geologic processes that influence groundwater flow in the region. The following summary of tectonic, glacial, and interglacial processes is based on previous geologic and hydrogeologic studies as well as published geologic maps, primarily Tabor and others (2014), Savoca and others (2010), and Borden and Troost (2001).

The study area is within the Cascadia subduction zone forearc (Johnson and others, 2004). The eastward subduction of the Juan de Fuca oceanic plate beneath the North American continental plate induced volcanism in the Cascade Range. The foothills of the Cascade Range expose Eocene to Miocene volcanic and sedimentary rocks that underlie the study area. In addition to east-west compression from the subduction zone, movement of the Pacific Plate along the San Andreas Fault, and Basin and Range extension, produce complex regional tectonic stresses (Booth and others, 2004). The northwest trending Tacoma Fault Zone defines the northern boundary of the Tacoma structural basin (Tacoma Basin), a regional depression created from the warping of rock formations due to tectonic stress. The Tacoma Basin accommodates a thick sequence of unconsolidated sediments in the northwestern part of the study area. Volcanism and tectonism have remained active processes during the Holocene, generating and deforming sediments (Barnett and others, 2010).

In the study area, a thick sequence of unconsolidated Quaternary glacial and interglacial sediments (unconsolidated sediments) was unconformably deposited over Tertiary volcanic and sedimentary bedrock units. The unconsolidated sediments were largely derived from continental glaciations that occurred during the Pleistocene, with minor contributions from alpine glaciations, alluvial processes, and mudflows or lahars (Jones, 1999; Savoca and others, 2010, table 1; Welch and others, 2015, table 1). The unconsolidated sediments taper from a thin (5–10 ft) veneer over bedrock in the Cascade Range foothills in the southeastern part of the study area to a thickness of more than 2,000 ft in the northwestern part.

Continental glaciations generated most of the unconsolidated sediments in the study area that form the primary aquifers and associated confining units. The Puget Lobe of the Cordilleran Ice Sheet advanced and retreated repeatedly in the study area during the Pleistocene, as the continental ice sheet thickened in response to global climate fluctuations. The most recent advance—referred to as the Vashon Stade of the Fraser glaciation (Jones, 1999)—occurred about 18,000 years ago. Bounded by the topography of the Cascade Range, the Puget Lobe neared its southern limit in the study area, depositing a succession of sedimentary facies (that is, distinct, adjacent bodies of sediment that result from different depositional environments as ice advanced and retreated from the area).

A typical sequence includes four sedimentary facies with distinct hydrologic properties: advance outwash, till, recessional outwash, and glaciolacustrine deposits. During periods of glacial advance, meltwater streams transported sediments southward away from the glacial terminus, depositing advance outwash. Advance outwash deposits typically consist of well-sorted coarse sand to gravel and are sufficiently permeable to form productive aquifers where saturated. The ice and outwash blocked drainages, forming proglacial lakes, which filled with silts and progressively coarser glaciofluvial sands and gravels. Glacial ice partially leveled topography, scouring, and overriding underlying sediments. Glacial till was deposited underneath and along the margins of the glaciers, in direct contact with ice. Till typically behaves as a confining unit, as it consists of a heterogenous mix of unsorted to poorly sorted sediments that range in size from clay to boulder. Lodgment till, present underneath the glacial sheet, is highly compact, reducing its ability to transmit water. During periods of glacial stagnation and retreat, meltwater streams reworked sediments into stratified recessional outwash deposits. Recessional outwash resembles advance outwash because it is typically coarse-grained (sand-gravel) and well-sorted. At the end of the Vashon Stade, proglacial lakes formed in valleys vacated by the retreating ice, accumulating stratified glaciolacustrine silts and clays. In some localities, sediment-laden outwash streams terminating in the glacially dammed lakes deposited deltas of well-sorted gravel. The stratigraphic position of these facies determines the occurrence of aquifer and confining units in the subsurface (Vaccaro and others, 1998).

An interglacial period—characterized by deposition of fluvial, lacustrine, bog, and marsh sediments—followed each major glacial period. These interglacial sediments typically consisted of clay; silt; or discontinuous lenses of sand and gravel, or peat (Borden and Troost, 2001). Alpine glaciation continued with varying intensities during interglacial periods, supplying streams with an influx of sediment from the Cascade Range. During the Holocene, the current interglacial period, isostatic rebound and changing global sea-levels has led to fluvial incision and deposition as river systems adjusted to base level and influxes of sediment.

Landslides are common along bluffs and incised channels, produced by the instability of glacial sediments and contrasts in their groundwater retention, fluvial undercutting, and wave action. Lahars also contribute sediment to the area, in quantities large enough to affect groundwater flow. Most notably, eruptions on Mount Rainier about 5,600 years ago triggered a water-saturated avalanche that transformed into a lahar known as the Osceola Mudflow (Vallance and Scott, 1997). Descending from the north and northeast flanks of the mountain, the lahar filled the valleys of the ancestral White River system (now South Prairie Creek) and extended into Puget Sound (Vallance and Scott, 1997). Although the Osceola Mudflow remains one of the most extensive lahars documented, more than 55 lahars originated from Mount Rainier during the Holocene (Crandell, 1971). Sediments deposited from the less extensive Electron Mudflow, about 500 years ago, occurred along the Puyallup River valley (Scott and Vallance, 1995; Cakir and Walsh, 2014). Mudflow and lahar deposits typically behave as confining units because they are poorly sorted with an abundant fine-grained fraction. The diversity in sediment deposition mechanisms throughout the geologic history of the region has produced a complex and heterogenous regional aquifer system.

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Chapter B. Conceptual Hydrogeologic Framework

By Wendy B. Welch, Valerie A. L. Bright, Sarah B. Dunn, and Elisabeth T. Fasser

Introduction

This chapter describes the conceptual hydrogeologic framework (hereinafter referred to as framework) including the three-dimensional representation of hydrogeologic units (HGUs), maps of the extents and thicknesses of the major water-bearing units, groundwater levels, potentiometric surfaces, groundwater-flow directions, and generalized groundwater/surface-water interactions. The framework is defined as the hydrostratigraphy, structural features, and hydraulic properties of the hydrogeologic units that constitute the groundwater-flow system. An understanding of these characteristics is important in determining the (1) occurrence, movement, and availability of groundwater in the aquifer system (2) and the exchange of water between the aquifer system and surface-water features.

Geologic units were grouped into 14 HGUs consisting of aquifers, confining units, and an underlying bedrock unit (plate). The geologic units were grouped based on their areal extent and general water-bearing characteristics. Saturated geologic units with high permeability (that is, those capable of yielding water in substantial quantities to wells or springs) were classified as aquifers, whereas less-permeable geologic units (that is, those that limit the movement of groundwater) were classified as confining units. Geologic units composed of coarse-grained sediments generally have higher permeabilities than fine-grained or poorly sorted deposits. In the Puget Lowland, saturated glacial outwash or coarse-grained interglacial sediments form primary aquifers, whereas till and glaciolacustrine sediments form confining units. Unconsolidated sediments are heterogeneous, resulting in localized areas of high permeability within confining units, or low permeability within aquifers. The Tertiary bedrock units have low hydraulic conductivities and form the basal unit of the study.

Potentiometric surfaces and directions of groundwater flow are estimated from monthly and synoptic water-level measurements taken in 273 and 85 wells, respectively, for the Chambers-Clover Creek (2007–08; 2010–15) and Puyallup River watershed (2011–13) studies (WL Measurements, Wells, McLean and others, 2024). These data were supplemented with additional water levels from the U.S. Geological Survey National Water Information System (NWIS) database, which included water levels from drillers' logs and water levels measured for previous investigations (U.S. Geological Survey, 2020). Differences in variable water-level altitudes provide potential for groundwater flow from locations of higher altitude to locations of lower altitude.

Groundwater flow in the active model area (AMA) generally flows northwest, toward Puget Sound, and toward the major river valleys through unconsolidated glacial and interglacial sediments. These generalized flow patterns are complicated by low-permeability confining units that separate discontinuous bodies of aquifer material and can impede local groundwater flow.

Groundwater recharge varies spatially across the AMA as a function of the distribution of precipitation, soils, and land cover. Precipitation is the dominant source of water recharging the groundwater-flow system. Factors such as the permeability of surficial soils and land-cover characteristics also affect the amount of recharge. For example, groundwater recharge rates would be largest in areas of high precipitation, high permeability of the soils, and low runoff land-cover types (see Chapter C, sections "Soil-Water-Balance Model" and "Discussion").

Groundwater discharge in the study area occurs as (1) seepage to streams, lakes, springs, marshes, and coastal bluffs; (2) evaporation and transpiration of shallow groundwater; (3) submarine groundwater discharge to Puget Sound; and (4) withdrawals from wells (fig. B1). Interaction between groundwater and surface-water flow is apparent in water-level changes in streams and wells, and from streamflow gains and losses measured during seepage runs (see Chapter C, section "Discharge to Streams"). Many stream reaches flow year-round; however, intermittent flow conditions are common, especially during summer when groundwater levels are lowest. Numerous springs are present throughout the study area that contribute late-summer base flow to streams and year-round groundwater discharge to Puget Sound along shoreline bluffs.

Hydrogeology—Methods

The HGUs in the study area were defined previously for the Chambers-Clover Creek and Puyallup River watershed studies using a combination of geologic data that included existing surficial geologic maps, well records with drillers'

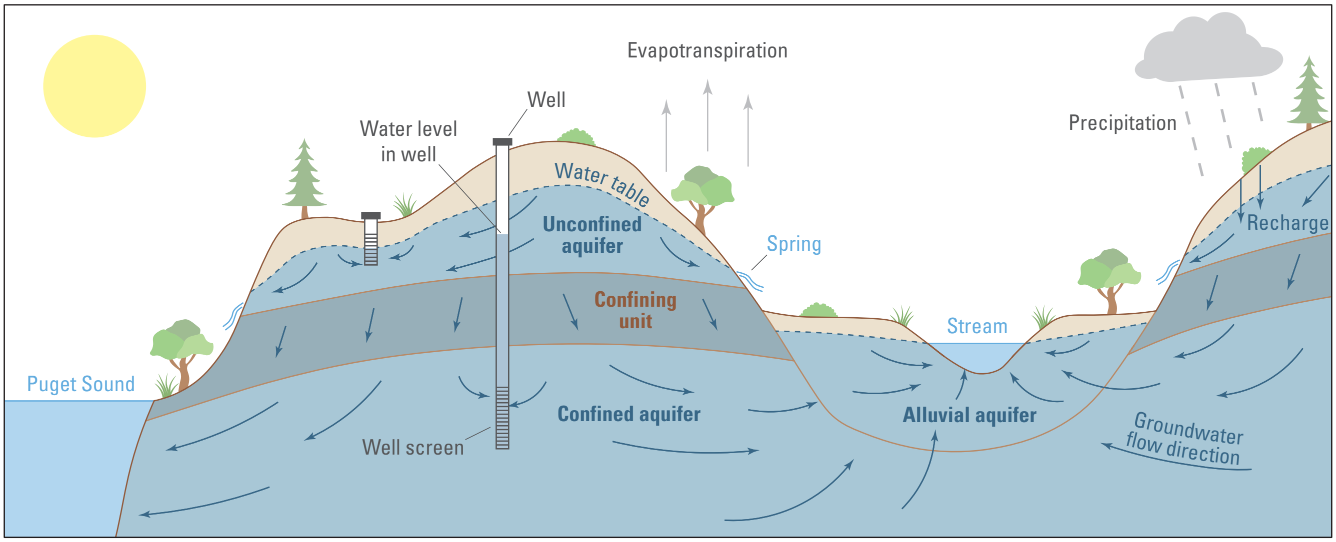


Figure B1. Cross-section sketch of typical groundwater-flow system showing hydrostratigraphic layers, water levels in wells, and discharge to streams. The sketch is shown with large vertical exaggeration for illustration purposes.

logs available from Washington State Department of Ecology (2022) and the NWIS database (U.S. Geological Survey, 2020), and previous investigations. Surficial hydrogeologic maps and hydrogeologic unit assignments were merged from the Chambers-Clover Creek and Puyallup River watershed studies. Geologic and hydrostratigraphic correlation charts and a more detailed description of the study methods are available in Savoca and others (2010) and Welch and others (2015).

The AMA consists of 14 HGUs; their lithologic and hydrologic characteristics and their geographic extents are shown in plate and figures B2–B13. Geologic units were grouped based on similarities in lithology (grain size and sorting), hydrologic characteristics, and relative stratigraphic position into HGUs consisting of aquifers and confining units. The HGUs defined in this study are based on HGUs identified in previous investigations (Brown and Caldwell, 1985; Clothier and others, 2003; Savoca and others, 2010; Welch and others, 2015). Differences between HGUs in this study, Savoca and others (2010), and Welch and others (2015) include the addition of mudflow-lahar deposits (upland mudflow confining unit MFLU [MFLU] and valley mudflow confining unit MFLV [MFLV]) and AL2 lower alluvial aquifer (only in subsurface) (AL2) deposits. These HGUs are present in parts of the eastern uplands and many of the major river valleys. The extent and thickness of the HGUs in this study might not be directly comparable to previously published HGUs.

Hydrogeologic Units

MFLU and MFLV Confining Units

The MFLU (upland mudflow) is a confining unit at the land surface in the eastern part of the AMA (fig. B2). It was distinguished from the MFLV (valley mudflow) geographically, with the MFLV occurring at land surface and beneath the AL1 upper alluvial aquifer (AL1) along the Puyallup and Green River valleys, the valley near Auburn, and along South Prairie Creek (plate; fig. B2). The MFLU and MFLV consist of unsorted, unstratified mixtures of pebble to boulder-size rock fragments in a clay, silt, and sand matrix derived from Mount Rainier mudflows and are summarized in Welch and others, 2015, table 1 (Walsh, 1987). The average thickness of MFLU and MFLV is about 34 feet [ft] but can exceed 100 ft along parts of the Puyallup River and Auburn valleys, and within upland areas in the eastern part of the study area. (fig. B2).

AL1 and AL2 Alluvial Aquifers

The AL1 was identified at land surface throughout the Puyallup, Carbon, White, Green, and Nisqually River valleys, along South Prairie Creek, and within the valley near Auburn (plate). The AL1 includes Quaternary unconsolidated alluvial, artificial fill, and peat deposits that are summarized in Welch and others, 2015, table 1 (Walsh, 1987). It consists of alluvial silt, sand, and gravel deposits that closely follow river valleys, and locally might contain elongated lenses of clay of varying thickness and extent. The AL1 has an average thickness of 106 ft but exceeds 250 ft along the lower Puyallup River as it nears Commencement Bay and in the northern part of the valley near Auburn (fig. B3). Groundwater in this aquifer generally is unconfined; however, confined conditions might occur locally beneath silt and clay.

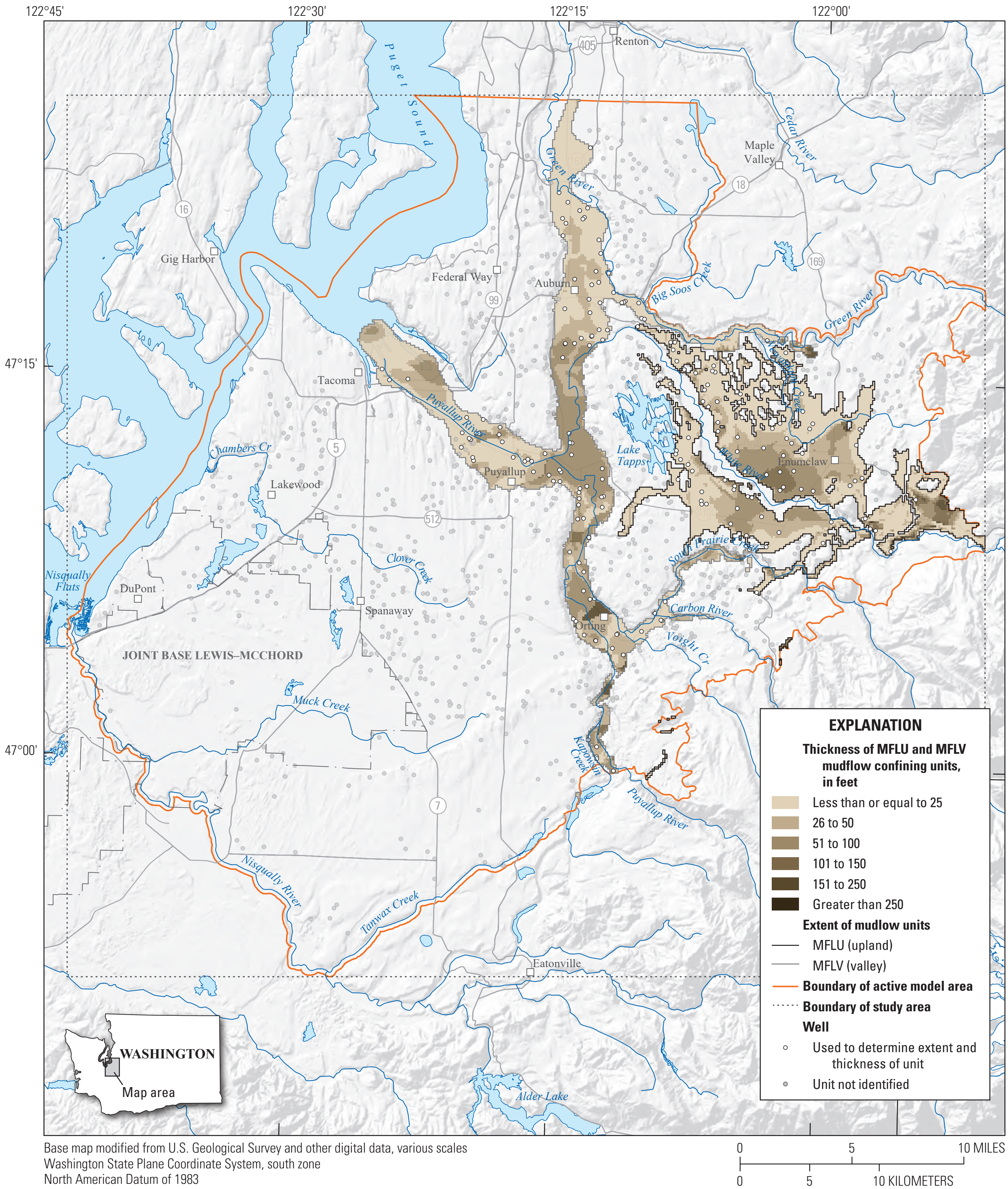


Figure B2. Extent and thickness of the upland mudflow confining unit (MFLU) and valley mudflow confining unit (MFLV) in the active model area, near the southeastern part of Puget Sound, Washington.

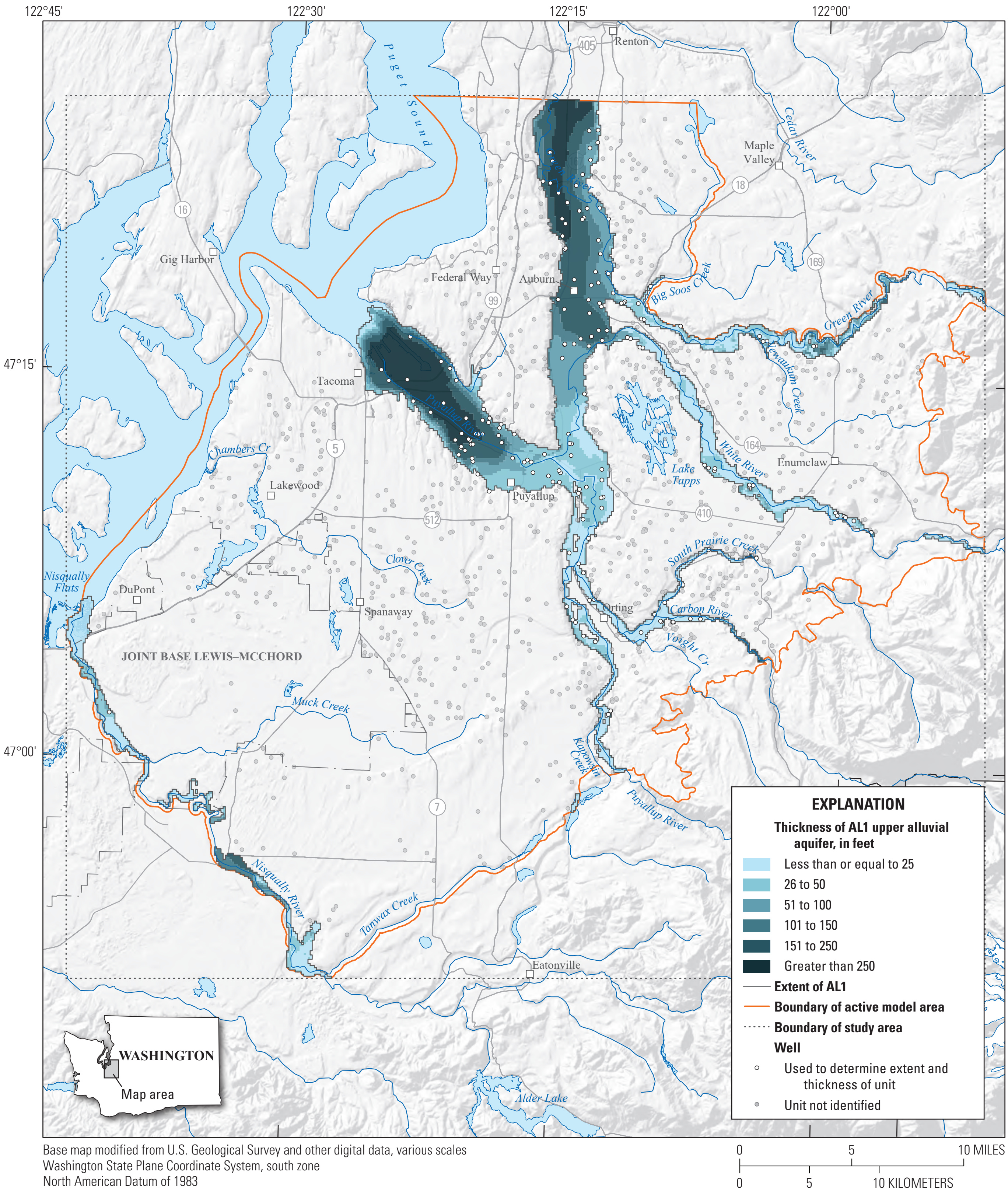


Figure B3. Extent and thickness of the AL1 upper alluvial aquifer in the active model area, near the southeastern part of Puget Sound, Washington.

The AL2 was identified beneath the MFLV within the Puyallup, lower White, and Green River valleys (fig. B4) and primarily consists of older Holocene alluvium and ancient deltaic sediments that accumulated along the estuarine margins of the ancestral Puyallup and Duwamish River valleys during the early to middle Holocene (Dragovich and others, 1994). Because of the spatial variability of stream sediments, and the inclusion of proximal to distal deltaic sediments, the lithologic character of this unit is heterogeneous and varies with depth. The average thickness of the unit is about 127 ft but exceeds 250 ft within the valley near Auburn (fig. B4). Groundwater in this aquifer is generally confined; however, unconfined conditions may occur where the overlying MFLV is locally thin or absent.

A1 Aquifer

The A1 aquifer unit was identified at land surface throughout much of the AMA (plate) and to a lesser extent beneath part of the MFLU in the eastern part of the study area. The A1 is composed primarily of one geologic unit: the Vashon recessional outwash of the Fraser glaciation, which consists of stratified silt, sand, and gravel deposited by large meltwater streams formed during the northward retreat of the Puget Lobe (Walsh and others, 2003). A subdivision of the recessional outwash, known as the Steilacoom Gravels, is present in successive outwash channels formed by streamflow originating from proglacial Lake Puyallup (Walsh and others, 2003). These gravels are characterized by their consistency and coarseness over a large part of the southwestern study area (fig. B5). Several other geologic units, including peat and undifferentiated Vashon drift (Walsh, 1987), were included in the A1 because of their limited areal extent, relative thickness, or proximity to other recessional outwash. Some alluvial sediments that were not connected with river valleys were also grouped with A1. More information about how geologic units were grouped into hydrogeologic units is available in Welch and others, 2015, table 1. The thickness of the A1 typically ranges from a veneer of less than 25 to about 80 ft but can locally exceed 200 ft where underlying units were not present or not identified. Groundwater is generally unconfined in this aquifer.

A2 Confining Unit

The A2 confining unit was identified throughout the AMA (plate) and is composed of several geologic units, primarily Vashon till and lesser amounts of ice-contact, moraine, and fine-grained glaciolacustrine sediments (Walsh, 1987; Booth and others, 2004). This low-permeability unit is absent within most major river valleys and consists of various proportions of clay, silt, sand, gravel, with locally occurring sand and gravel lenses capable of providing water for domestic use. The average thickness of the A2 is about 74 ft, but it can locally exceed 250 ft (fig. B6).

A3 Aquifer

The A3 aquifer unit was identified in the subsurface (fig. B7) throughout most of the study area with surface exposures limited to a few steep slopes and along the walls of deeply incised river valleys and coastal bluffs (plate). The unit is absent within most river valleys. The A3 is composed of several geologic units: primarily advance outwash of the Vashon Drift (Walsh, 1987) and small amounts of coarse-grained, non-glacial deposits older than the Fraser glaciation (Booth and others, 2004), and consists of well-sorted sand, or sand and gravel, with occasional lenses of silt and clay. The average thickness of the A3 is 74 ft but can locally exceed 150 ft (fig. B7). Groundwater in this aquifer generally is confined by the overlying A2; however, unconfined conditions might occur locally where the aquifer is not fully saturated or is exposed at land surface.

B Confining Unit

The B confining unit was identified in the subsurface throughout the AMA (fig. B8) with surface exposures limited to areas along the steep slopes of river valleys and coastal bluffs (plate). This unit and similar massive, organic-rich clayey units throughout central Pierce County have commonly been referred to as the Olympia-aged Kitsap Formation; however, use of that term has been abandoned. The B confining unit also includes several additional laterally continuous geologic units or units having similar lithologic characteristics. See table 1 in Welch and others, 2015, for further details. The average thickness of B is about 57 ft but locally exceeds 100 ft (fig. B8).

C Aquifer

The C aquifer unit, often referred to as the sea-level aquifer because of its coincident altitude, is also present at higher altitudes within upland parts of the AMA. The C is present in the subsurface throughout the AMA and within the Puyallup River valley and parts of the valley near Auburn (fig. B9). Surface exposures of the C are limited to a few areas along the steep slopes of river valleys and coastal bluffs (plate). The C is primarily composed of glacial drift that is older than Olympia-age glacial drift; is locally referred to as the Salmon Springs Drift (Walters and Kimmel, 1968); and consists of sand and gravel, with minor lenses of silt, clay, and till. The thickness of the C ranges from less than 40 to 125 ft but exceeds 185 ft in places. Groundwater in the C is generally confined by the overlying B, but unconfined conditions might occur locally where B is not present (fig. B8), or where the C is not fully saturated.

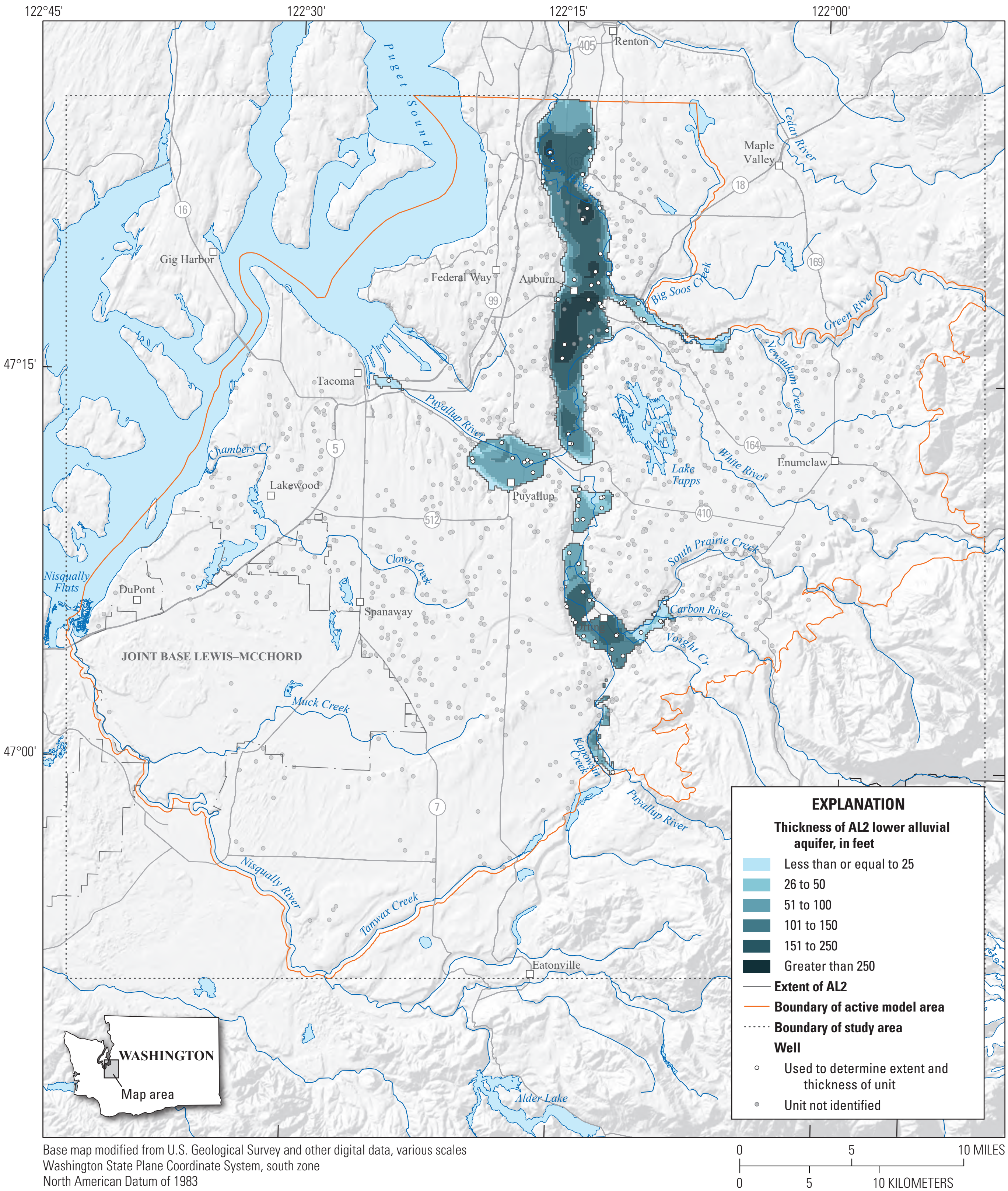


Figure B4. Extent and thickness of the AL2 lower alluvial aquifer (only in subsurface) in the active model area, near the southeastern part of Puget Sound, Washington.

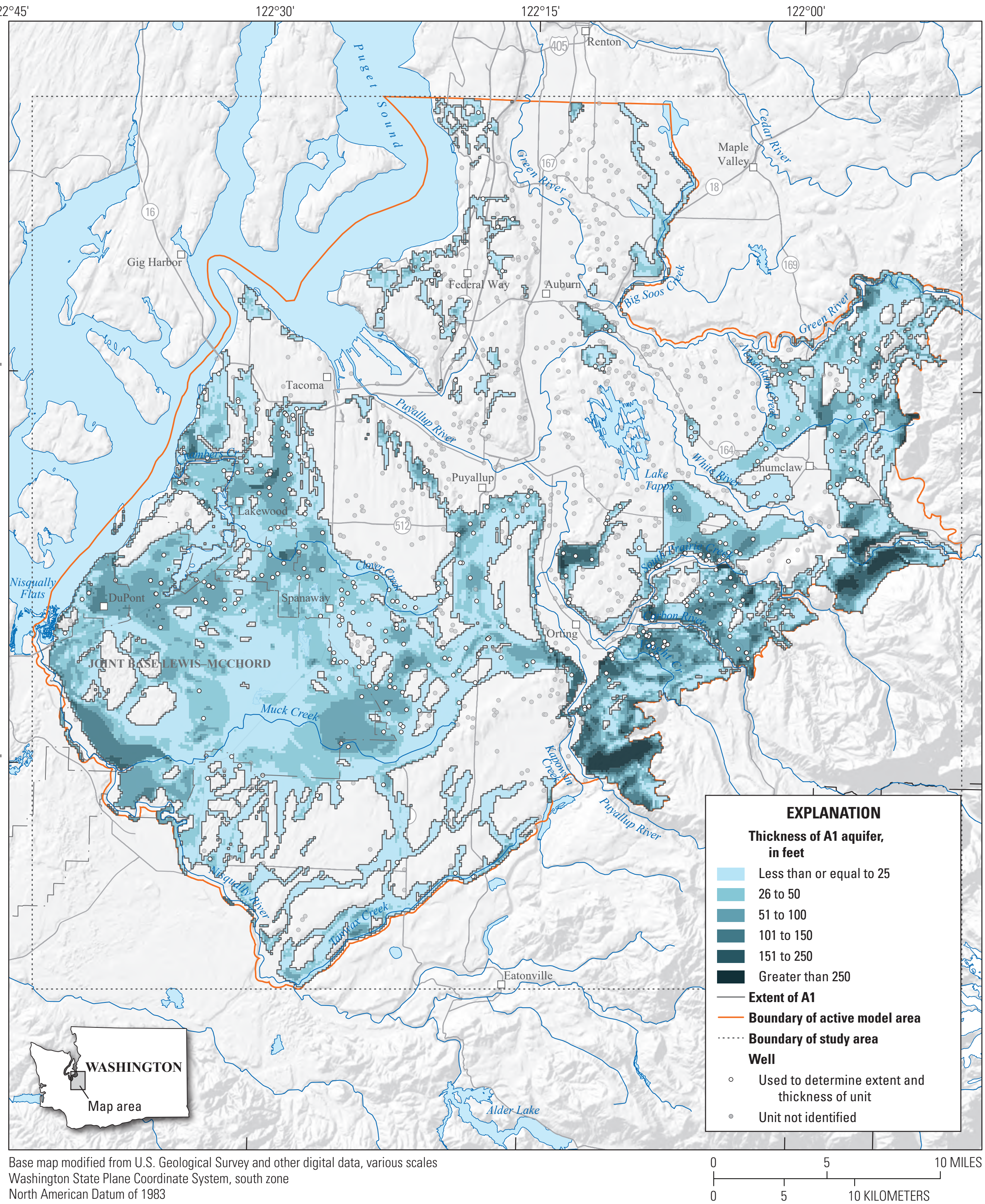


Figure B5. Extent and thickness of the A1 aquifer in the active model area, near the southeastern part of Puget Sound, Washington.

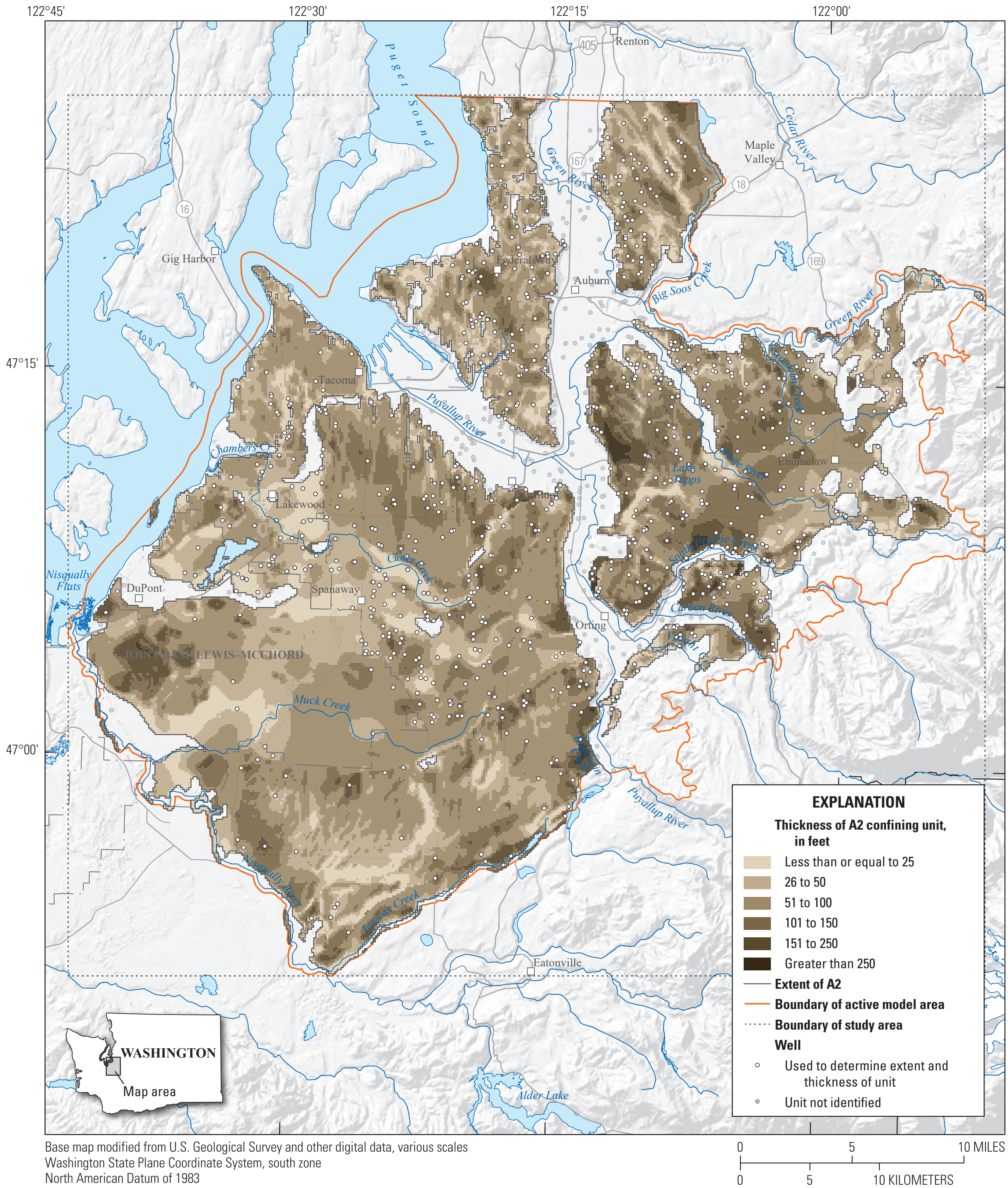


Figure B6. Extent and thickness of the A2 confining unit in the active model area, near the southeastern part of Puget Sound, Washington.

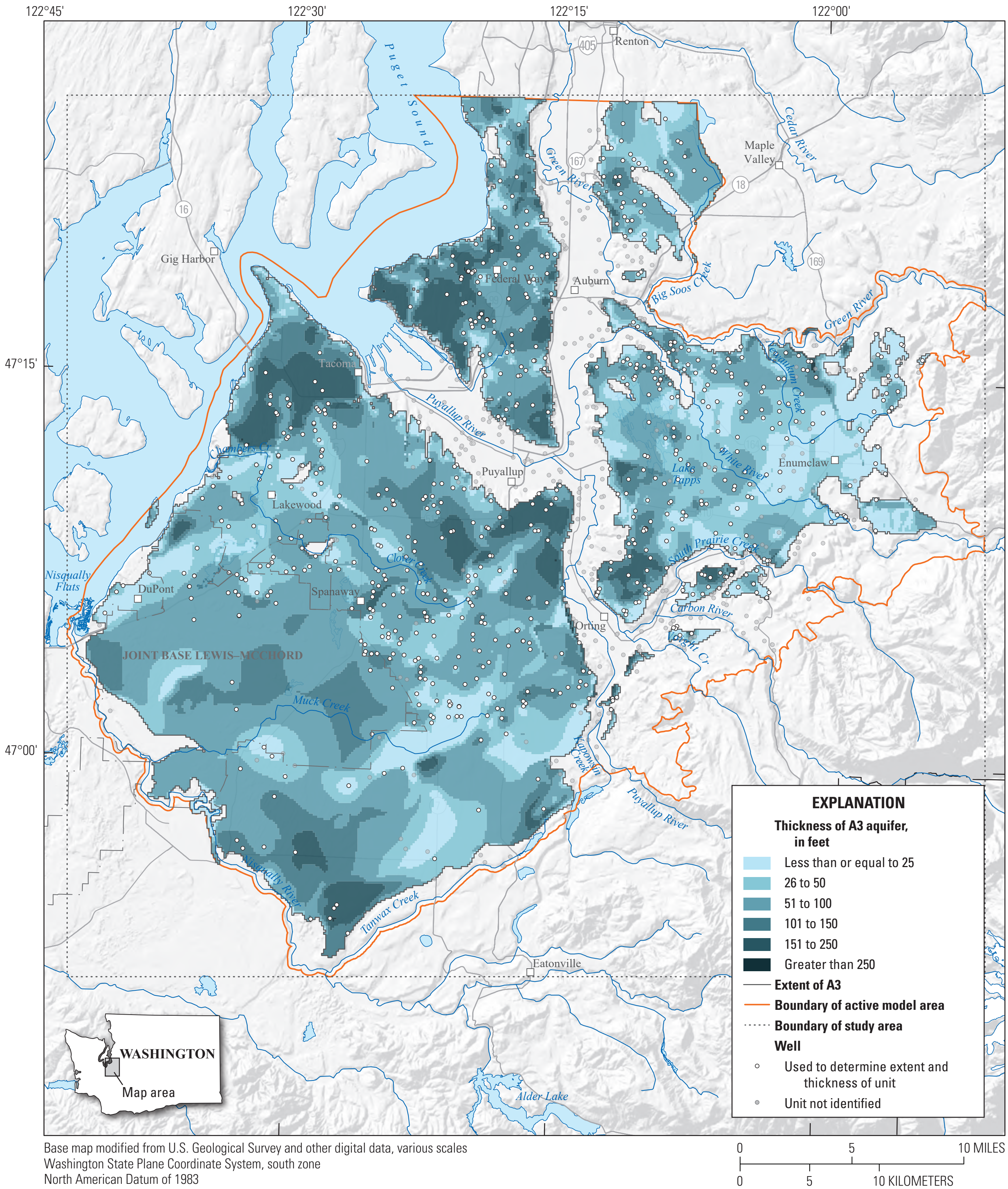


Figure B7. Extent and thickness of the A3 aquifer in the active model area, near the southeastern part of Puget Sound, Washington.

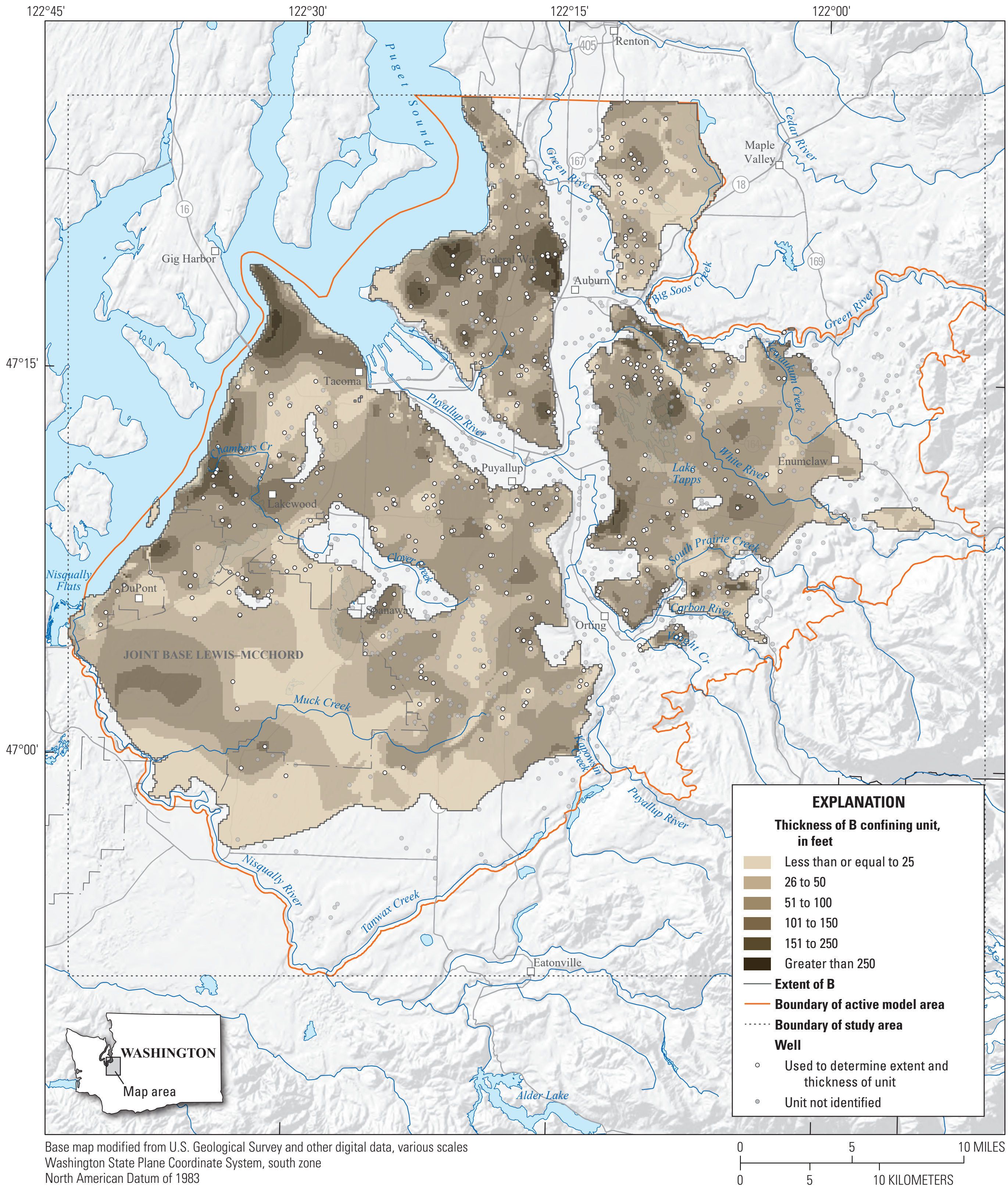


Figure B8. Extent and thickness of the B confining unit in the active model area, near the southeastern part of Puget Sound, Washington.

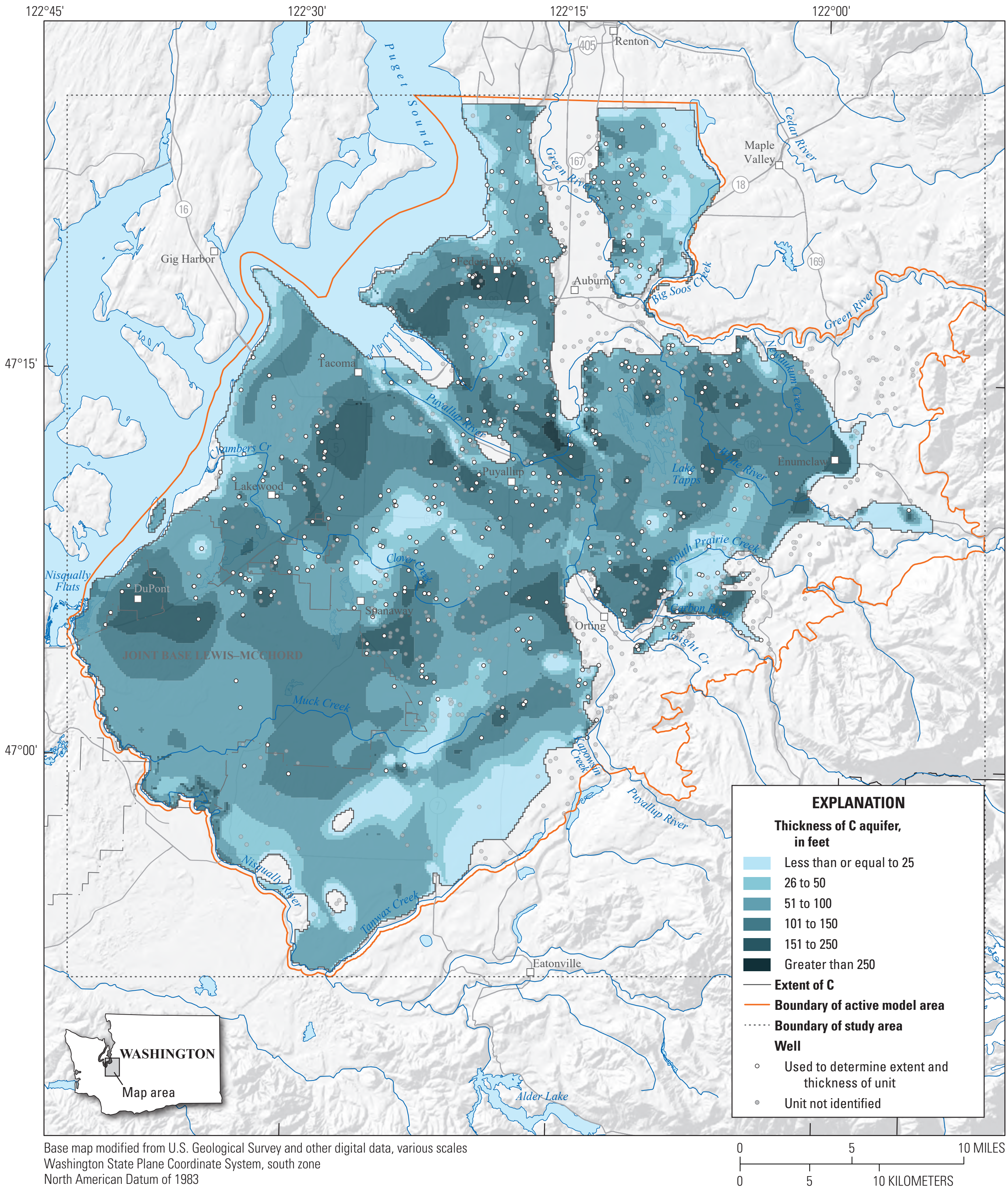


Figure B9. Extent and thickness of the C aquifer in the active model area, near the southeastern part of Puget Sound, Washington.

D Confining Unit

The D is a confining unit in the subsurface throughout the central and western parts of the AMA and within all major river valleys except for the northern part of the valley near Auburn and southern Puyallup River valley (fig. B10). Surface exposures of the D are limited to a few areas along lower Big Soos Creek and to the west of the Green River near the northern border of the study area. It also has submarine exposures along the margins of Puget Sound (plate). This low-permeability HGU is likely correlated with the Puyallup Formation (Walsh, 1987) and consists of alluvial and lacustrine sands, silts, and clays, and occasional volcanic ash. The average thickness is about 105 ft but exceeds 200 ft in several parts of the study area (fig. B10). An area of substantial thickness of D occurs along the western edge of the study area south of Chambers Creek, where C or E are not present (or both). Brown and Caldwell (1985) and Noble (1990) described this feature as being a probable ancestral Narrows channel that was filled with fine-grained lacustrine sediments.

E Aquifer

The E is an aquifer unit in the subsurface throughout the western and central parts of the AMA and is limited in northern parts of the study area (fig. B11). The E, identified during this study only in drillers' logs, is not present at land surface, except in submarine exposures along the margins of Puget Sound (plate). The E likely correlates with the Stuck Drift (Walsh, 1987), deposited during the third recognized glaciation of the southern Puget Sound area (Walters and Kimmel, 1968), and primarily consists of silt, sand, and gravel with discontinuous till and lacustrine deposits. The average thickness of the E is about 98 ft but exceeds 200 ft in several parts of the study area and where underlying HGUs are not present. (fig. B11). Groundwater in this aquifer is confined by the overlying D.

F Confining Unit

The F confining unit is in the subsurface throughout the central and western parts of the study area and in the lower parts of all major river valleys except for the northern valley near Auburn (fig. B12).The F, identified during this study only in drillers' logs, is not present at land surface except in submarine exposures near the Puget Sound margin (plate). It is a low-permeability HGU that correlates with the Alderton Formation (Walsh, 1987) and primarily consists of silt and clay, with minor lenses of sand and gravel. Limited data from drillers' logs indicated that the average thickness of the F is about 122 ft but exceeds 250 ft in a few parts of the study area (fig. B12).

G Undifferentiated Deposits

The G aquifer unit is composed of undifferentiated deposits throughout the subsurface in the central and western parts of the study area (fig. B13). The G, recognized only in drillers' logs, is not present at land surface, except in submarine exposures beneath Puget Sound (plate). The upper part of G primarily consists of stratified sand and gravel, with discontinuous layers of till. Few wells in the study area fully penetrate G to the bedrock surface, and little is known about the spatial distribution of water-bearing and non-water-bearing sediments in the deeper parts of this HGU (Brown and Caldwell, 1985). The upper part of G likely correlates with the Orting drift (Walsh, 1987), the oldest identified Pleistocene glaciation in the Puget Sound area (Walters and Kimmel, 1968). Several public water-supply systems in the study area withdraw water from the upper part of G. Thickness estimates for this unit were computed by subtracting the top of bedrock from the top of unit G and range from less than 300 ft to greater than 1,200 ft (fig. B13).

Bedrock

The bedrock unit crops out in the foothills and mountainous terrain along the southeastern and eastern margins of the study area (plate). This low-permeability unit consists of sedimentary claystone, siltstone, sandstone, beds of coal, and volcanic rocks. Alpine glacial deposits composed of various proportions of clay, silt, sand, and gravel, overlie some areas of bedrock; they were included in the bedrock unit based on the assumption that these unconsolidated deposits resemble glacial tills and are primarily non-water bearing.

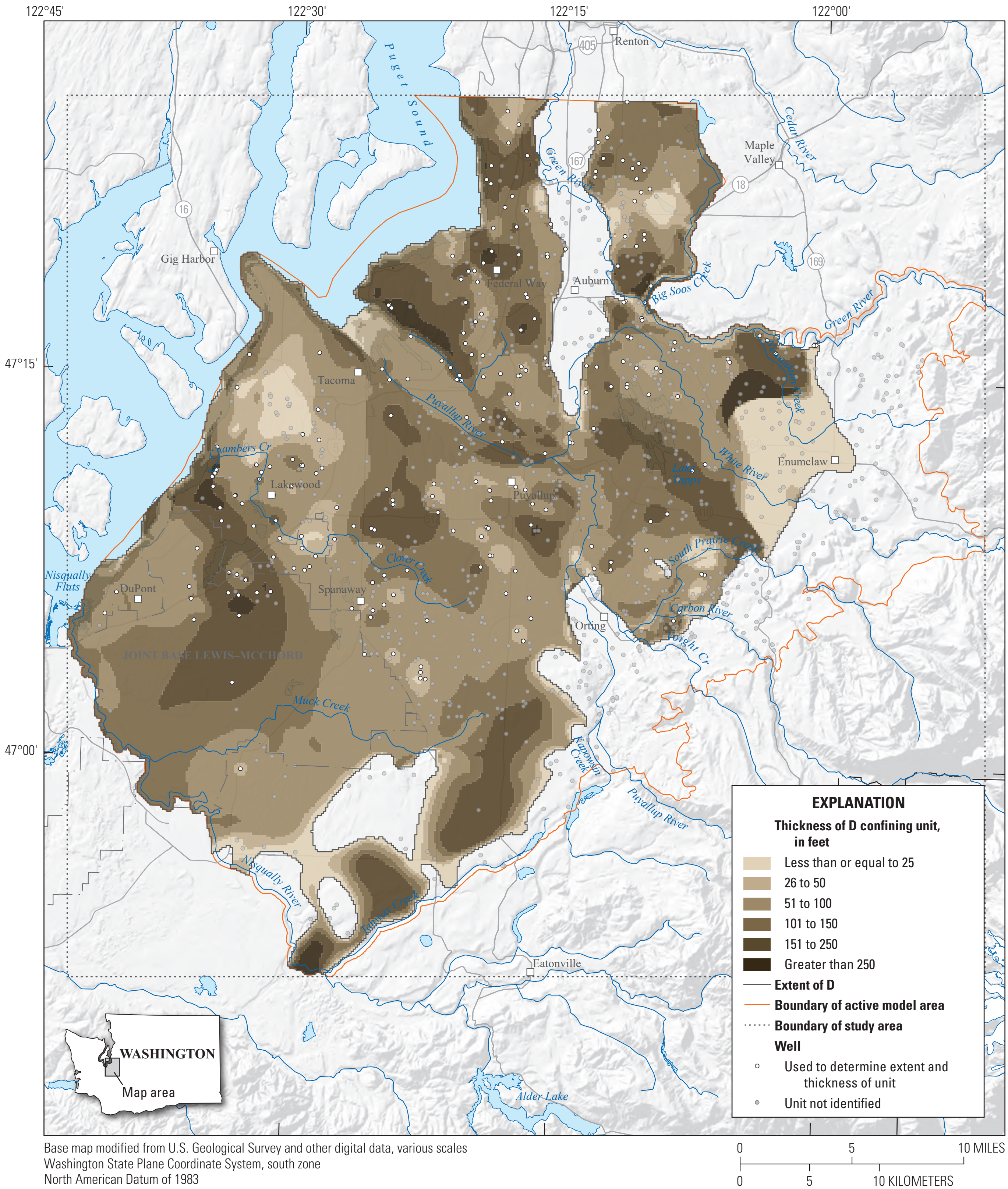


Figure B10. Extent and thickness of the D confining unit in the active model area, near the southeastern part of Puget Sound, Washington.

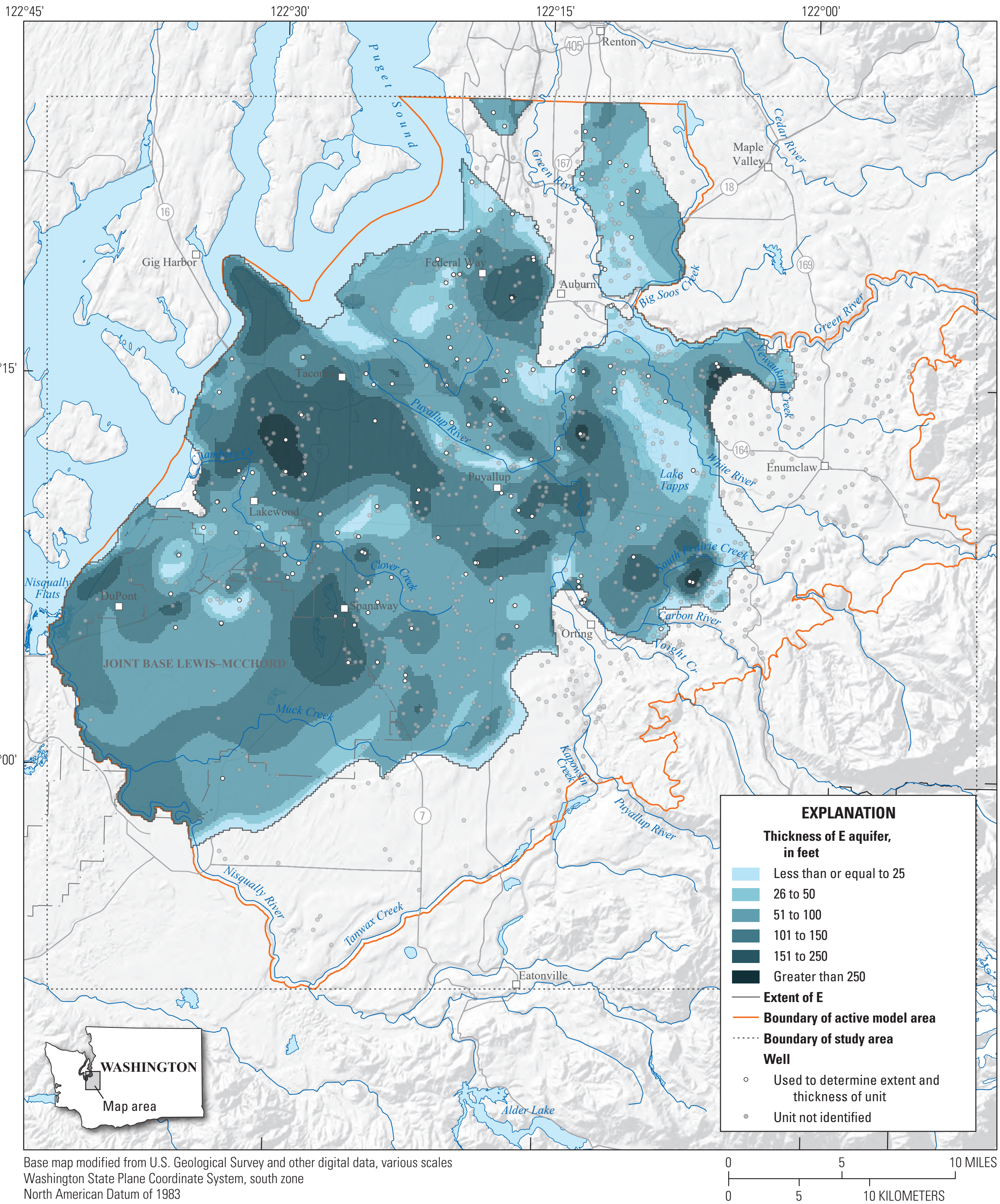


Figure B11. Extent and thickness of the E aquifer in the active model area, near the southeastern part of Puget Sound, Washington.

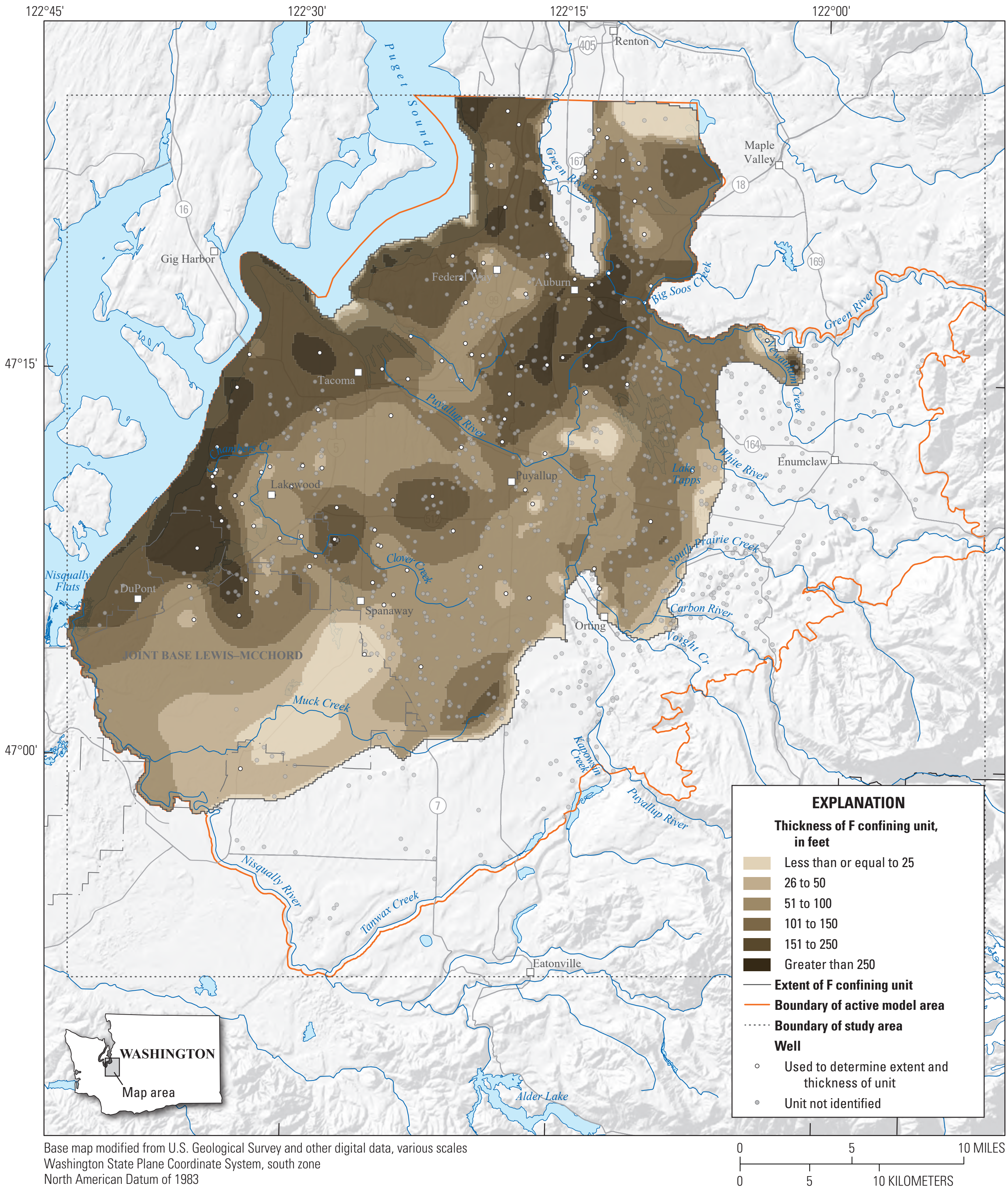
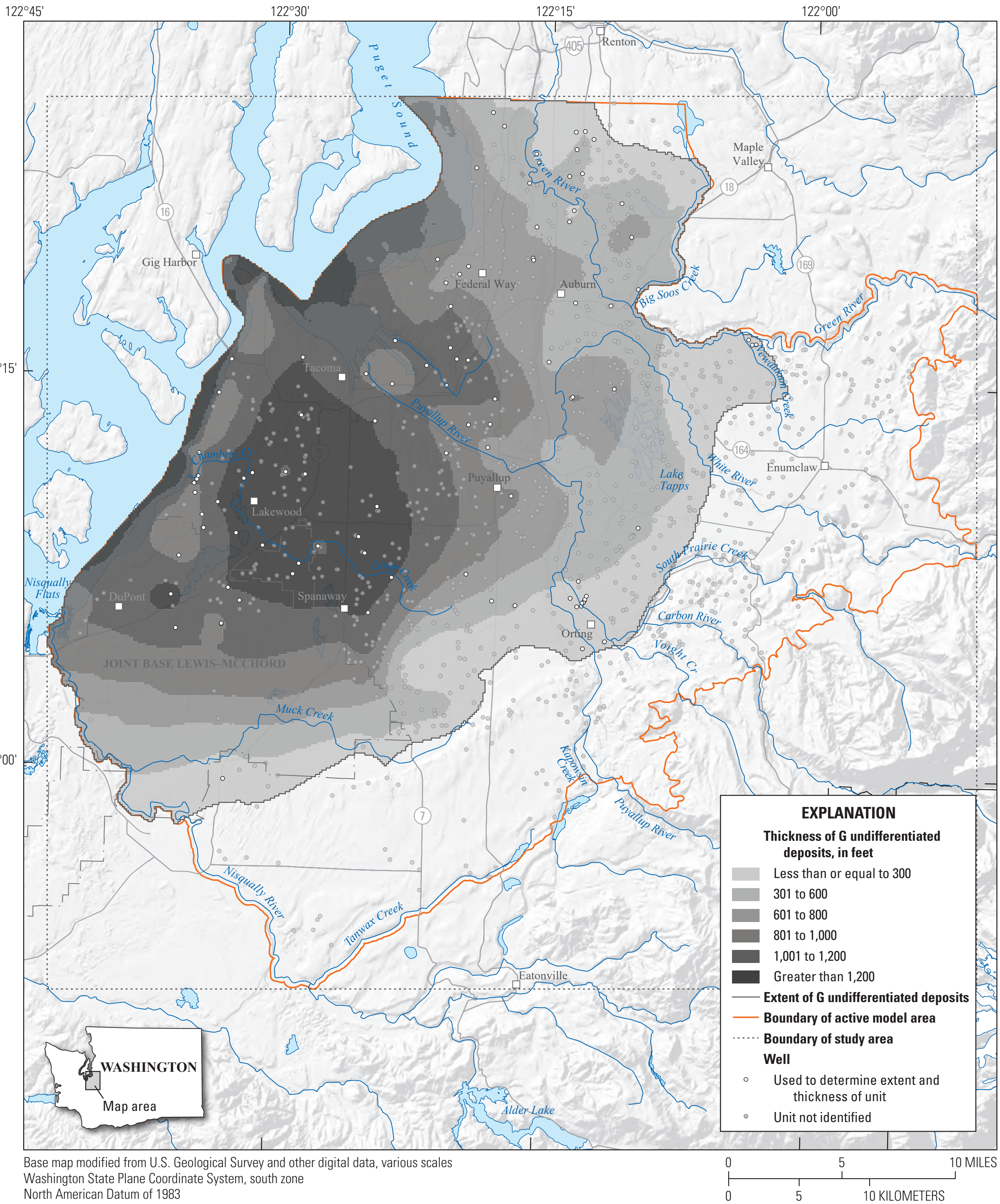


Figure B12. Extent and thickness of the F confining unit in the active model area, near the southeastern part of Puget Sound, Washington.



Base map modified from U.S. Geological Survey and other digital data, various scales
Washington State Plane Coordinate System, south zone
North American Datum of 1983

Figure B13. Extent and thickness of the G undifferentiated deposits in the active model area, near the southeastern part of Puget Sound, Washington.

Hydraulic Properties

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

Horizontal hydraulic conductivity (Kh) was estimated for the hydrogeologic units using data from 303 drillers' logs. A detailed explanation of the methods and equations used to estimate Kh is available in Savoca and others (2010) and Welch and others (2015). These methods use discharge rate, time of pumping, drawdown, static water level, well-construction data, and lithologic descriptions from drillers' logs to calculate specific capacity for wells, and, in turn, to estimate Kh. Of the 1,157 wells analyzed for the framework, 253 wells were constructed with a screened or perforated open interval and 50 wells were constructed with an open-ended casing and met the above criterion.

Estimates of Kh values and statistical summaries were prepared for each hydrogeologic unit (table B1). Median values of Kh for the aquifers (AL1, 310 feet per day [ft/d]; AL2, 126 ft/d; A1, 399 ft/d; A3, 148 ft/d; C, 92 ft/d; E, 41 ft/d; and G, 28 ft/d) are similar in magnitude to values compiled by Vaccaro and others (1998) and Savoca and others (2010) for the Puget Lowland and within the range of typical Kh values reported by Freeze and Cherry (1979) for similar materials. Median estimated Kh values for the confining units (MFLU and MFLV, 1,588 ft/d; A2, 17 ft/d; B, 55 ft/d; D, 56 ft/d; and F, 46 ft/d) and the bedrock unit (5 ft/d) are higher than is typical for most of the material in these units because data for confining units are usually from wells that are preferentially open to lenses of coarse water-bearing material, or in the case of bedrock, where water-bearing fractures are present. As a result, the data are preferentially biased toward the most productive zones in these units and are not representative of the entire unit.

Hydraulic conductivity (horizontal and vertical) is scale dependent. The bias toward the most productive zones for Kh values estimated from specific capacity data is an example of this scale dependence because this method applies to the areas encompassed by the zones of hydraulic influence for individual wells. As a comparison, a regional-scale numerical model estimates Kh values at scales encompassing hundreds of feet to miles.

Table B1. Summary of horizontal hydraulic conductivity values estimated from specific capacity data, by hydrogeologic unit, in the active model area, near the southeastern part of Puget Sound, Washington.

[<, less than]

Hydrogeologic unit	Number of wells	Hydraulic conductivity (feet per day)		
		Minimum	Median	Maximum
MFLU and MFLV confining units[1]	2	522	1,588	2,655
AL1 aquifer	14	2	310	24,190
AL2 aquifer	11	7	126	957
A1 aquifer	6	106	399	4,125
A2 confining unit	12	<1	17	129
A3 aquifer	54	<1	148	12,370
B confining unit	23	<1	55	2,451
C aquifer	106	1	92	16,200
D confining unit	17	1	56	136
E aquifer	31	3	41	1,058
F confining unit	6	1	46	503
G undifferentiated deposits	17	3	28	162
Bedrock	4	2	5	9

[1]Hydraulic conductivity estimated as average value and reported as median value.

Groundwater-Flow Directions and Potentiometric Surfaces

Water-Level Measurements—Methods

The characterization of the groundwater-flow system was based on the analysis of spatially distributed information about groundwater levels and the physical properties of the geologic units documented during well construction. Well records that document the drilling (drillers' log description of borehole lithology), construction, and, sometimes, hydraulic testing of wells, were compiled from U.S. Geological Survey National Water Information System (NWIS) database (U.S. Geological Survey, 2020) and Ecology (Washington State Department of Ecology, 2022) databases to identify potential wells for water-level measurements. Wells with insufficient location and construction information, or incomplete or poorly documented drillers' logs were excluded. The goal was an even distribution of wells throughout the study area. However, this was not possible because some areas had a low density of wells having adequate data.

Much of the water-level data were collected from 273 wells from which monthly measurements were made for the Chambers-Clover Creek and Puyallup River watershed studies (March 2007 through September 2015) (McLean and others, 2024). The beginning and ending measurement periods for individual wells varied. Wells measured monthly that are within the AMA are shown in plate.

The spatial distribution of the monthly wells was insufficient to accurately characterize the spatial variability of water levels in the AMA. Therefore, data for 4,470 additional wells were examined for potential use in creating groundwater altitude contours and maps of potentiometric surfaces of groundwater for each HGU in the framework. These additional wells were selected from the U.S. Geological Survey National Water Information System (NWIS) database (U.S. Geological Survey, 2020) for all records within the AMA. NWIS records represent groundwater data collected for U.S. Geological Survey (USGS) investigations in the area over the past century. Wells with no water-level measurement, dry wells, and water levels measured from a recently pumped or pumping well were removed from the dataset. The number of remaining wells used for potentiometric surfaces, including those measured monthly, was 4,009 (WL Measurements, McLean and others, 2024).

Records were not filtered by time or season. Most of the wells in the NWIS database include an initial reported water level measured by the drilling company after well installation. For wells with multiple water-level measurements, the drillers' measurement was removed from the dataset and the mean water-level value for the period of record was used to represent average annual conditions of water level. For wells with time-series records, anomalously low or high water levels could have been the result of pumping the well, measurement errors, or data errors; these values were removed prior to averaging.

Water-level altitude above the North American Datum of 1988 was obtained by subtracting the average depth to water from the 10-meter (1/3 arc-second) digital elevation model (U.S. Geological Survey, 2018). The altitude of the well-screen interval was obtained by subtracting the well screen or well depth (used when well screen information was unavailable) from the surface of the framework. Each well was assigned to a HGU based on altitude of the well screen or well depth, and the layer present at that altitude in the framework. Wells were weighted by number of available water levels. Points representing the groundwater levels were plotted along with the framework extent for each respective hydrogeologic layer using geographic information system (GIS) software and manually contoured by visually interpolating between data, with preference given to wells with a higher number of measurements. The contours are dashed in areas where data are sparse (figs. B14–B26).

Potentiometric Surfaces

The potentiometric surface represents the static head of groundwater in tightly cased wells that are open to a confined or unconfined HGU; a water table is a special case of a potentiometric surface for unconfined HGUs (Wilson and Moore, 1998). The generalized direction of horizontal groundwater movement in each HGU was inferred from maps of potentiometric contours, created from recorded water-level altitudes in wells. Potentiometric contours for most HGUs are based on limited water-level data and are subject to uncertainty.

Groundwater generally moves from recharge areas to discharge areas in the direction of decreasing hydraulic head and is assumed to be perpendicular to potentiometric contours. The change in hydraulic head per unit horizontal distance (that is, the horizontal hydraulic gradient) is represented by the slope of the water table. Closely spaced contours indicate a steep hydraulic gradient, whereas widely spaced contours indicate a moderate or low gradient. The horizontal hydraulic gradient for a HGU is influenced by variability of horizontal hydraulic conductivity, flow to or from other aquifers, and flow convergence or divergence caused by hydraulic boundary conditions. For example, a pumping well is a boundary condition causing flow convergence toward the well. Groundwater-flow directions shown in figures B14–B26 represent the horizontal component of flow; however, groundwater flow generally includes an additional vertical component that is not shown in the horizontal plane.

MFLU confining unit.—The potentiometric surface of upland mudflow confining unit MFLU is shown in figure B14. The surface is based on water-level measurements in 15 wells and the potentiometric surface altitude is estimated to range from 775 to 500 ft. Groundwater in MFLU generally flows to the northwest, following the slope of decreasing land-surface elevation. Flow direction is inferred south of the White River where no water-level measurements were available.

AL1 upper alluvial aquifer.—The potentiometric surface of the AL1 upper alluvial aquifer is based on water-level measurements in 159 wells (fig. B15) and the potentiometric surface altitude is estimated to range from 575 to 0 ft. Groundwater flow in the AL1 aquifer is generally down-valley following the Puyallup River valley to Puget Sound in the northwest and following the Green River valley to Puget Sound to the north of the AMA. In addition to down-valley longitudinal flow, groundwater also converges horizontally and upward toward rivers then discharges into rivers. Water-level data suggest the presence of a groundwater divide where the White and Green Rivers enter the valley near Auburn that separates flow south toward the Puyallup River and groundwater movement north out of the study area to the Duwamish River (Welch and others, 2015).

MFLV valley mudflow.—The potentiometric surface of valley mudflow confining unit MFLV is based on water-level measurements in 43 wells (fig. B16), and the potentiometric surface altitude is estimated to range from 500 to 25 ft. Groundwater flow in MFLV is generally down-valley, with variations similar to those of AL1.

AL2 lower alluvial aquifer.—The potentiometric surface of the AL2 lower alluvial aquifer is based on water-level measurements in 90 wells (fig. B17) and the potentiometric surface altitude is estimated to range from 500 to 25 ft. Most water-level measurements in this layer are concentrated at or just downstream from the confluence of the Puyallup and Carbon Rivers. Water-level data suggest that the groundwater divide in AL1 upper alluvial aquifer is also present in AL2 where the White River enters the valley near Auburn.

A1 aquifer.—The potentiometric surface of the A1 aquifer is based on water-level measurements in 289 wells (fig. B18) and the potentiometric surface altitude is estimated to range from 1,175 to 200 ft. Groundwater in this aquifer generally flows to the northwest toward Puget Sound. The hydraulic gradient is steep where A1 is present on the eastern edge of the AMA, from the foothills of the Cascade Range to the Puyallup and Carbon River valleys.

A2 confining unit.—The potentiometric surface of the A2 confining unit is based on water-level measurements in 1,029 wells (fig. B19) and the potentiometric surface altitude is estimated to range from 975 to 150 ft. Groundwater flow in A2 is highly variable. Local potentiometric highs and outward radial flow occur where A2 is present at the land surface. Groundwater flow in A2 is generally toward Puget Sound and major river valleys.

A3 aquifer.—The potentiometric surface of the A3 aquifer is based on water-level measurements in 1,026 wells (fig. B20) and the potentiometric surface altitude is estimated to range from 900 to 125 ft. In the upland area south and west of the Puyallup River, groundwater flow is generally toward the northwest, with local flow deviations resulting from local areas of high or low hydraulic head. The upland area, north of the Puyallup River and west of the Green River valley, contains several distinct groundwater highs with radial flow outward toward the river valleys and Puget Sound. Potentiometric highs in the upland areas on the eastern side of the AMA indicate flow toward the Puyallup, White, and Green River valleys.

B confining unit.—The potentiometric surface of the B confining unit is based on water-level measurements in 386 wells (fig. B21) and the potentiometric surface altitude is estimated to range from 750 to 0 ft. Groundwater flow in B is generally toward Puget Sound and the Puyallup and Green River valleys. In the upland area east of the confluence of the White River and Puyallup River, groundwater flow directions are similar to those of A3.

C aquifer.—The potentiometric surface of the C aquifer is based on water-level measurements in 502 wells (fig. B22) and the potentiometric surface altitude is estimated to range from 900 to 25 ft. In general, groundwater flow directions are similar to those of overlying HGUs of similar horizontal extent. The C aquifer is the uppermost HGU that extends below the Puyallup Valley; overlying HGUs are absent in this area. A steep groundwater gradient is present where groundwater flows below the east bluffs of the Puyallup River valley near the confluence of the White and Puyallup Rivers.

D confining unit.—The potentiometric surface of the D confining unit is based on water-level measurements in 174 wells (fig. B23) and the potentiometric surface altitude is estimated to range from 600 to 0 ft. In the southern part of the AMA, groundwater flows northwest toward Puget Sound and lower Puyallup River valley, with the groundwater gradient steeper near the valley and Puget Sound bluffs. Overall, the potentiometric surface is smoother than for overlying HGUs because there is less influence from land-surface topography. One notable exception is in the area east of Auburn, where exceptionally steep southward and westward groundwater gradients are present below the White River.

E aquifer.—The potentiometric surface of the E aquifer is based on water-level measurements in 75 wells (fig. B24) and the potentiometric surface altitude is estimated to range from 600 to 0 ft. Groundwater in E flows generally northwest toward Puget Sound and locally toward the Puyallup River valley. The potentiometric surface in this deep aquifer is smoother than that of the D confining unit.

F confining unit.—The potentiometric surface of the F confining unit is based on water-level measurements in 28 wells (fig. B25), and the potentiometric surface altitude is estimated to range from 225 to 0 ft. The potentiometric surface is smoother than that of the E aquifer, with low gradients and flow directions to the north and west toward Puget Sound.

G undifferentiated unit.—The potentiometric surface of the G undifferentiated unit is based on water-level measurements in 45 wells (fig. B26), and the potentiometric surface altitude is estimated to range from 225 to 25 ft. The potentiometric surface is similar to that of the F confining unit.

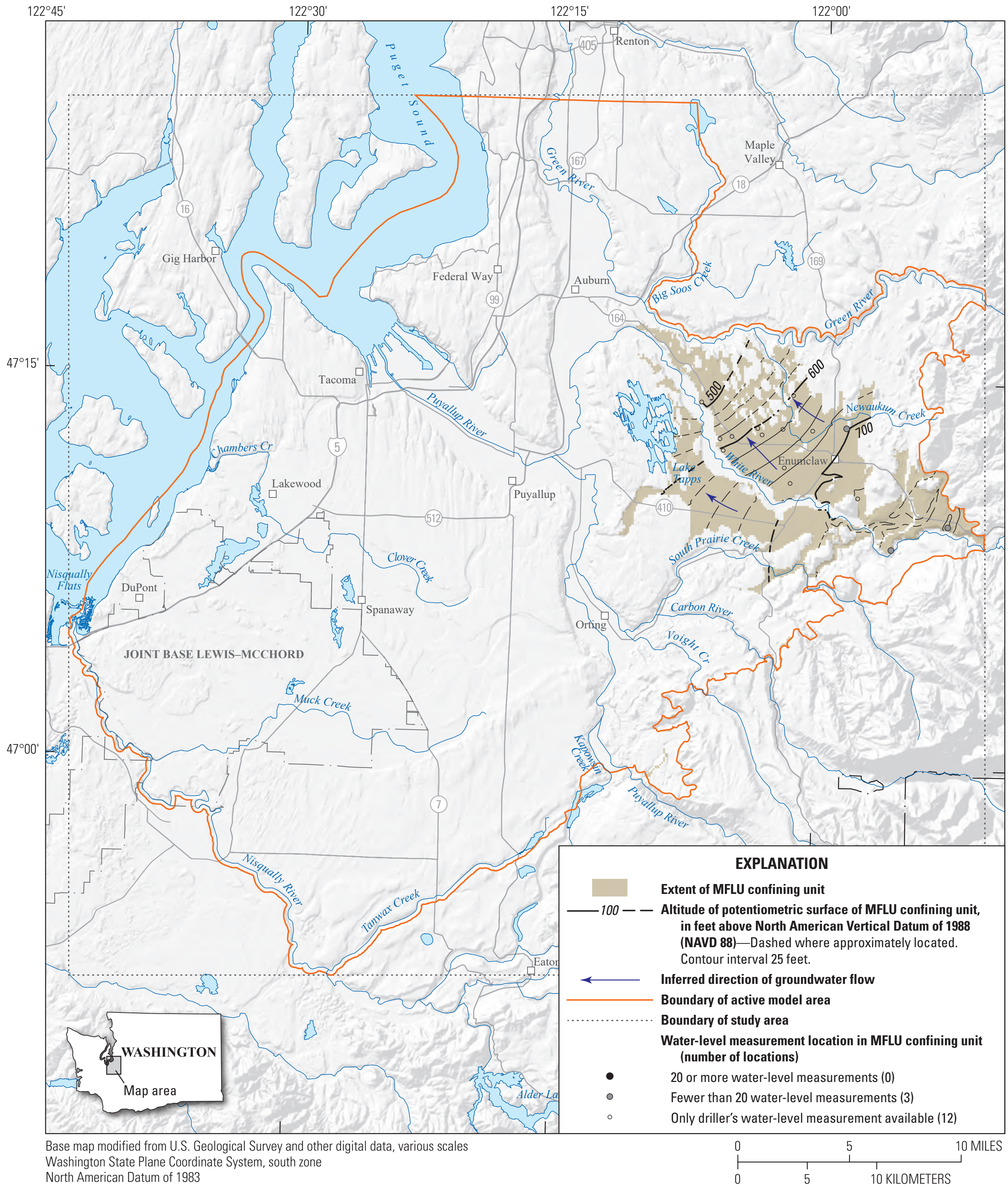


Figure B14. Potentiometric surfaces and direction of groundwater flow in the upland mudflow confining unit (MFLU) in the active model area, near the southeastern part of Puget Sound, Washington.

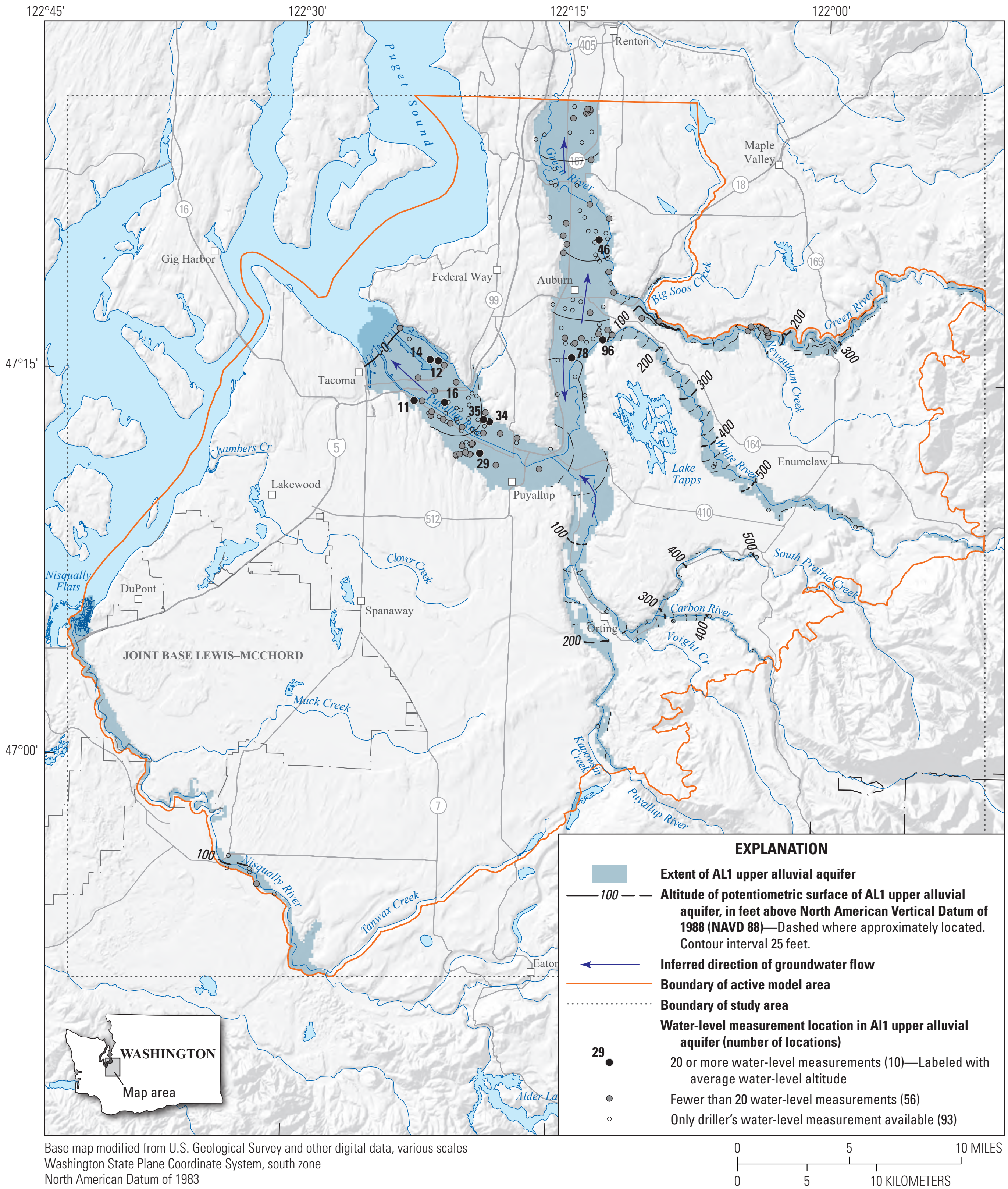


Figure B15. Potentiometric surfaces and direction of groundwater flow in the AL1 upper alluvial aquifer in the active model area, near the southeastern part of Puget Sound, Washington.

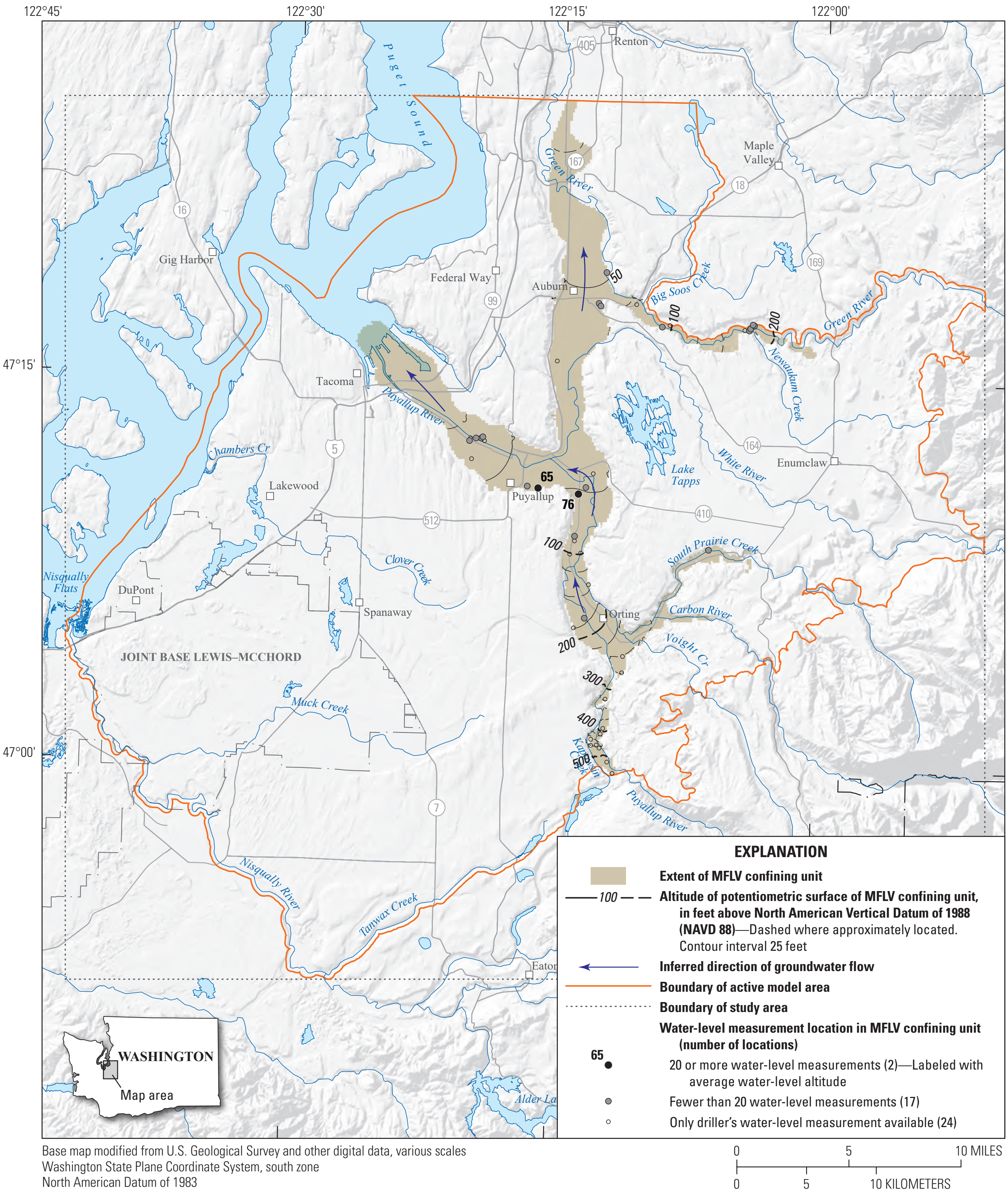


Figure B16. Potentiometric surfaces and direction of groundwater flow in the valley mudflow confining unit (MFLV) in the active model area, near the southeastern part of Puget Sound, Washington.

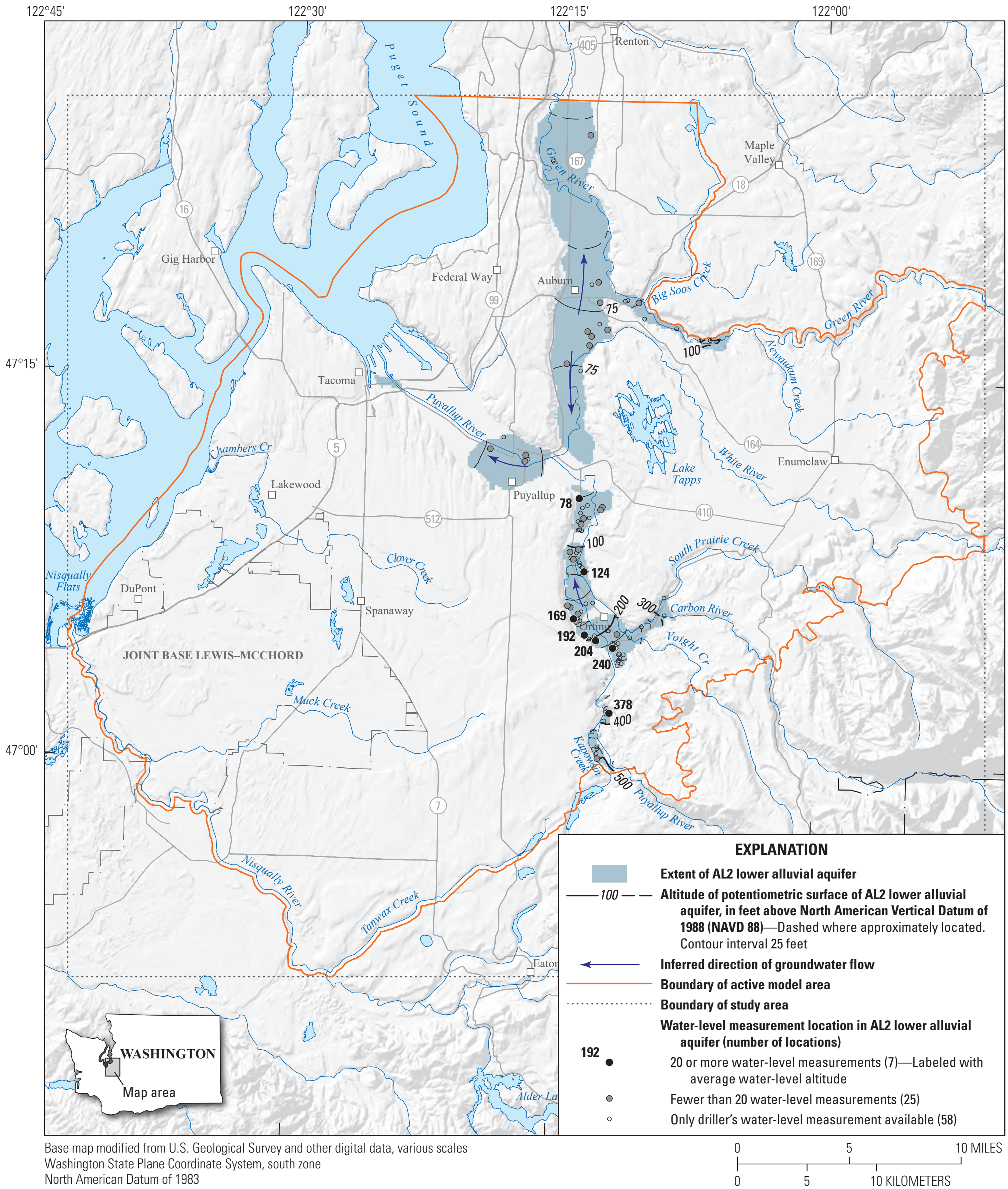
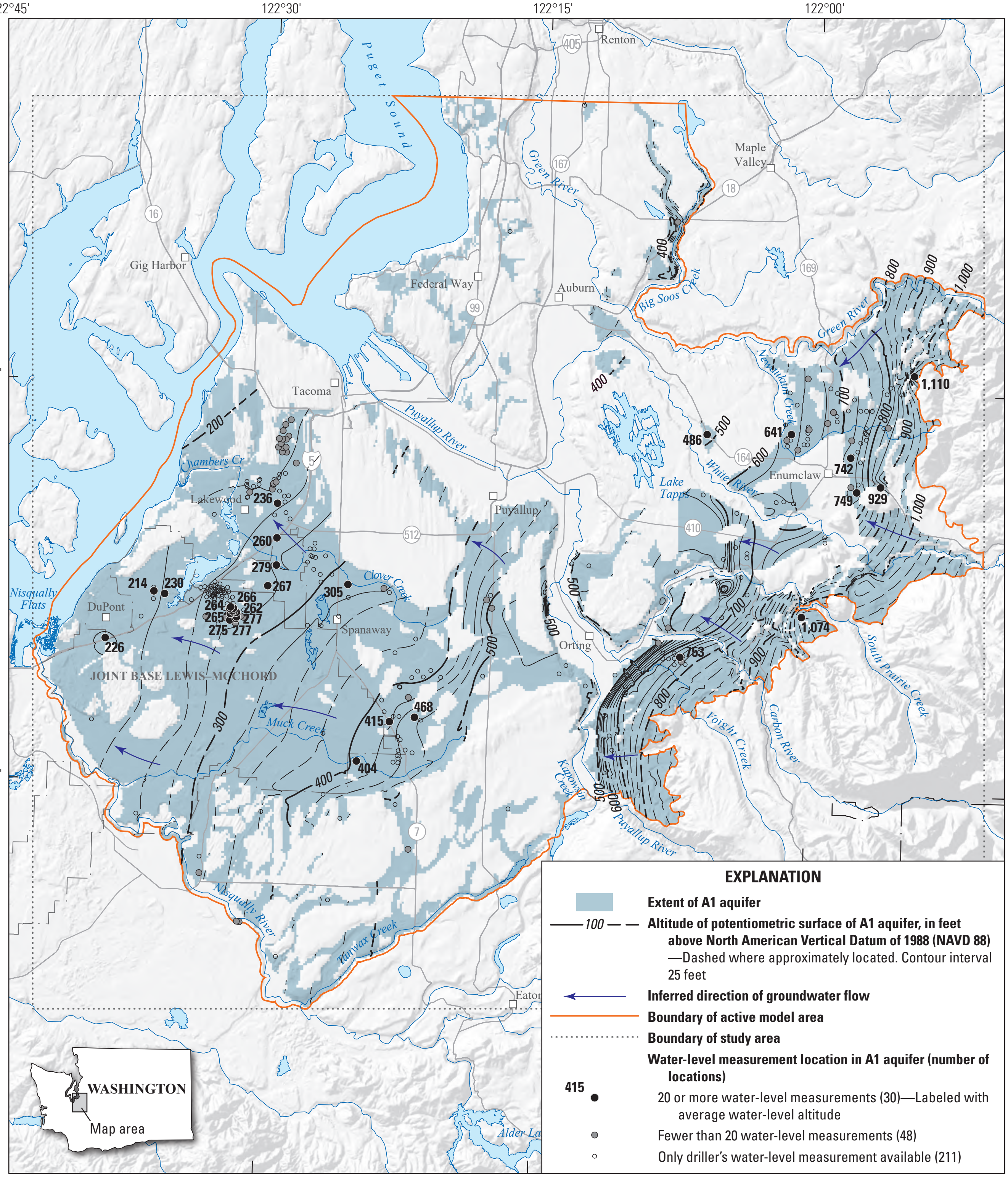


Figure B17. Potentiometric surfaces and direction of groundwater flow in the AL2 lower alluvial aquifer in the active model area, near the southeastern part of Puget Sound, Washington.



Base map modified from U.S. Geological Survey and other digital data, various scales
Washington State Plane Coordinate System, south zone
North American Datum of 1983

0 5 10 MILES
0 5 10 KILOMETERS

Figure B18. Potentiometric surfaces and direction of groundwater flow in the A1 aquifer in the active model area, near the southeastern part of Puget Sound, Washington.

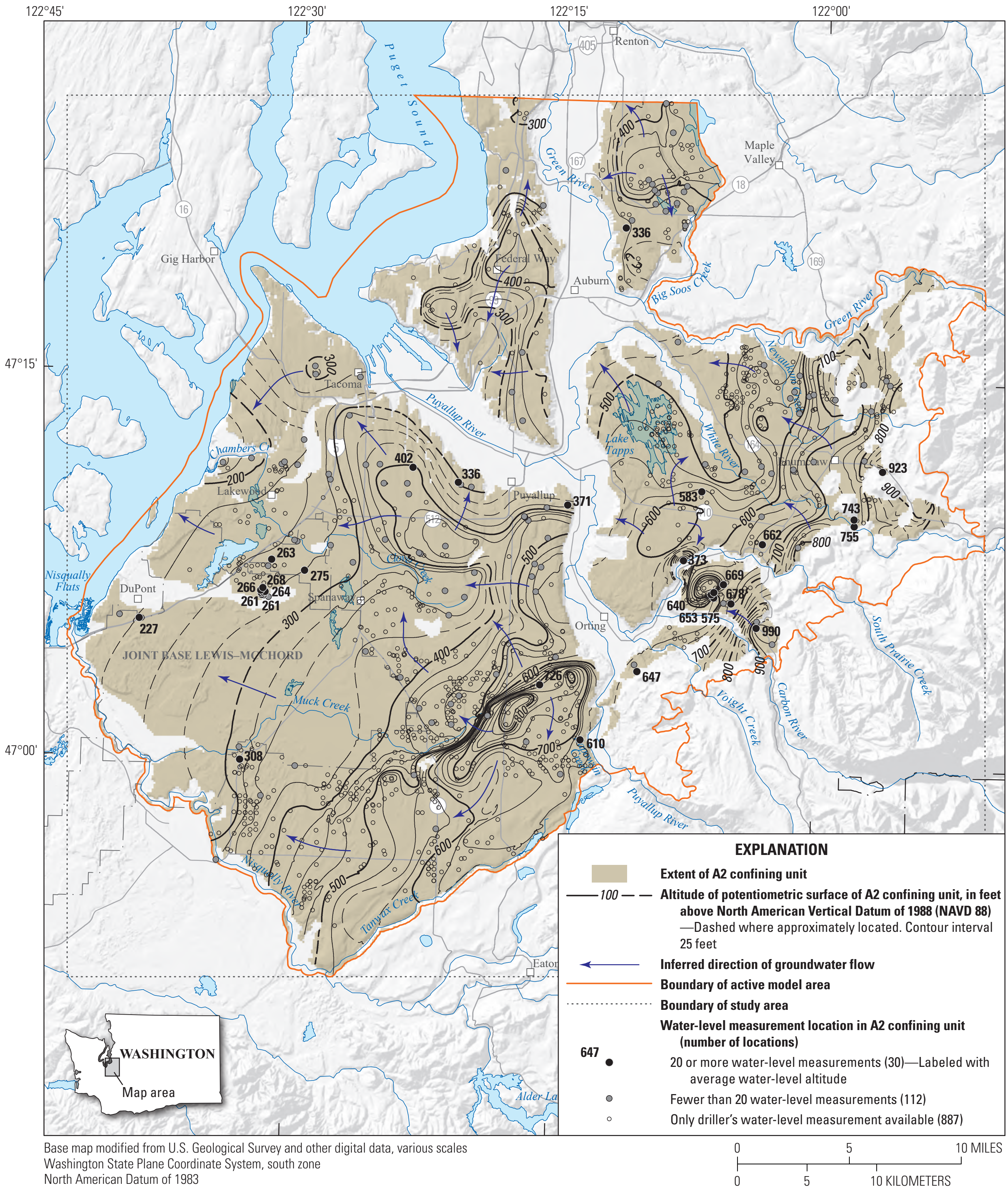


Figure B19. Potentiometric surfaces and direction of groundwater flow in the A2 confining unit in the active model area, near the southeastern part of Puget Sound, Washington.

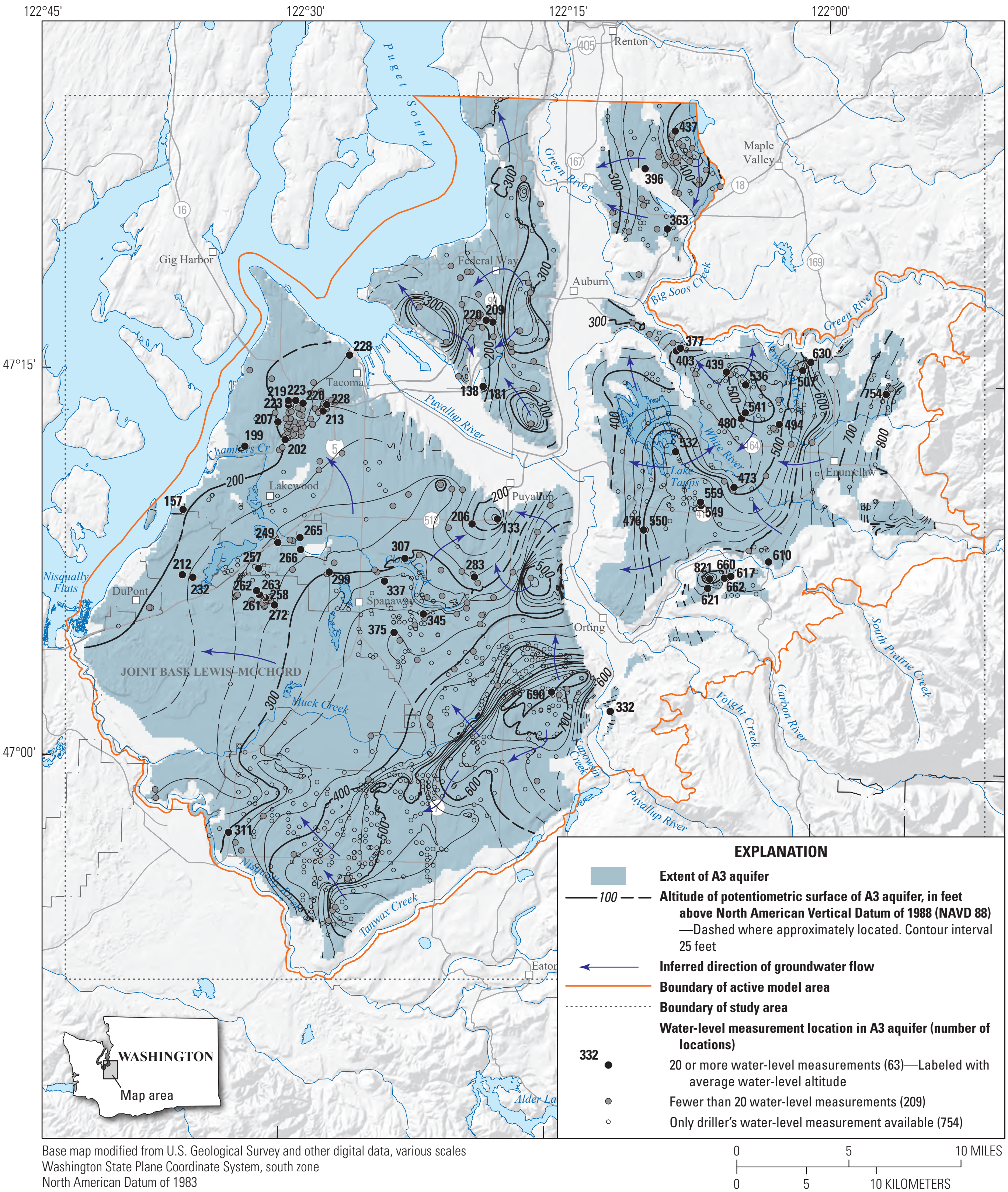


Figure B20. Potentiometric surfaces and direction of groundwater flow in the A3 aquifer in the active model area, near the southeastern part of Puget Sound, Washington.

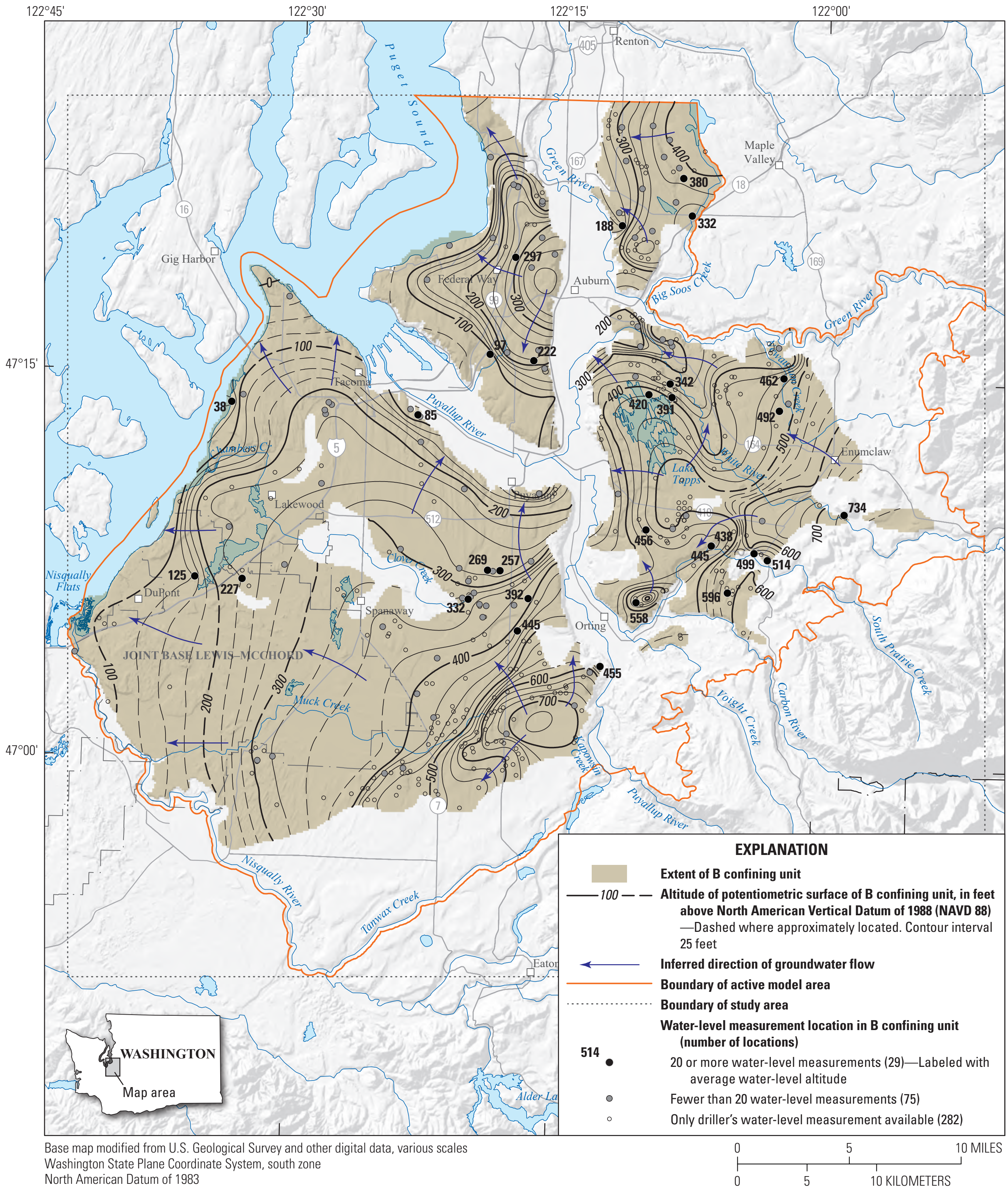


Figure B21. Potentiometric surfaces and direction of groundwater flow in the B confining unit in the active model area, near the southeastern part of Puget Sound, Washington.

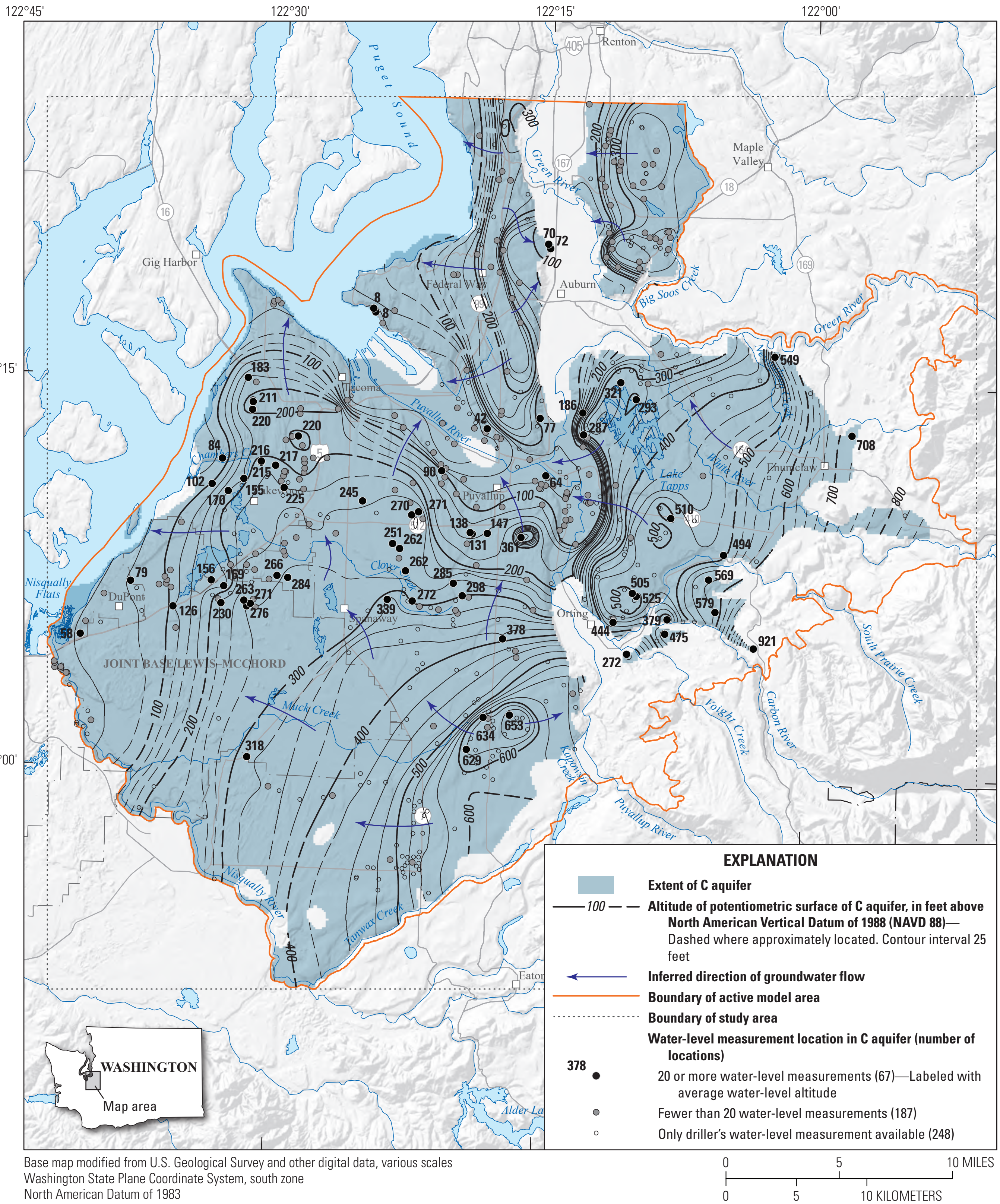


Figure B22. Potentiometric surfaces and direction of groundwater flow in the C aquifer in the active model area, near the southeastern part of Puget Sound, Washington.

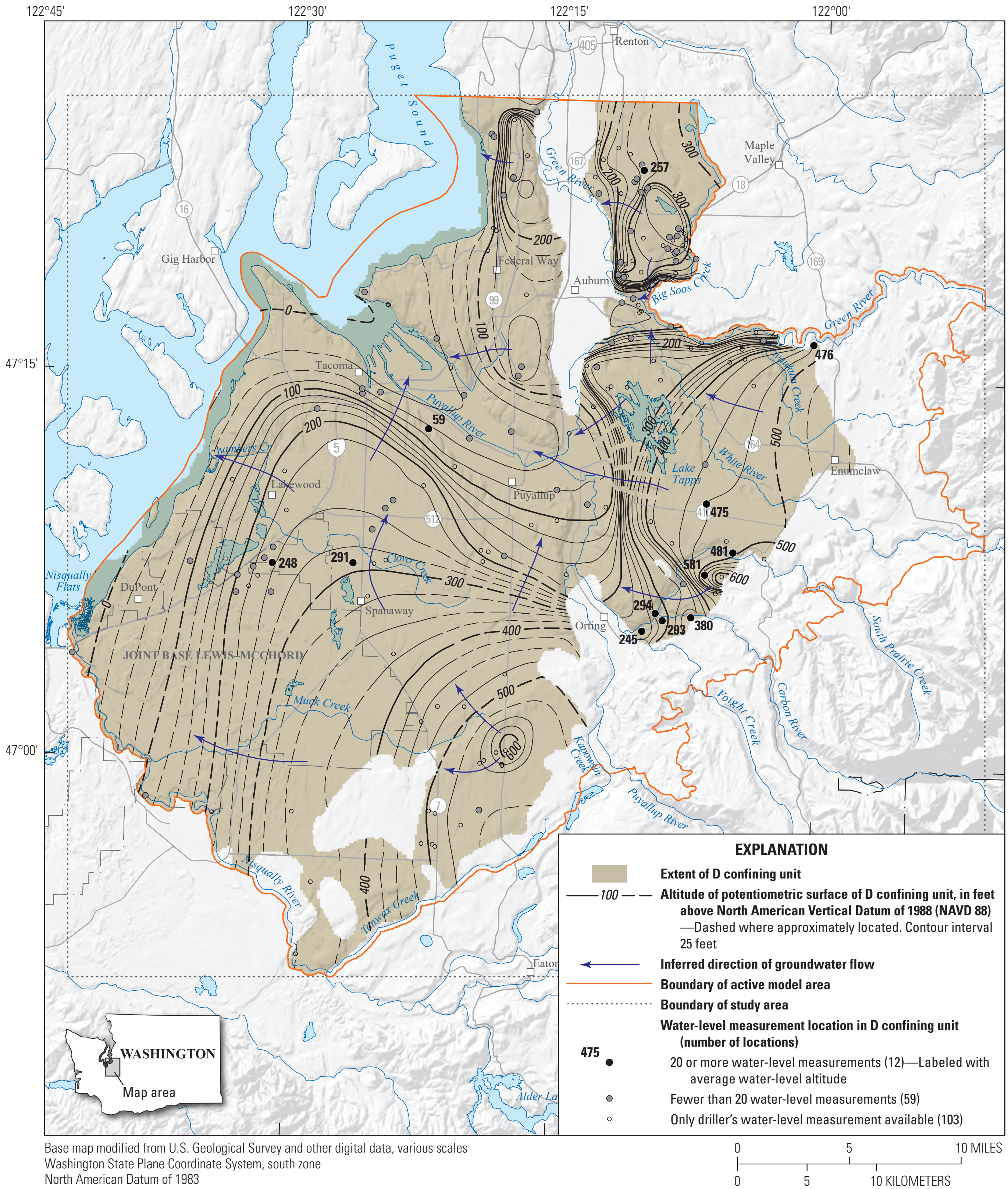


Figure B23. Potentiometric surfaces and direction of groundwater flow in the D confining unit in the active model area, near the southeastern part of Puget Sound, Washington.

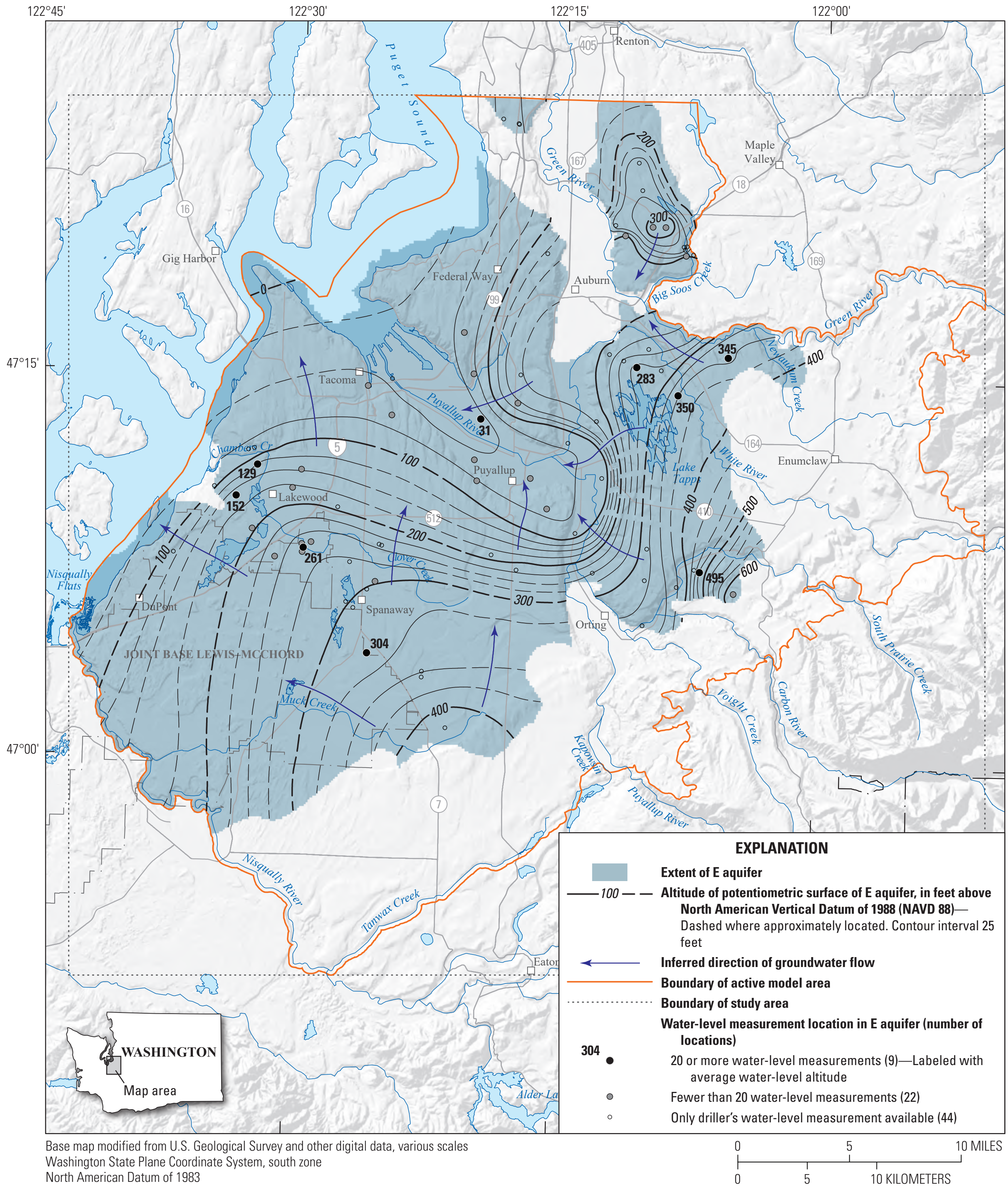


Figure B24. Potentiometric surfaces and direction of groundwater flow in the E aquifer in the active model area, near the southeastern part of Puget Sound, Washington.

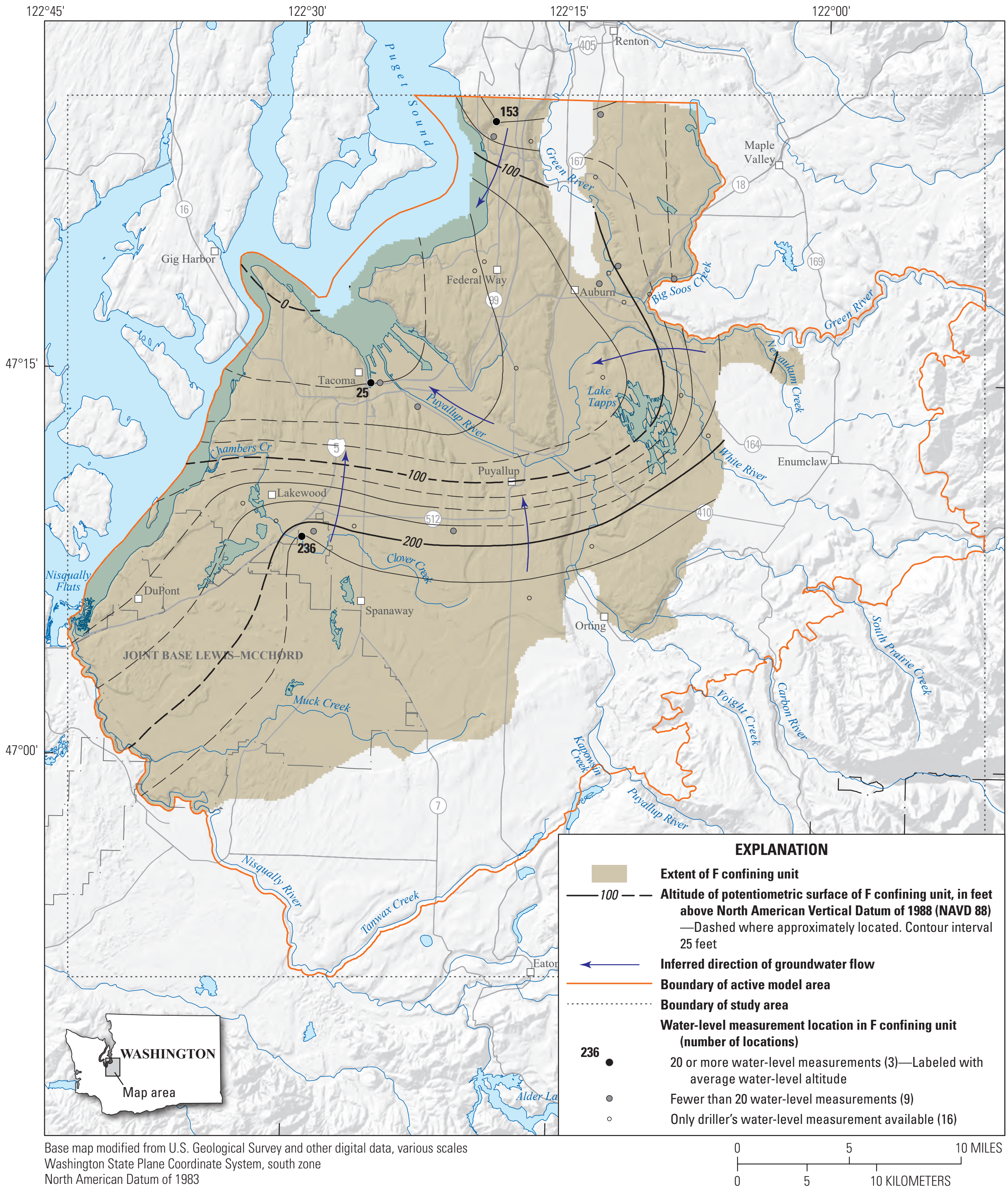


Figure B25. Potentiometric surfaces and direction of groundwater flow in the F confining unit in the active model area, near the southeastern part of Puget Sound, Washington.

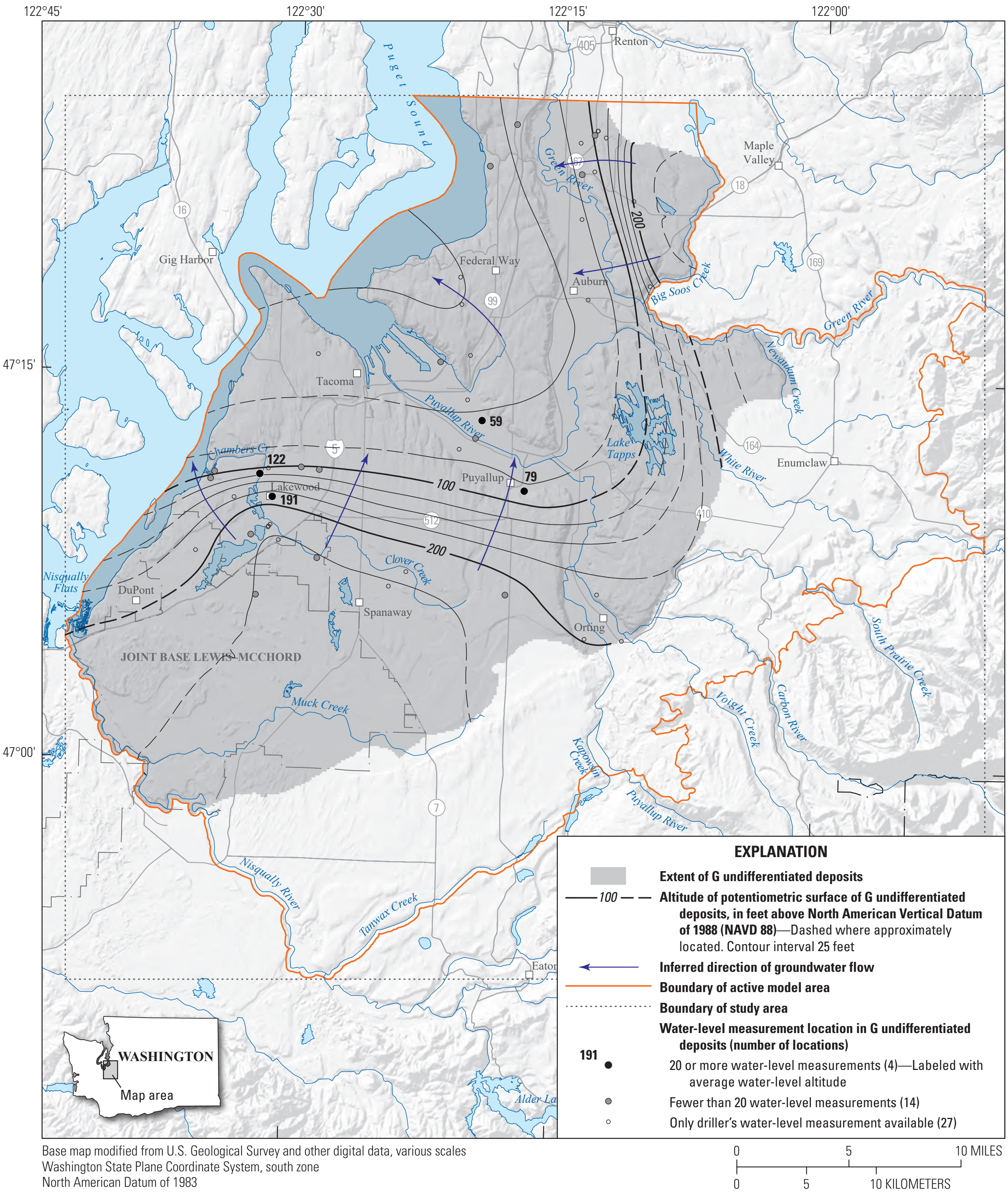


Figure B26. Potentiometric surfaces and direction of groundwater flow in the G undifferentiated deposits in the active model area, near the southeastern part of Puget Sound, Washington.

Generalized Groundwater and Surface-Water Interactions

Groundwater movement and interaction with surface-water features occur in the physical domain described by the framework and are influenced by the hydrogeologic characteristics of the aquifer system. Groundwater in the study area discharges as (1) seepage to streams, lakes, springs, marshes, and coastal bluffs; (2) evaporation and transpiration of shallow groundwater; (3) submarine groundwater discharge to Puget Sound; and (4) withdrawals from wells. Surface water interacts with groundwater in aquifers, resulting in exchange or seepage, which can recharge aquifers or maintain streamflow (depending on the hydraulic gradient). Groundwater is discharged to streams where the altitude of the water table is higher than the altitude of the stream surface (gaining reach/stream). Conversely, if the altitude of the stream surface is higher than the altitude of the water table, streamflow will seep into the underlying groundwater system (losing reach/stream). Additionally, groundwater pumping in nearby wells can reduce the amount of water available to maintain streamflow and can draw streamflow into the underlying groundwater system. Within the study area, major rivers receive a substantial part of their flow from groundwater; however, contributions from melting snow and glacial ice are also important. Chapter C discusses in detail surface-water measurements and the exchange of water between the groundwater-flow system and streams.

Five major rivers within the AMA (from north to south)—the Green, White, Carbon, Puyallup, and Nisqually Rivers—originate outside the area and either empty into Puget Sound directly or are tributaries to rivers that empty into Puget Sound (fig. A1). Major tributaries to these rivers that originate outside of the AMA include (from north to south) Big Soos, Coal, Boise, Scatter, South Prairie, Wilkeson, and Voight Creeks. These streams primarily gain flow from groundwater, which, together with melting snow and ice, sustains flow during summer.

Although streams entering the model area are generally at their lowest flow rates of the year in late summer, streams with a glacial origin can see an increase in flow at this time of the year because of higher rates of glacial melt during periods of relatively warm temperatures. Continuous streamflow data from USGS streamgages are available for most of the aforementioned streams and were evaluated to provide flow estimates. These streamflow data include active and inactive streamgages. Flow values for streams entering the model were estimated at the model boundary edge using the procedure outlined in the “Discharge to Streams” section of Chapter C.

Lakes in the study area interact with groundwater like streams. They receive and lose groundwater through their lake beds, and there often is inflow and outflow to the underlying groundwater system at different parts in the same lake, depending on the lake-bed sediments and their relative permeability. Lake levels, which reflect local groundwater levels, were available or estimated for the major lakes within the study area using the methods described in Long and others (2024).

Large and small springs and seeps occur throughout the study area along hillsides, valley bottoms, bluffs of Puget Sound, and in areas where groundwater intersects with the land surface. Some larger springs have been located, identified, and measured, and some are public sources of water (Springs, McLean and others, 2024).

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Chapter C. Groundwater Budget

By Andrew S. Gendaszek, Valerie A. L. Bright, and Alexander O. Headman

Introduction

The relation between storage, inputs, and outputs to the groundwater-flow system were evaluated through a groundwater budget, which states that changes in groundwater storage must be balanced by inputs to and outflows from the groundwater-flow system (Healy and others, 2007). A groundwater budget within the active model area (AMA) (fig. A1) was estimated through the development of a soil-water-balance model, estimation of water use, and estimation of stream base flow through hydrograph separation and synoptic streamflow measurements. Surface-water features that interact with groundwater include streams, lakes, wetlands, springs, seeps, and Puget Sound. Within the AMA, the primary inflow to the groundwater-flow system is from precipitation that infiltrates below the root zone, hereinafter referred to as precipitation recharge. Other inflows consist of anthropogenic recharge from septic systems, leaking underground pipelines, excess irrigation, groundwater inflow from adjacent aquifers, and infiltration of surface water. Outflow from the groundwater-flow system occurs through surface-water features, groundwater outflow to adjacent aquifers, and the pumpage from wells for residential, commercial, and agricultural water uses. These components, coupled with a change in groundwater storage, collectively define the terms of a groundwater budget, which are described in equation form with all components in consistent units of volume per time:

$$R_P + R_{GWR} + SF_{in} + GW_{in} - SF_{out} - GW_{out} - W_{out} + \Delta S = 0 \quad \text{(C1)}$$

where

- R_P is precipitation recharge,
- R_{GWR} is anthropogenic recharge,
- SF_{in} is infiltration of surface water,
- GW_{in} is groundwater inflow from adjacent aquifers,
- SF_{out} is surface-water inflow,
- GW_{out} is groundwater outflow to adjacent aquifers,
- W_{out} is pumpage from wells, and
- ΔS is change in groundwater storage.

The groundwater-budget components (eq. C1) were averaged over the 11-year period from January 1, 2005, to December 31, 2015, for input and comparison to the steady-state groundwater-flow model output. Monthly values of groundwater-budget components also were estimated for each of the 132 one-month stress periods from January 2005 to December 2015 for the groundwater-flow model described by Long and others (2024).

Groundwater budgets were previously developed for overlapping parts of the 887-square mile (mi^2) AMA, including the 520-mi^2 Puyallup River watershed (Welch and others, 2015), which constitutes 61 percent of the northern AMA, and the 432-mi^2 Chambers-Clover Creek watershed (Savoca and others, 2010; fig. A1), which constitutes 51 percent of the southern AMA. The groundwater budget for Chambers-Clover Creek watershed was estimated from September 2006–August 2008, while the groundwater budget for Puyallup River watershed was estimated from January 2011–December 2012. The groundwater budget for this study incorporates the Chambers-Clover Creek and Puyallup River watershed budgets and was estimated from January 2005–December 2015. In the Puyallup River and Chambers-Clover Creek watersheds, recharge was estimated by applying regional precipitation-recharge relations that account for the hydraulic properties of surficial hydrogeologic units (Bidlake and Payne, 2001) and groundwater discharge was characterized through synoptic streamflow measurements. Updated methods for estimating groundwater recharge and discharge to streams are explained in this chapter.

Methods

Components of the groundwater budget were developed through three complimentary methods: a Soil-Water-Balance model, compilation and estimation of water use, and hydrograph separation. The fate of precipitation into evapotranspiration, surface runoff, interception, change in soil moisture, and groundwater recharge was estimated by a Soil-Water-Balance model developed from spatially distributed climate, land cover, and soils data. Additional groundwater recharge from water-distribution pipeline leakage, septic systems, and irrigation was calculated from the distribution of infrastructure and estimates of water-delivery efficiency and per-capita non-consumptive water use. The fate of groundwater recharge was differentiated between anthropogenic and natural components of discharge from the groundwater-flow system. Anthropogenic components (which included groundwater pumpage from public-supply, self-supply, and irrigation wells) were compiled or estimated from water-use records. Natural components, which included discharge to streams, were estimated through hydrograph separation. Discharge of groundwater to other natural features including wetlands, springs, and Puget Sound was not quantified and was inferred to be the residual groundwater discharge.

Soil-Water-Balance Model

The Soil-Water-Balance (SWB) model (SWB version 1.2; U.S. Geological Survey, 2016) was used to simulate the precipitation recharge (R_P), which fulfills one component of equation C1, as well as evapotranspiration, interception, surface runoff, and change in soil moisture for the study area. The SWB model implements a modified Thornthwaite-Mather soil-water-balance approach (Thornthwaite and Mather, 1955, 1957) to calculate groundwater-budget components at a daily timestep across a two-dimensional grid (Westenbroek and others, 2010). The SWB model calculates R_P for each cell within the model's grid as inputs minus outputs and the net change in soil moisture, which are described in equation form with all components in consistent units of volume per time:

$$\begin{aligned} R_P = {} & Rainfall + Snowmelt + Surface\ Runoff\ Inflow \\ & - Interception - Surface\ Runoff\ Outflow \\ & - Evapotranspiration - \Delta\ Soil\ Moisture \end{aligned} \quad \text{(C2)}$$

where

R_P	is precipitation recharge,
Rainfall	is rainfall,
Snowmelt	is snowmelt,
Surface Runoff Inflow	is inflow of surface-water runoff,
Interception	is interception,
Surface Runoff Outflow	is outflow of surface-water runoff,
Evapotranspiration	is evapotranspiration, and
Δ *Soil Moisture*	is the net change in soil moisture.

The SWB model area was discretized consistently with the numerical model, which consisted of 500-foot [ft] cells in 433 columns and 416 rows (Gendaszek, 2023). The SWB model was run at a daily timestep for the 14-year period from January 2002 to December 2015. This time period included a 3-year model initialization period from January 2002 to December 2005 to estimate antecedent soil-moisture and snow-cover conditions prior to the groundwater-budget period of analysis from January 2005 to December 2015. Flow routing was disabled in the SWB model so that surface-runoff inflow from and surface-runoff outflow to adjacent cells was not simulated because the model grid resolution was too coarse to adequately represent routing of water across the landscape. Surface-water runoff from adjacent cells was assumed to be zero, and surface-water outflow from each cell was assumed to immediately leave the model domain.

Spatially distributed inputs to the SWB model included gridded climate, land-cover, and soils data, which were assigned to each SWB model grid cell based on nearest value to the centroid of each model cell. The SWB model used land-cover and soil characteristics of each cell to determine the rates at which daily precipitation (the model's principal water source) was differentiated into groundwater recharge, evapotranspiration, interception, surface-runoff, and other sinks from the model. Model parameters governing the rates of these processes for each unique land-cover/hydrologic soil group combination included runoff curve numbers, maximum infiltration rates, interception rates, and rooting depths.

Daily precipitation, minimum temperature, and maximum temperature were interpolated from DAYMET climatological data (version 3; Thornton and others, 2017), which was gridded at a 1-kilometer resolution (fig. C1). Precipitation averaged 50.5 inches per year (in/yr) across the basin from January 2005 to December 2015. From January 2005 to December 2015, mean monthly precipitation was unevenly distributed across seasons and was highest in November (7.9 inches [in.]) and lowest in July (0.8 in.). Precipitation was spatially variable across the AMA; the highest precipitation occurred in eastern part of the AMA in the foothills of the Cascade Range, and the lowest precipitation occurred at the lowest elevation in the western and central part of the AMA.

Land cover for each model cell was resampled from the 30-meter resolution 2011 National Land Cover Database (Homer and others, 2015) to 500-ft model grid (fig. C2). Fifteen NLCD land-cover classifications occurred within the AMA in 2011 (table C1). Among the primary land-cover classifications, developed land collectively covered 43 percent of the AMA, mainly in the western and northern parts of the AMA near the City of Tacoma and its suburbs. Forested land collectively covered 28 percent of the AMA and was present mainly in the southwestern part of the AMA in Joint Base Lewis-McChord and in the Cascade Range foothills of the eastern part of the AMA. Pasture, cultivated cropland, grasslands, and shrub land covers were present in 17 percent of the AMA, with wetlands collectively constituting 4 percent of the AMA. An additional land-cover classification, "Water, Internally drained," was created for cells classified in NLCD11, which did not have a surface-water connection to outside of the model domain.

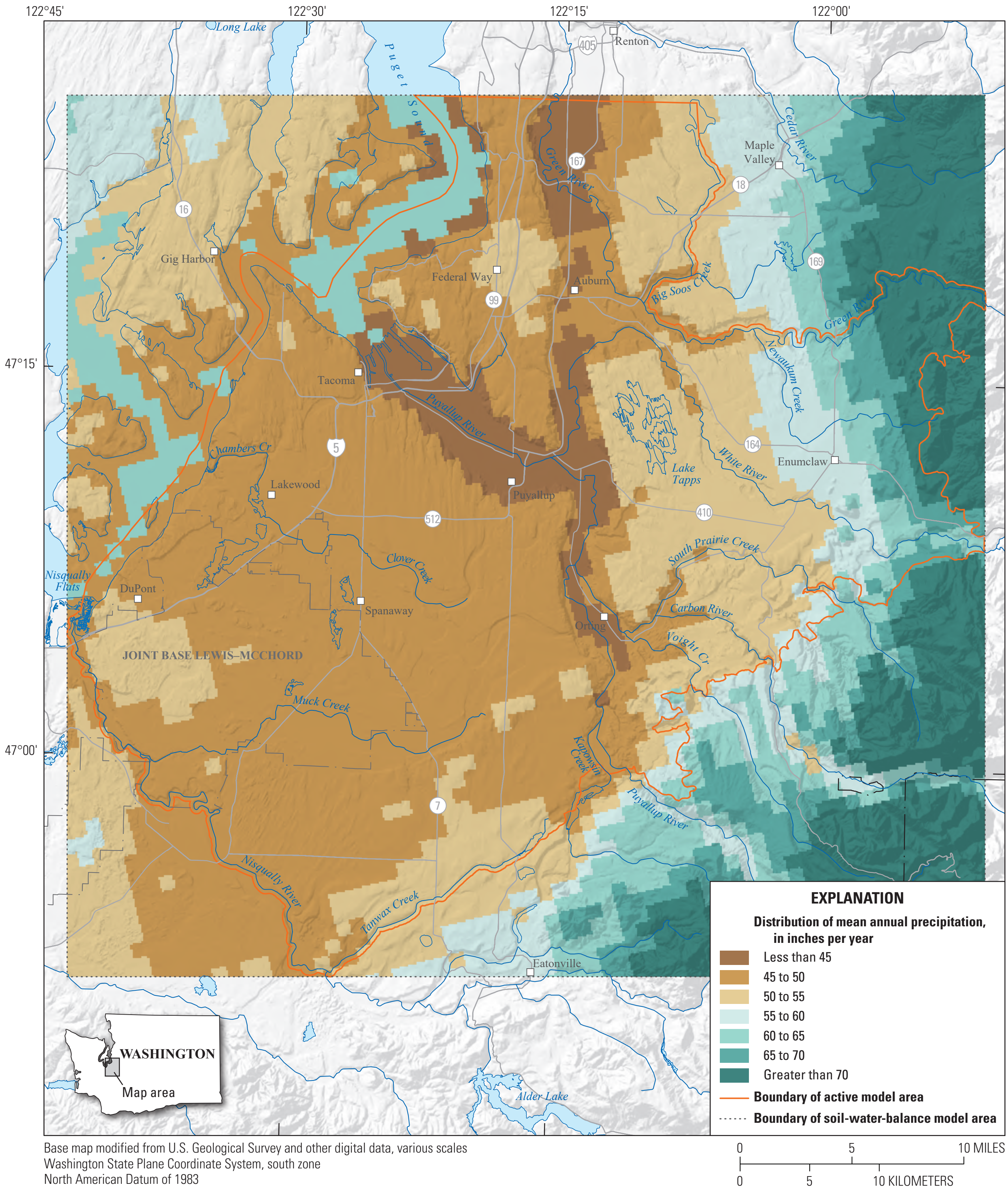


Figure C1. Distribution of mean annual precipitation in the study area, near the southeastern part of Puget Sound, Washington.

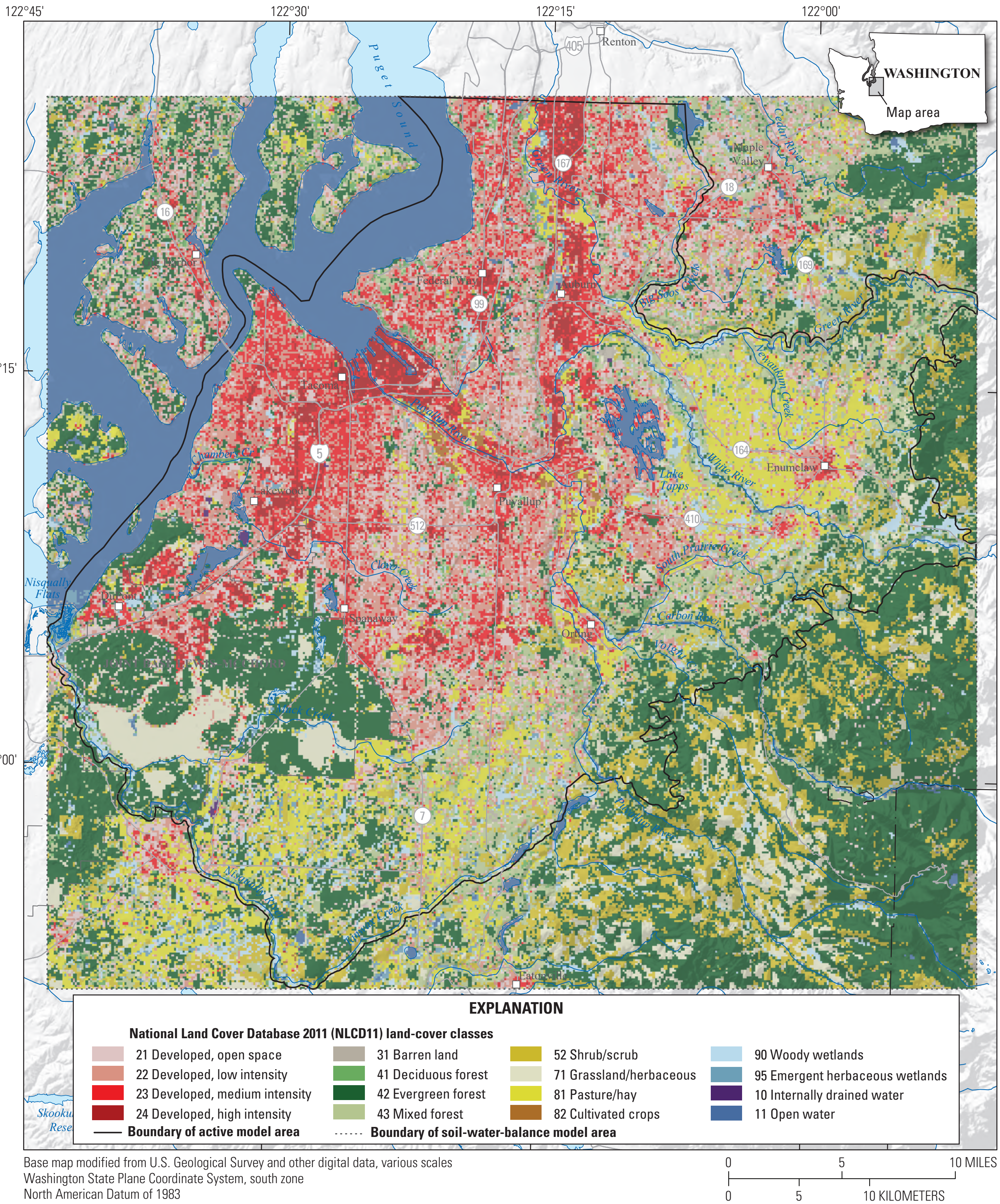


Figure C2. Distribution of 2011 National Land Cover Database (Homer and others, 2015) land-cover classes for the study area, near the southeastern part of Puget Sound, Washington.

Table C1. Land-cover classes for the Soil-Water-Balance model based on 2011 National Land Cover Database (Homer and others, 2015).

[<, less than]

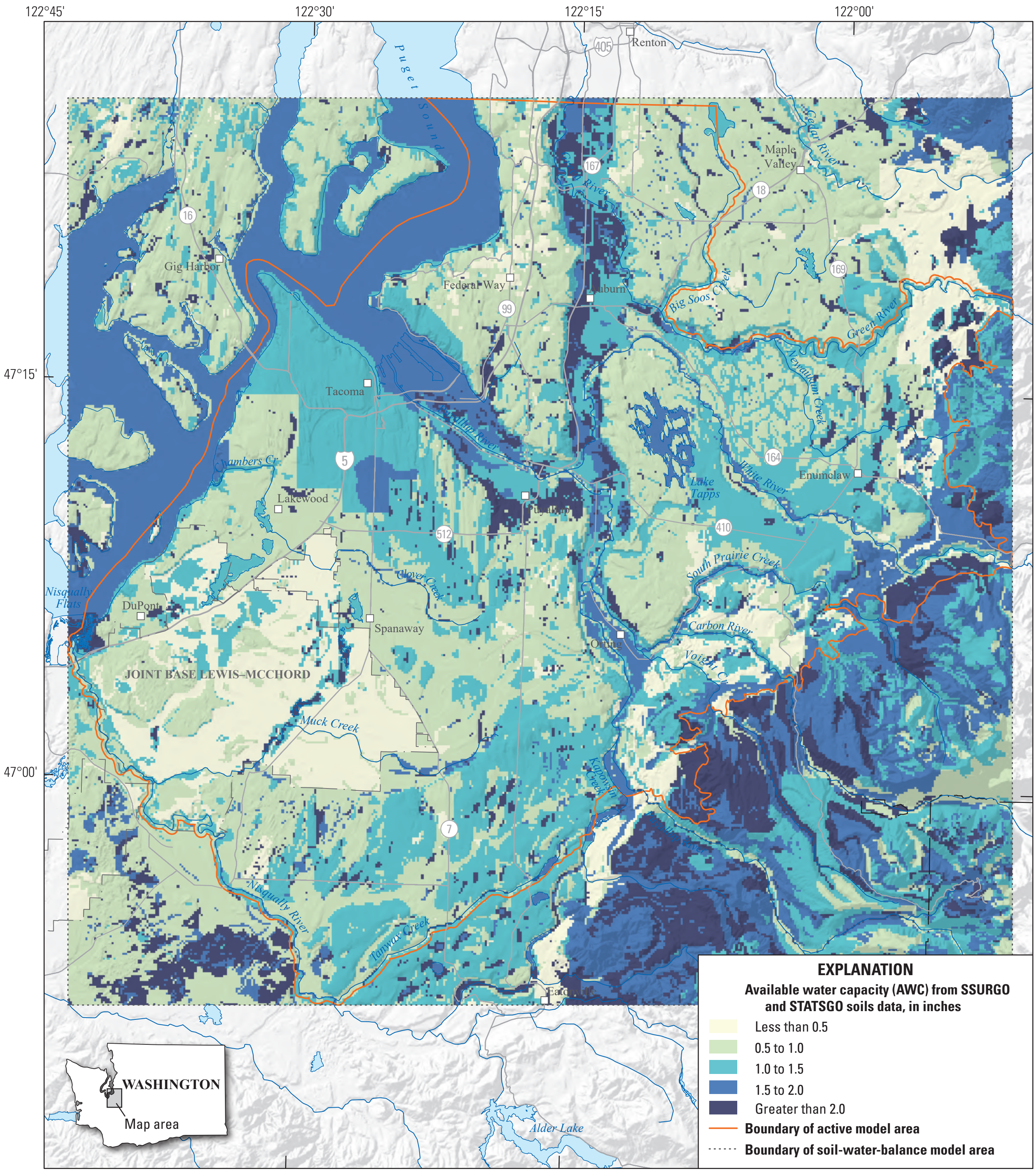
Land-cover code	Land-cover class	Percentage of model area
10	Water, internally drained	<1
11	Open water	6
21	Developed, open space	11
22	Developed, low intensity	17
23	Developed, medium intensity	10
24	Developed, high intensity	4
31	Bare Rock/Sand/Clay	1
41	Deciduous forest	2
42	Evergreen forest	15
43	Mixed forest	11
52	Shrub/Scrub	4
71	Grasslands/Herbaceous	4
81	Pasture/Hay	9
82	Cultivated crops	<1
90	Woody wetlands	3
95	Emergent herbaceous wetlands	1

Precipitation applied to cells classified as open water with a surface-water connection to outside of the model, was categorized as surface-water runoff with no groundwater recharge component. Some ponds, lakes, and storm-water retention basins classified as “Open water,” had no surface-water outlet, and the only way for water to leave the surface was through evapotranspiration or groundwater recharge. Cells classified as open water in NLCD 2011 that had no connection to a river, stream, or ditch were reclassified from “Open water” to “Water, Internally drained.” We assumed that precipitation falling on these water bodies either evaporates or seeps into the underlying subsurface to become groundwater recharge. Curve numbers for this land-cover classification were set to zero so that no precipitation was removed as surface-water runoff, which leaves 100 percent of precipitation to become groundwater recharge. To account for evaporation losses, SWB output was post-processed by subtracting estimated evaporation from recharge for areas encompassing these internally drained water bodies. Evaporation was assumed to equal potential evaporation that was calculated by SWB. Because interception for cells classified as “Water, Internally drained” was set to zero, flow routing was not enabled in the SWB model.

Determination of recharge for cells classified as “Water, Internally drained” assumed that surface water was available throughout the year, which would satisfy the assumption that evaporation is equal to potential evaporation. At larger internally drained lakes (for example, Gravelly Lake), this assumption was satisfied for the period of analysis, but at smaller ponds and retention basins that might have dried up during the summer, this assumption might have resulted in an underestimation of recharge.

Soil data, including hydrologic soil group and available water capacity (AWC), were from the Natural Resources Conservation Service (NRCS) Soil Survey Geographic (SSURGO) and State Soil Geographic (STATSGO) databases (Soil Survey Staff, 2021). Values for each grid cell were assigned based on the SSURGO or STATSGO hydrologic soil group and AWC at the centroid of each model cell. SSURGO soils data, which are more detailed than STATSGO soils data, were used throughout the SWB model area except for the City of Tacoma where it was unavailable and STATSGO soils data were used instead. AWC ranged from greater than 2.0 in. in soils in the main floodplains to less than 0.5 in. in soils developed on glacial outwash in the uplands (fig. C3). The NRCS differentiates mapped soils into four hydrologic soil groups (A–D) based on their infiltration capacity. Soils in group A have high infiltration capacity and low runoff potential, soils in group D have low infiltration capacity, and soils in groups B and C have intermediate values of infiltration capacity and runoff potential (fig. C4).

SWB model parameters for each unique land-cover/hydrologic soil group combination were defined in a lookup table (Gendaszek, 2023), which consist of runoff curve number, maximum recharge rate, interception rate, and root-zone depth, with selected parameters shown in table C2. Surface runoff was calculated using the NRCS curve number rainfall-runoff relation (Cronshey and others, 1986), which represents the collective processes that contribute to runoff. Curve numbers for each land-cover and hydrologic soil group combination were from the NRCS National Hydrology Handbook (U.S. Department of Agriculture, 2004). Because surface-flow routing was disabled, any surface-runoff estimated by the SWB model was removed from the soil-water balance and summed in the surface-runoff term along with any recharge that exceeded the maximum recharge rate for each land-cover/hydrologic soil group combination. Maximum recharge rates, interception rates for the growing season and non-growing season, and root zone depths for each land-cover/hydrologic soil group combination were from Westenbroek and others (2010).



Base map modified from U.S. Geological Survey and other digital data, various scales
Washington State Plane Coordinate System, south zone
North American Datum of 1983

0 5 10 MILES
0 5 10 KILOMETERS

Figure C3. Distribution of available water capacity from Soil Survey Geographic (SSURGO) and State Soil Geographic (STATSGO) data for the study area, near the southeastern part of Puget Sound, Washington.

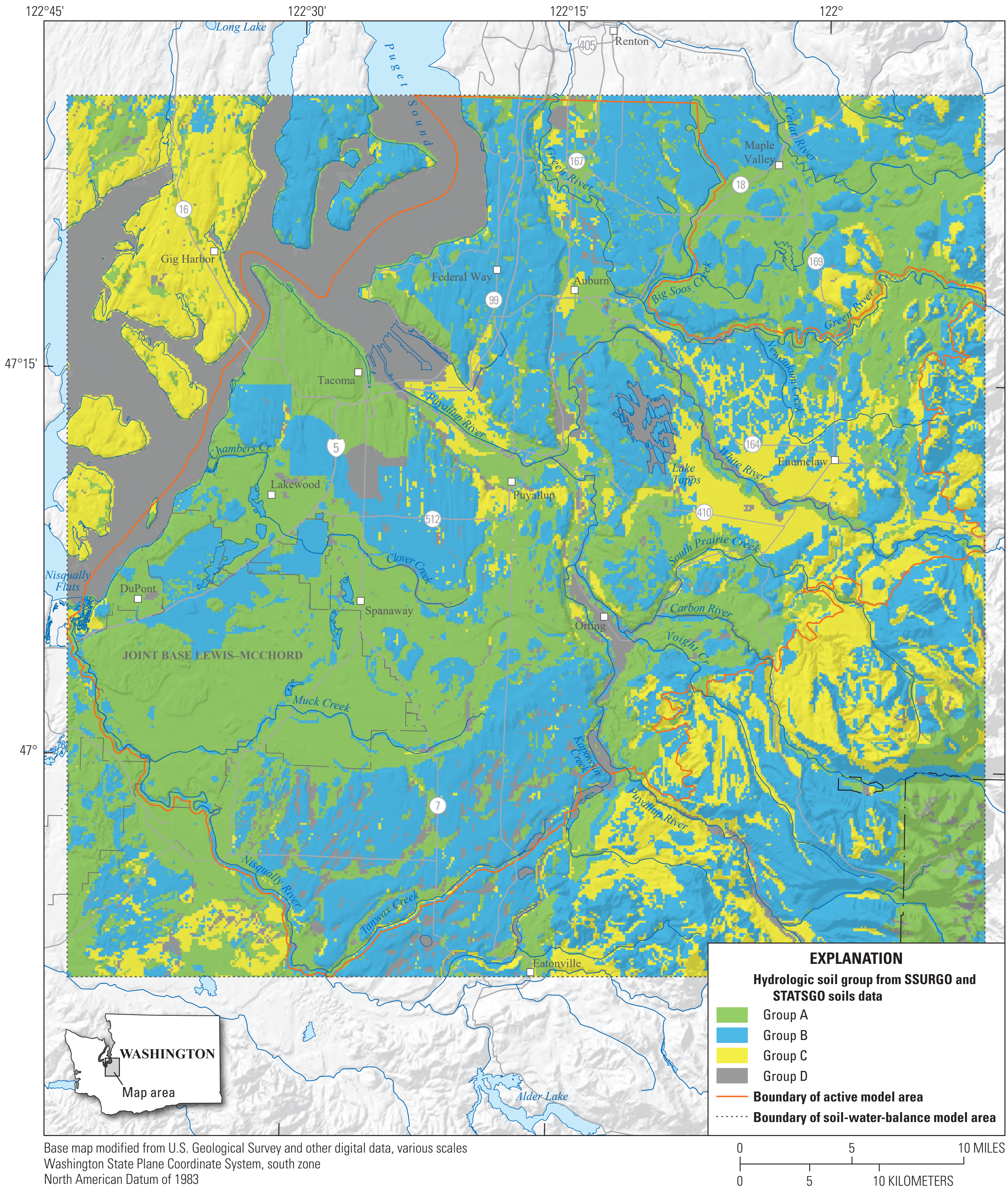


Figure C4. Distribution of hydrologic soil group classifications from Soil Survey Geographic (SSURGO) and State Soil Geographic (STATSGO) soils data for the study area, near the southeastern part of Puget Sound, Washington.

Table C2. Selected parameters from the Soil-Water-Balance model lookup table for the study area, near the southeastern part of Puget Sound, Washington (Gendaszek, 2023).

[HSG, hydrologic soil group]

Land-cover code	Land-cover class	Curve number				Depth of root zone (feet)			
		HSG A	HSG B	HSG C	HSG D	HSG A	HSG B	HSG C	HSG D
10	Water, internally drained	0	0	0	0	0	0	0	0
11	Open water	100	100	100	100	0	0	0	0
21	Developed, open space	49	69	79	84	2	2	2	2
22	Developed, low intensity	61	75	83	97	2	2	2	2
23	Developed, medium intensity	77	85	90	92	2	2	2	2
24	Developed, high intensity	89	92	94	95	2	2	2	2
31	Bare rock/Sand/Clay	77	86	91	94	1	1	1	1
41	Deciduous forest	32	48	57	63	2	1.97	1.74	1.82
42	Evergreen forest	39	58	73	80	2	1.97	1.74	1.82
43	Mixed forest	46	60	68	74	2.67	2.79	2.17	2.61
52	Shrub/Scrub	49	68	79	84	3.33	3.61	2.59	3.4
71	Grasslands/Herbaceous	64	71	81	89	3.33	3.61	2.11	3.4
81	Pasture/Hay	49	69	79	84	3.33	3.61	2.11	3.4
82	Cultivated crops	71	80	87	90	1.67	2	0.63	1.67
90	Woody wetlands	88	89	90	91	4.5	4.5	4.5	4.5
95	Emergent herbaceous wetlands	89	90	91	92	4.5	4.5	4.5	4.5

Water Use

Groundwater and surface-water withdrawals to meet residential, commercial, and agricultural demands within the AMA were compiled from water-use records when available. Otherwise, withdrawals were estimated on a per-capita basis for residential and commercial users or on a basis of irrigated crop area for agricultural users (McLean and others, 2024). Information about well location and construction, used to determine the hydrogeologic unit from which wells withdrew water, was available for larger public-supply systems but was not available for some smaller public water-supply systems, self-supply wells, or agricultural irrigation wells. Although most water use was met by groundwater, surface water also supplied water to the AMA including water sourced from the Howard Hanson Reservoir (which was imported from outside the AMA) for the municipal water supply of the City of Tacoma and adjacent communities (fig. C5). Public water districts and utilities supplied most urban and suburban areas within the AMA, but self-supply wells served residential users in more rural areas. The return of groundwater as recharge from water-supply infrastructure, septic systems, and irrigation losses was also estimated for the study area (McLean and others, 2024).

According to the Washington State Department of Ecology, six water quality permits have been issued for upland hatcheries within the study area (Washington State Department of Ecology, 2022). Water-quality permits are required for any municipality or commercial industry that releases water into State or Federal water bodies (groundwater or surface water). However, data about the source of fresh water (groundwater or surface water), depth of well for groundwater source, volume of water used, and amount of consumptive use are insufficient to quantify aquaculture water use in the AMA, and, therefore, these data are not included in the groundwater budget.

Groundwater and Surface-Water Withdrawals

From January 2005 to December 2015, monthly and mean groundwater withdrawals for the AMA were quantified for Group A and B public-supply systems, self-supply domestic wells, and wells supplying irrigated lands (including agricultural land and golf courses). Among these categories, Group A public-supply systems, which serve at least 15 connections or more than 25 people, generally account for the largest withdrawals and have the most detailed information about withdrawal rates, well construction, and hydrostratigraphy. Group A public-supply systems comprise one or more supply wells or water source and provide water for domestic commercial, industrial, and agricultural use. Less information is generally known about Group B public-supply systems, which serve less than 15 connections or fewer than 25 people, self-supply wells, and irrigation wells. Consequently, different methods were used for each category to quantify mean annual and monthly withdrawal rates and to assign these withdrawals to hydrogeologic units.

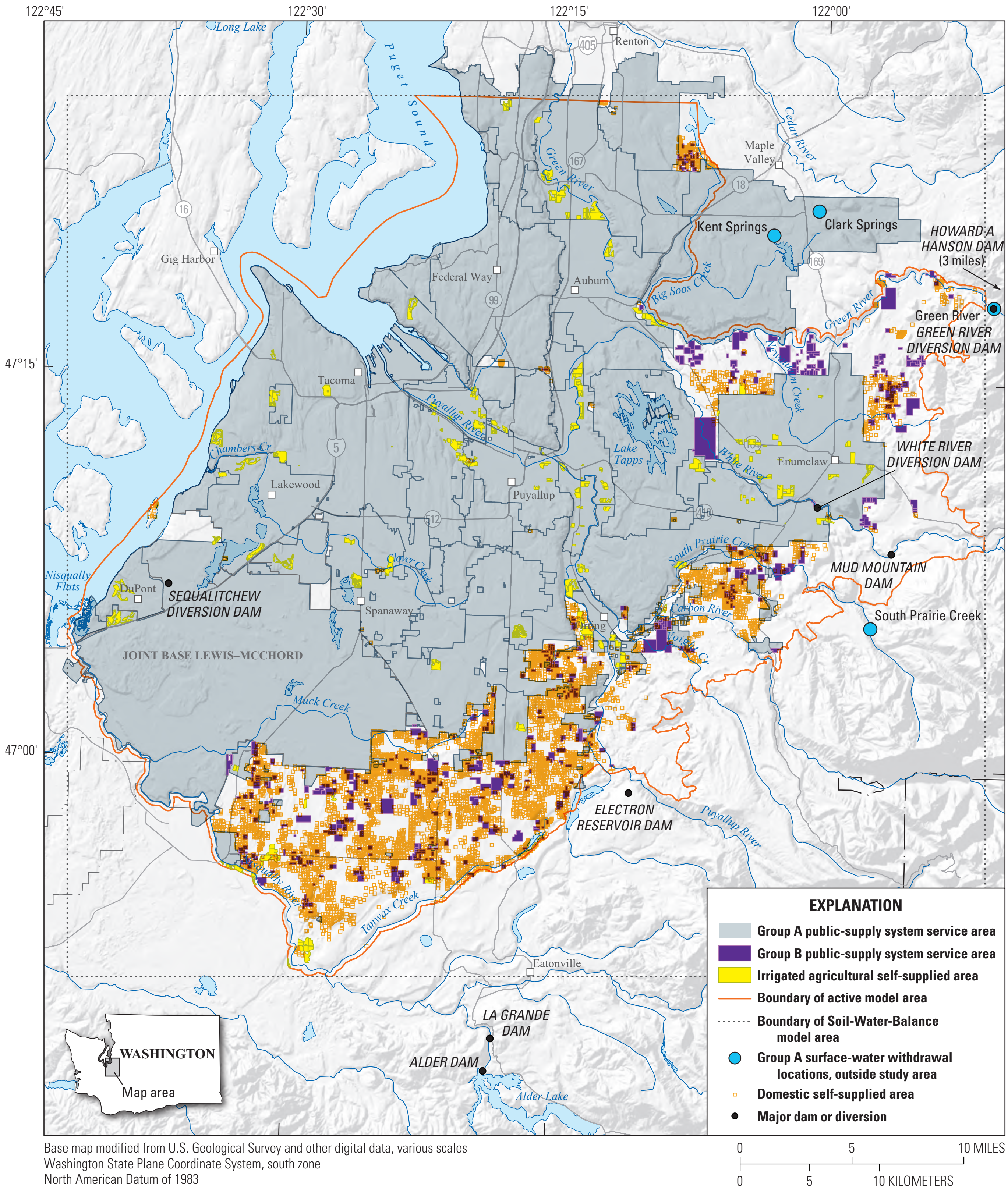


Figure C5. Location and distribution of Group A and B public-supply system service areas, domestic self-supplied areas, and irrigated agricultural self-supplied areas in the active model area, near the southeastern part of Puget Sound, Washington. Major Group A surface-water withdrawal locations outside the active model area, dams, and diversions are also shown.

Groundwater and surface-water withdrawals for the 149 Group A public-supply systems, which served nearly 1,200,000 people in the AMA, were quantified from (1) monthly withdrawal data self-reported by public-supply systems, (2) annual withdrawal data reported by the Washington State Department of Health (WADOH), and (3) per-capita water-use estimates for Pierce and King Counties (Dieter and others, 2018). Monthly withdrawal data from January 2005 to December 2015 were provided by 22 Group A public-supply systems, though completeness of withdrawal records varied by system and reporting year. An estimate of the fraction of annual withdrawals attributed to each month from January 2005 to December 2015 was determined by dividing monthly withdrawal data by annual withdrawals for each of the 22 Group A public-supply systems.

Annual withdrawal data reported by the WADOH were obtained for approximately 118 Group A public-supply systems, though completeness of annual withdrawal records varied by system and reporting year. For Group A systems that did not have reported monthly data or annual withdrawals from the WADOH, annual withdrawals were estimated by multiplying the population served by each Group A public-supply system by an average per-connection water use estimated from WADOH data. Annual withdrawals from 2005 to 2015 were then partitioned into estimated monthly withdrawals from January 2005 to December 2015 by multiplying the fraction of annual withdrawal attributed to each month in the study period by the annual withdrawal. The fraction of Group A public-supply system water delivered to domestic use (79.4 percent) was separated from “other” uses which includes commercial, industrial, and agricultural use (20.6 percent) by using the average domestic fraction of total public-supply water use for King and Pierce Counties from Dieter and others (2018). Mean annual withdrawals averaged from 2005 to 2015 were also assigned as an estimate of the long-term withdrawal rate for each public-supply system.

Monthly and annual withdrawals were not reported for the 1,120 Group B public-supply systems or self-supply users, which collectively serve nearly 13,000 and 20,000 people in the AMA, respectively; therefore, withdrawals by Group B public-supply systems and self-supply users were estimated from the full-time resident population multiplied by per-capita water use estimated from WADOH Group A data. The population served by Group B public-supply systems was obtained from WADOH records of full-time residential population by system. The population served by self-supply wells was estimated to be 2.51 people per residential parcel, determined by taking the average of the residential population divided by the number of residential connections for all Group A systems, as reported by WADOH. Annual per-capita water-use estimates were derived for each year in the study by dividing domestic system withdrawal totals for Group A systems by the full-time residential population for each system. Per-capita rates from each system were then averaged to generate a per-capita rate for the entire study area, which ranged from 85 to 103 gallons of water used per person per day. Annual withdrawals were proportioned into monthly estimates by multiplying the fraction of annual withdrawal determined from monthly data supplied by Group A public-supply systems.

Agricultural fields within the AMA were assumed to be irrigated with groundwater, but limited information was available regarding the location and rate of withdrawals for agricultural irrigation. To estimate groundwater withdrawals, the location and area of irrigated land within the AMA was obtained from the Washington State Department of Agriculture 2017 agricultural land use geodatabase (Washington State Department of Agriculture, 2017). For agricultural irrigation outside Group A public-supply boundaries, groundwater withdrawals were assigned to the centroid of each parcel of agricultural land. Agricultural irrigation within Group A public-supply boundaries was assumed to be supplied by Group A public-supply systems and was not estimated separately. Total withdrawals during the May–September irrigation season were calculated as the product of the area of each parcel and estimated countywide per-acre groundwater irrigation rates for Pierce and King Counties (Dieter and others, 2018). Irrigation withdrawals were assigned to the uppermost aquifer present at the location the irrigation withdrawals.

The locations and completion depths of wells associated with Groups A and B public-supply systems were obtained from WADOH or provided directly by public-supply systems. Withdrawals from each well were assigned to model layers based on the HGU present at the completion depth of the well or deepest well screen for the model cell in which each well was located. The properties of hydrogeologic units and their distribution within the AMA (figs. B2–B13) were described in Chapter B. In some cases, uncertainty in well location, interpolation of HGUs, and depth of screened intervals in WADOH records limited accurate assignments of wells, leading to cases where a confining unit was present at the completion depth of the well. In these cases, the well was assigned to the next aquifer stratigraphically above the confining unit. For some Group A and B wells, particularly large production wells, detailed well-construction and hydrostratigraphic data were available, which superseded assignment of wells to model layers based on completion depths. The consistency of well assignments to hydrogeologic units with previous studies within the AMA (Savoca and others, 2010; Welch and others, 2015) was evaluated with respect to the updated framework presented in Chapter B.

The locations of self-supply wells within the AMA were inferred from the presence of residential parcels not served by either Groups A or B public-supply systems. Information about parcels and residential improvements were obtained from available King and Pierce County tax parcel data. Some residential parcels within Group A system boundaries likely have self-supplied wells and are not connected to Group A systems; however, because of a lack of information about the distribution of public-supply residential connections or self-supplied wells, all residential parcels within Group A public-supply system boundaries were assumed to be served by Group A systems. Limited boundaries were available for Group B public-supply systems; therefore, the number of residential connections listed by WADOH for Group B public-supply systems were apportioned to the nearest residential parcels. After accounting for residential parcels served by Group A and B public-supply systems, residual residential parcels were assumed to be served by self-supply wells. For each Public Land Survey System (PLSS) section within the AMA (Bureau of Land Management, 2017), the median depth of residential-sized wells in the Washington State Department of Ecology's well report database (Washington State Department of Ecology, 2018) was calculated and used to assign groundwater withdrawals to HGUs. If a confining unit was present at the depth of the median well in each section and the well completed within 100 vertical feet of an aquifer, withdrawals from each well were assigned to the next aquifer stratigraphically above the confining unit.

Anthropogenic Recharge

Groundwater recharge from anthropogenic sources (including returns from agricultural and residential irrigation, leakage of water-supply pipelines, and septic tank returns) was calculated for the AMA. Collectively, these sources of groundwater recharge were termed anthropogenic recharge. Agricultural and residential irrigation was differentiated into consumptive use, which was removed by evaporation or transpiration, and non-consumptive use, which was assumed to recharge to groundwater.

Residential water use supports indoor uses as well as outdoor uses such as irrigation for lawns and gardens. To determine the residential-irrigation fraction, water use from Group A public-supply systems was averaged across all systems for each month. During the winter months (October–April), outdoor use is assumed to be zero and, therefore, water use during the winter is assumed to be entirely indoor use. The average indoor (winter) water use was subtracted from water use for summer months (May–September) to determine the portion of outdoor water use applied as irrigation (table C3). For agricultural water use, all withdrawals are assumed to be applied to fields as irrigation. Irrigation returns to groundwater were estimated by assuming an 80-percent rate of consumptive use for agricultural and residential irrigation (Dieter and others, 2018) during May–September, when irrigation is applied to crops and lawns. Groundwater recharge from residential and agricultural irrigation was applied at the centroids of residential and agricultural model cells, respectively.

Group A water-supply system pipelines were digitized from publicly available county maps and city water plans from nine of the largest cities in the study area (Auburn, Bonney Lake, Covington, Enumclaw, Fircrest, Lakewood, Puyallup, Sumner, and Tacoma). The amount of groundwater recharge from pipeline leakage was estimated from water use efficiency reports from WADOH and was distributed evenly along the digitized water-supply pipelines within the AMA.

Table C3. Monthly mean indoor and outdoor water-use rates, for domestic public-supply water use in the active model area, near the southeastern part of Puget Sound, Washington, 2005–15.

Month	Water use rate (gallons per person per day)		
	Indoor	Outdoor	Total
January	82	0	82
February	82	0	82
March	82	0	82
April	82	2	84
May	82	15	97
June	82	39	121
July	82	73	155
August	82	68	150
September	82	34	116
October	82	4	86
November	82	0	82
December	82	0	82

Groundwater recharge for residential parcels outside Group A systems included data from large on-site sewage systems (LOSS) provided by WADOH (Washington State Department of Health, 2018) and individual septic systems on residential parcels with self-supply wells. Recharge from LOSS was estimated by assuming that systems operated at 70 percent of system capacity. Septic systems for self-supply parcels were assumed to recharge 90 percent of indoor water use, which was non-consumptive (Culhane, 2018).

Discharge to Streams

Groundwater discharge to streams within the AMA was estimated by synoptic streamflow measurements and graphical separation of streamflow hydrographs into their base-flow and surface-runoff components. Near-simultaneous synoptic streamflow measurements were used to calculate the net volume of groundwater discharge to or recharge from streams by determining the net increase or decrease in streamflow, respectively, that was not accounted for by tributary inflows or diversions between two streamflow measurement sites. Synoptic streamflow was measured during summer and early autumn when surface runoff was minimal, and all streamflow was assumed to have originated as groundwater discharge. In contrast to synoptic streamflow measurements that only quantified groundwater discharge during low-flow conditions, estimates of groundwater discharge through graphical hydrograph separation included both high- and low-flow conditions throughout the year.

Six sets of synoptic streamflow measurements, or seepage runs, within the AMA were made at 108 locations, with some locations measured multiple times. This report and the data release associated with it (Seepage Runs, McLean and others, 2024) present the results of streamflow measured at (1) 51 locations during 2007 and 2008 within the Chambers-Clover Creek watershed (Savoca and others, 2010), (2) 62 sites during 2011 and 2012 within the Puyallup River watershed (Welch and others, 2015), and (3) 11 sites by the Pierce Conservation District during 2012 and 2015. Streamflow measured at upstream and downstream measurement sites was differenced to determine the net streamflow gain or loss along the intervening stream length after accounting for streamflow gains and losses from intervening tributaries and diversions.

Total groundwater discharge to streams within the AMA was determined by summing the mean discharges of the most downstream streamflow measurement sites. To account for the part of the Puyallup River watershed that lies outside the AMA, the cumulative discharge for the White, Carbon, and Puyallup River streamgages near the AMA boundary was subtracted from the most downstream Puyallup River streamflow measurement. Groundwater discharge to the Green River was estimated as the difference between discharge measured at the upstream and downstream Green River streamgages but was reduced by 40 percent to account for the contributing watershed outside the AMA. The area within the AMA that drains to the most downstream measurement sites was 633 mi^2 (75 percent) of the AMA. Small watersheds draining directly to Puget Sound and much of the Nisqually River watershed (except for Muck Creek) were not included within the 633-mi^2 area.

Groundwater discharge to streams within the AMA was also estimated by separating hydrographs recorded at 29 long-term streamgages into their base-flow and surface-runoff components. Graphical, chemical, and isotopic methods have been developed to separate hydrographs (Healy, 2010), but only graphical methods were considered to estimate base flow for the AMA because streamgage records, but not chemical or isotopic data, were widely available throughout the AMA. The hydrograph separation program HYSEP (Sloto and Crouse, 1996) is an automated approach to traditional graphical hydrograph separation methods. The sliding interval method in HYSEP was applied to the mean daily streamflow records, resulting in daily estimates of base flow and surface runoff for each streamgage. Base-flow estimates were temporally averaged for the 11-year period from January 1, 2005, to December 31, 2015, and for each month during that time period.

Because the AMA did not directly coincide with watershed boundaries, the base-flow contribution for the part of the watershed within the AMA was determined by subtracting estimates of base flow at locations where streams enter the AMA from base flow estimated at the most downstream streamgage within the AMA. The estimated base flow at the AMA boundary was determined by adjusting the base flow in proportion to the watershed area between the streamgage used to estimate base flow and the AMA boundary. If the streamgage was outside the AMA, base flow was increased in proportion to the watershed area between the streamgage and the AMA boundary; conversely, base flow was proportionally decreased if the streamgage was inside the AMA. Base flow entering the AMA was also estimated from the basin-averaged recharge that was estimated by the SWB model for three small ungaged basins: Boise and Scatter Creeks within the Puyallup River Basin and Coal Creek within the Green River Basin. SWB-based base-flow estimates assume that groundwater recharge approximates base flow (for example, Risser and others, 2005). For the Green River, the points of inflow to and outflow from the AMA coincide with U.S. Geological Survey (USGS) stations 12106700 and 12113344, respectively. Fifty-eight percent of the watershed area between these two streamgages is inside the AMA. We multiplied the base-flow difference between the two streamgages by 0.58 to estimate the streamflow gain between them that can be attributed to the AMA. Base flow for the Nisqually River at the southwestern boundary of the AMA was not estimated because discharge records were only available from one streamgage for the Nisqually River (USGS streamflow gaging station 12089500). The AMA draining to the streamgages where base flow was estimated from hydrograph separation was 487 mi^2 (57 percent of the AMA).

Results

The fate of precipitation (separated into the components of precipitation recharge [R_P], evapotranspiration, surface runoff, interception, and change in soil moisture) was estimated by the SWB model (table C4) for the 11-year period from January 2005 to December 2015. Precipitation, which averaged 50.5 in/yr across the 887-mi^2 AMA during this period, was the primary input. Precipitation recharge, R_P, accounted for the largest percentage of

Table C4. Fate of precipitation simulated by the Soil-Water-Balance model for the active model area, near the southeastern part of Puget Sound, Washington, averaged for 2005–15.

Fate of precipitation	Inches per year	Percentage of total precipitation
Precipitation recharge to groundwater	21.9	43
Evapotranspiration	15.3	30
Surface runoff	10.0	20
Interception	3.3	6
Change in soil moisture	0.0	0
Total precipitation	**50.5**	**100**

total precipitation (21.9 in/yr; 43 percent), followed by evapotranspiration (15.3 in/yr; 30 percent), and surface runoff (10.0 in/yr; 20 percent). Interception accounted for only 3.3 in/yr (6 percent) of total precipitation, and changes in soil moisture over the 11-year period were negligible. Additional groundwater recharge (0.3 in.) from anthropogenic sources—including domestic irrigation, water-system leakage, large on-site sewage systems, septic systems, and agriculture irrigation—was estimated from water-use data (table C5). Most of these groundwater-return flows originated from Group A water-system leakage (73.8 percent), with lesser contributions from other sources. Pacific Groundwater Group (1999) estimated that additional groundwater recharge from the seepage of Lake Tapps was 9,418 acre-feet (acre-ft) (0.2 in. averaged across the AMA).

Precipitation recharge, R_P, as estimated by the SWB model, was applied to the groundwater budget for the AMA (table C6). Total inflows for this groundwater budget averaged 22.4 in/yr and consisted of R_P, groundwater return flows, and seepage from Lake Tapps. Groundwater outflows consisted of discharge to streams, springs, lakes, Puget Sound, and withdrawals from wells (table C6).

Groundwater withdrawals from wells were estimated to be 1.6 in/yr (7 percent) of total groundwater recharge, based on water-use records, population estimates, and per-capita water-use rates. About 95 percent of groundwater withdrawals

Table C5. Number of sources and mean annual average recharge from anthropogenic groundwater-return flows by infrastructure category in the active model area, near the southeastern part of Puget Sound, Washington.

Return by infrastructure category	Number of sources (model cells)	Mean annual recharge (acre-feet per year)	Mean annual recharge (inches)	Percentage of total
Group A domestic irrigation (lawns)	37,463	549	0.01	4.0
Group A water-system leakage	6,484	10,056	0.22	73.8
Group B large on-site sewage systems	33	255	0.01	1.9
Group B septic	2,644	455	0.01	3.3
Self-supply septic	7,824	1,542	0.03	11.3
Agriculture irrigation	2,541	774	0.02	5.7
Total	**56,989**	**13,631**	**0.30**	**100**

Table C6. Estimated groundwater budget in the active model area, near the southeastern part of Puget Sound, Washington, averaged for 2005–15.

Groundwater flows	Inches per year	Acre-feet per year	Percentage of total inflows
Groundwater inflows			
Precipitation recharge	21.9	1,037,717	98
Groundwater return flows	0.3	13,631	1
Lake Tapps seepage to groundwater	0.2	9,418	1
Total inflows	**22.4**	**1,060,766**	**100**
Groundwater outflows—Estimated from synoptic streamflow measurements			
Discharge to streams	7.6	360,536	34
Other natural discharge	13.2	622,301	59
Withdrawals from wells	1.6	77,929	7
Total outflows	**22.4**	**1,060,766**	**100**
Groundwater outflows—Estimated from hydrograph separation			
Discharge to streams	14.8	700,983	66
Other natural discharge	6.0	281,854	27
Withdrawals from wells	1.6	77,929	7
Total outflows	**22.4**	**1,060,766**	**100**

Table C7. Number of sources, population served, and mean annual total withdrawals by water-supply category in the active model area, near the southeastern part of Puget Sound, Washington.

[NA, not applicable]

Withdrawal by water-supply category	Number of sources	Population	Mean annual withdrawal (acre-feet per year)	Mean annual withdrawal (inches)	Percentage of total
Group A (public supply for domestic use)	346	1,184,684	58,838	1.3	75.5
Group A (public supply for non-domestic uses)	346	NA	15,265	0.34	19.6
Group B (public supply with fewer than 15 connections, domestic and non-domestic)	1,219	12,756	1,267	0.03	1.6
Domestic self-supply	7,826	19,683	2,006	0.04	2.6
Agricultural self-supply	74	NA	552	0.01	0.7
Total	**9,811**	**1,217,123**	**77,928**	**1.73**	**100.0**

were from Group A public-supply systems and about 5 percent of groundwater withdrawals were from Group B public-supply systems, self-supply users, and agricultural users (table C7). Groundwater withdrawals were greatest during summer, when most outdoor irrigation occurred, and lowest during the winter, when most water use was indoors. For example, residential water use was highest from May through September and peaked in July, during which an average of 13.0 percent of all Group A water withdrawals occurred (fig. C6).

Groundwater discharge to streams within the AMA was quantified by synoptic streamflow measurements (covering 75 percent of the AMA; table C8) and hydrograph separation (covering 57 percent of the AMA; table C9), respectively. Groundwater discharge estimated through synoptic streamflow measurements (7.6 in.) was less than groundwater discharge estimated through hydrograph separation (14.8 in.) despite accounting for less of the AMA (table C6). This discrepancy reflects, in part, the annual time period over which hydrograph separation averages groundwater discharge compared to the summer and early-autumn period over which synoptic

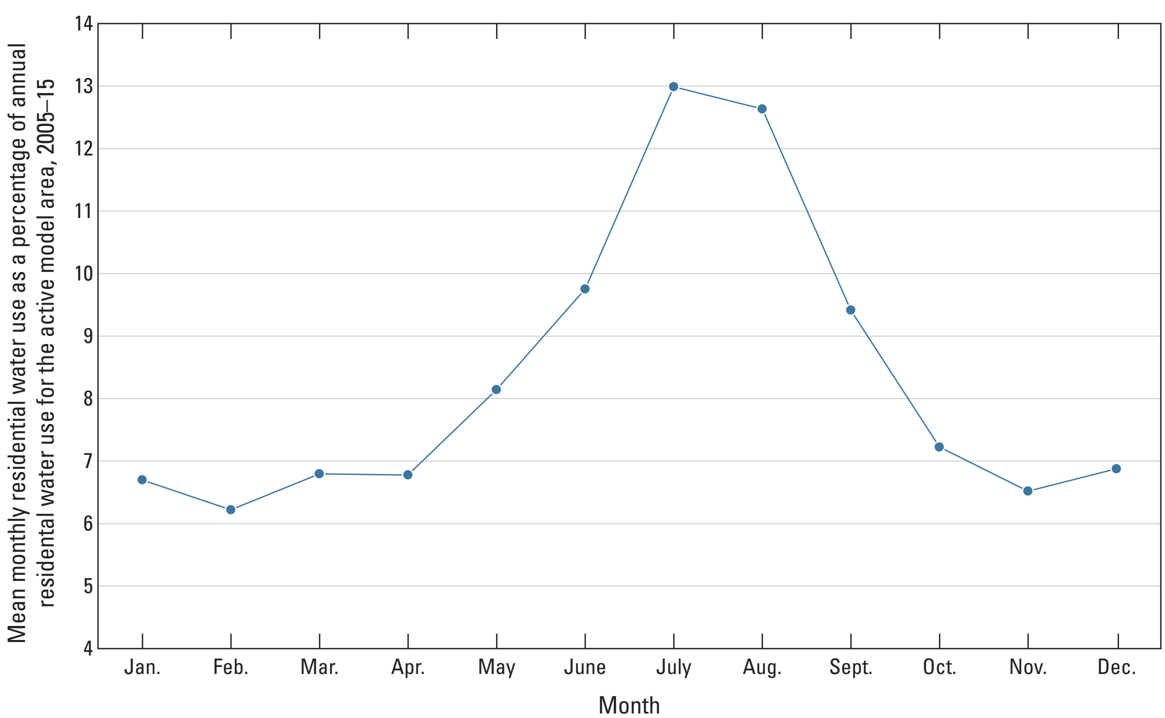


Figure C6. Seasonal variability in mean monthly residential public-supply water use as a percentage of annual residential public-supply water use in the active model area, near the southeastern part of Puget Sound, Washington, 2005–15.

Table C8. Mean groundwater discharge estimated from synoptic streamflow measurements and evaporative loss from lakes in the active model area, near the southeastern part of Puget Sound, Washington, calendar years 2005–15 (data from U.S. Geological Survey, 2020).

[**Measurement site name:** Name and location of sites. **Abbreviations:** Ave, Avenue; SR, State Route; ft^3/s, cubic foot per second; NA, not applicable]

Measurement site name	Site number	Mean groundwater discharge to streams (ft^3/s)
Swan Creek at Pioneer Way East	12102212	2.67
Clear Creek at 31st Ave East	12102175	15.4
Clarks Creek at Stewart Ave at railroad bridge	12102060	53.9
Chambers Creek upstream of Chambers Bay	12091590	48.1
Murray Creek at 41st Division Way (Camp Murray)	12090290	1.53
Sequalitchew Creek at Center Drive	12090315	0
Muck Creek at Roy (bridge at Warren Street)	12090200	0.9
Evaporative loss from Lake Steilacoom[1]	NA	1.7
Evaporative loss from Spanaway Lake[1]	NA	1.3
Mill Creek near Mouth at Orillia	12113349	2.6
Springbrook Creek at Orillia	12113346	5.3
Green River at 200th Street at Kent	12113344	82.8
Cold Creek near mouth at Poverty Bay	NA	1.02
Lakota Creek near mouth at Poverty Bay	NA	1.45
Hylebos Creek near Milton	NA	3.38
Des Moines Creek below SR 509 near mouth	NA	2.76
Puyallup River at Puyallup	12101500	273
Total estimated groundwater discharge to streams		**498**

[1]Evaporative loss estimated by Savoca and others (2010).

streamflow measurements estimate groundwater discharge. McLean and others (2024) and plate present additional synoptic streamflow measurements detailing gains and losses of streamflow from groundwater discharge to and recharge from underlying aquifers, respectively. Synoptic streamflow measurements include additional measurements within the AMA that quantify groundwater/surface-water exchange, but these additional measurements were not used for estimation of the groundwater budget. Synoptic streamflow measurements were made at discrete times during summer and early fall base-flow periods, precluding monthly base-flow estimates.

Other natural discharge (including discharge to springs, lakes, Puget Sound, and other streams not listed in table C9) was calculated as the residual groundwater recharge that was not assigned to groundwater discharge to streams through synoptic streamflow measurements and hydrograph separation. Other natural discharge was greater when stream discharge was estimated through synoptic streamflow measurements (13.2 in.) than when stream discharge was estimated through hydrograph separation (6.0 in.; table C6).

Discussion

Input of water into the AMA primarily occurs through precipitation, which averaged 50.5 in. annually across the study area from 2005 to 2015. Aquifers bordering the AMA were assumed to contribute minimal water to the AMA. On the eastern boundary of the AMA, groundwater inflow was restricted by low-permeability bedrock confining units. Major hydrologic features, including the Green and Nisqually Rivers and Puget Sound, formed the northeastern, southern, and western boundaries of the AMA. Generalized groundwater-flow directions toward these features (Savoca and others 2010; Welch and others 2015) suggest the outflow of groundwater to these features as groundwater discharge to rivers, coastal springs and seeps, and submarine groundwater discharge to Puget Sound. Surface-water inputs of water from rivers including the Green, White, Carbon, and Puyallup Rivers, and their tributaries were assumed, on average, to pass through the AMA because both hydrograph separation and synoptic streamflow measurements showed net discharge of groundwater to rivers throughout the AMA. Precipitation was not geographically uniform across the AMA, increasing from less than 45 in. in the lower elevations of the central

Table C9. Estimates of base flow from hydrograph separation used to determine mean annual groundwater discharge to streams in the active model area, near the southeastern part of Puget Sound, Washington, calendar years 2005–15 (data from U.S. Geological Survey, 2020).

[Values are from McLean and others (2024). Mean annual base flow, discharge, and surface runoff were reported for U.S. Geological Survey streamgages that have discharge records from January 2005 to December 2015. Discharge records for Voight Creek were outside this period and base flow was estimated from a linear regression model developed between Voight and South Prairie Creeks. Base flow for Coal, Scatter, and Boise Creeks at the active model area boundary were estimated from mean recharge estimated by Soil-Water-Balance model of their contributing basins. **Mean runoff:** Mean annual runoff estimated by HYSEP sliding interval method. **Mean base flow**: Mean annual base flow estimated by HYSEP sliding interval method. **Abbreviations:** St, Street**;** ft^3/s, cubic feet per second; NA, not applicable]

Measurement site name	Site number	Mean annual discharge (ft^3/s)	Mean runoff	Mean base flow
Nisqually River at McKenna	12089500	1,385	270.5	1,114
North Fork Clover Creek near Parkland	12090400	8.04	2.98	5.06
Spanaway Creek at Spanaway Lake Outlet near Spanaway	12090452	15.63	0.51	15.11
Clover Creek near Tillicum	12090500	37.91	4.22	33.69
Flett Creek at Tacoma	12091100	14.97	2.36	12.61
Leach Creek near Fircrest	12091200	6.24	2.69	3.55
Leach Creek near Steilacoom	12091300	11.86	3.13	8.73
Chambers Creek below Leach Creek near Steilacoom[1]	12091500	113	11.2	101.8
Puyallup River near Orting	12093500	791.2	188.7	602.5
South Prairie Creek at South Prairie	12095000	247	73.06	173.9
Puyallup River at Alderton	12096500	1,762	489.6	1,272
Puyallup River at East Main Bridge at Puyallup[2]	12096505	NA	NA	NA
White River Below Clearwater River near Buckley	12097850	1563	394	1,169
White River Above Boise Creek at Buckley	12099200	1,460	352.1	1,108
Boise Creek at Buckley	12099600	38.12	8.93	29.18
White River at R Street near Auburn	12100490	1,657	390.5	1,267
White River near Auburn	12100496	1,742	424.8	1,317
Puyallup River at 5th St Bridge at Puyallup[2]	12101470	NA	NA	NA
Puyallup River at Puyallup[1,3]	12101500	3,524	843	2,681
Clarks Creek at Tacoma Road near Puyallup[1]	12102075	59.6	2.64	56.96
Swan Creek at 80th St East near Tacoma[1,2]	12102190	NA	NA	NA
Green River at Purification Plant near Palmer	12106700	970.7	235.8	734.9
Newaukum Creek near Black Diamond	12108500	59.93	10.18	49.75
Big Soos Creek Above Hatchery near Auburn	12112600	140.8	20.94	119.8
Green River near Auburn	12113000	1,467	385.7	1,081
Green River at 200th Street at Kent[1,3]	12113344	1,600	414.7	1,185
Mill Creek at Earthworks Park at Kent	12113347	3.76	1.04	2.71
Mill Creek near Mouth at Orillia[1]	12113349	15.17	4.79	10.38

Table C9. Estimates of base flow from hydrograph separation used to determine mean annual groundwater discharge to streams in the active model area, near the southeastern part of Puget Sound, Washington, calendar years 2005–15 (data from U.S. Geological Survey, 2020)—Continued.

[Values are from McLean and others (2024). Mean annual base flow, discharge, and surface runoff were reported for U.S. Geological Survey streamgages that have discharge records from January 2005 to December 2015. Discharge records for Voight Creek were outside this period and base flow was estimated from a linear regression model developed between Voight and South Prairie Creeks. Base flow for Coal, Scatter, and Boise Creeks at the active model area boundary were estimated from mean recharge estimated by Soil-Water-Balance model of their contributing basins. **Mean runoff:** Mean annual runoff estimated by HYSEP sliding interval method. **Mean base flow**: Mean annual base flow estimated by HYSEP sliding interval method. **Abbreviations:** St, Street**;** ft^3/s, cubic feet per second; NA, not applicable]

Measurement site name	Site number	Mean annual discharge (ft^3/s)	Mean runoff	Mean base flow
Carbon River near Fairfax	12094000	443.2	114.8	328.4
Voight Creek near Crocker[4]	12095495	NA	NA	47.9
Boise Creek at model boundary[5]	NA	NA	NA	14
Coal Creek at model boundary[5]	NA	NA	NA	23.4
Scatter Creek at model boundary[5]	NA	NA	NA	18.7

[1]Station data used to estimate groundwater-budget area discharge to streams.

[2]Seasonal station having no summer data. Mean annual values could not be computed because of missing data. Estimates of mean base flow are available in Long and others (2024).

[3]Base flow for the Puyallup River (12101500) computed as difference between downstream and upstream base flow estimated for area-adjusted base flow of South Prairie Creek (12095000), White River (12097850), Carbon River (12094000), Puyallup River (12093500), Boise Creek at model boundary, Scatter Creek at model boundary, and Voight Creek near Crocker.

[4]Base flow estimated from linear regression between discharge measured at Voight Creek (12095495) and South Prairie Creek (12095000).

[5]Base flow for Coal, Scatter, and Boise Creeks at the model boundary were estimated from mean recharge estimated by the Soil-Water-Balance model of their contributing basins.

and western AMA to more than 70 in. in the higher elevations of the eastern part of the AMA. Precipitation was also not distributed evenly across the year, occurring primarily during autumn and winter: Seventy-two percent of mean annual precipitation occurred during the 6-month period from October 1 to March 31.

Inter-annual and seasonal variability in precipitation, temperature, and plant growth resulted in changes in the absolute and relative magnitudes of components of the soil-water balance estimated by the SWB model. Seasonal changes in precipitation drove seasonal changes in groundwater recharge and surface runoff, with the highest values of these components occurring during the October–March wet season and the lowest values occurring during the July–September dry season (fig. C7). Mean monthly groundwater recharge from precipitation was highest in December (5.0 in.) and lowest in July (0.0 in.), and surface runoff was similarly highest in November (1.9 in.) and lowest in July (0.2 in.). Evapotranspiration rates are not only dependent on increased soil moisture from precipitation, but also on temperature and increased transpiration during the May through October growing season. These factors contributed to the highest rates of actual evapotranspiration during March–June, when warmer temperatures are coupled with relatively high precipitation. Evapotranspiration was less during July and August because of low precipitation, despite warmer temperatures. Interception rates, which peak in May during the wettest part of the year when deciduous trees have leafed out, are similarly influenced by precipitation. Soil moisture declines during the growing season when water demand by plants is greatest and increases after the growing season once precipitation increases in the autumn. Groundwater recharge and other groundwater-budget components also varied across years depending on variability in inter-annual climate. During a dry year like 2013, when mean annual precipitation was 41.7 in., groundwater recharge was 16.0 in., compared to 28.1 in. during the wet year of 2006 when mean annual precipitation was 56.7 in. (fig. C8).

Groundwater recharge varied spatially across the AMA as a function of the distribution of precipitation, soils, and land cover (fig. C9). Mean annual recharge varied from less than 15 in/yr in the main river valleys, where low-permeability soils of hydrologic soil groups C and D coincided with low precipitation rates, to more than 50 in. in the northeastern part of the AMA, where high precipitation rates coincided with permeable soils of hydrologic soil groups A and B. Land cover also affected the distribution of groundwater recharge with cells classified as developed land covers in the developed urban areas of the central parts of the AMA receiving less groundwater recharge and producing more surface runoff than less developed areas of the southern and eastern parts of the AMA. Groundwater recharge by internally drained lakes was accounted for by the SWB model, but recharge by lakes with surface-water outlets was not estimated by SWB.

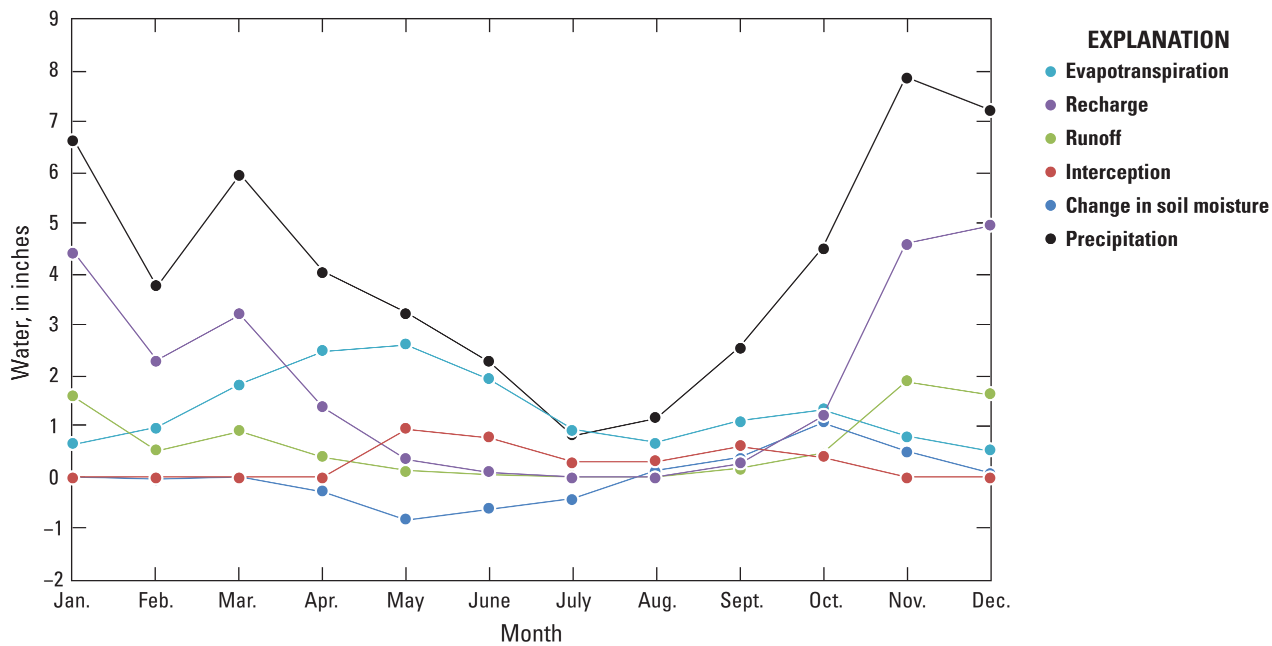


Figure C7. Seasonal variability in mean monthly groundwater-budget components estimated by the Soil-Water-Balance model in the active model area, near the southeastern part of Puget Sound, Washington, averaged for 2005–15.

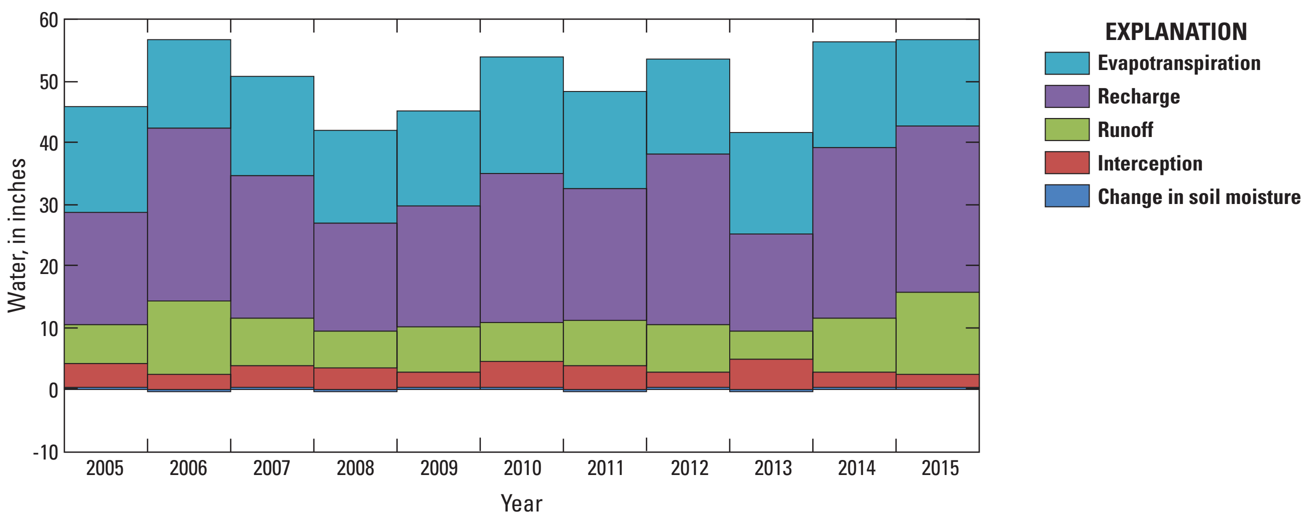


Figure C8. Inter-annual variability in mean annual groundwater-budget components estimated by the Soil-Water-Balance model in the active model area, near the southeastern part of Puget Sound, Washington, 2005–15.

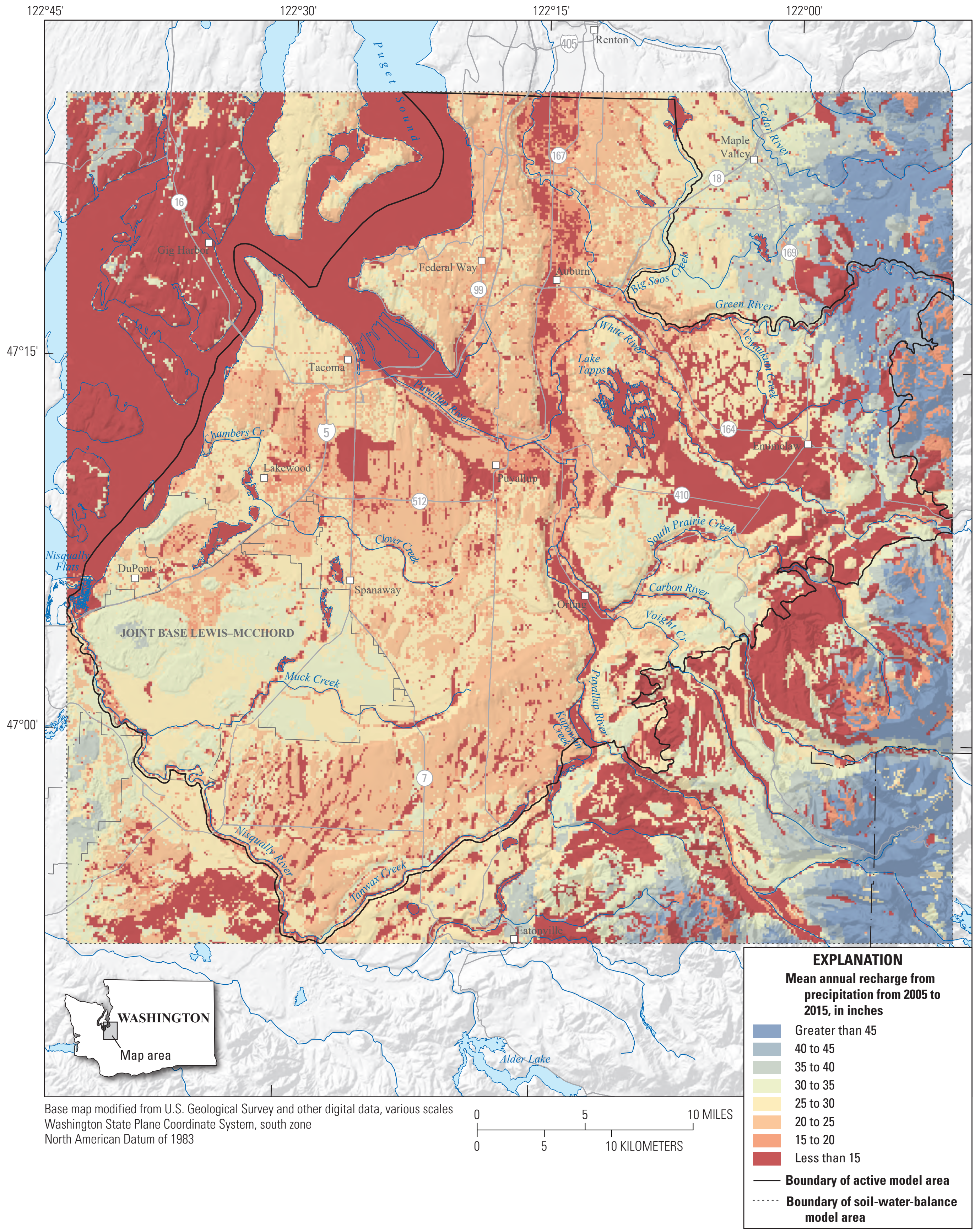


Figure C9. Distribution of mean annual recharge from precipitation in the active model area, near the southeastern part of Puget Sound, Washington, 2005–15.

Estimates of exchange between groundwater and most lakes with surface-water outlets were not available, except for Lake Tapps (Golder Associates and HDR Engineering, Inc., 2001).

Although precipitation was the primary source of groundwater recharge to the AMA, additional recharge occurred from irrigation returns, water-system leakage, septic systems, and other infrastructure. Recharge from groundwater-return flows was estimated to be 0.3 in/yr, averaged across the study area, but occurred in discrete locations around agricultural and residential parcels where irrigation occurred, residential development using large on-site sewage systems and septic systems, and water-system pipelines (fig. C10). In areas without this type of infrastructure, recharge from groundwater-return flows did not occur.

A groundwater budget was quantified for the AMA describing the fate of groundwater recharge as withdrawals for water supply and as natural discharge to streams, springs, and Puget Sound. Mean annual groundwater withdrawals for water supply were almost 78,000 acre-feet but were unevenly distributed spatially across the AMA. Groundwater withdrawals by Group A and B water-supply systems were focused near urban and suburban areas in the western and central AMA (fig. C11). Groundwater withdrawals by self-supplied users were predominantly in rural parts in the eastern part of AMA (fig. C12). Groundwater withdrawals were distributed unevenly throughout the year; they were highest when precipitation was least and demand for outdoor irrigation water was greatest. The period from June to September accounted for 46 percent of the mean annual groundwater withdrawals for residential water use. Withdrawals for agricultural water use were similarly highest during this period and were negligible during winter. Total withdrawals from wells estimated for the AMA (1.6 in/yr; 78,000 acre-feet per year [acre ft/yr]) were similar to estimates by Savoca and others (2010) for the Chambers-Clover Creek watershed (2.5 in/yr; 59,000 acre-ft/yr) and by Welch and others (2015) for the Puyallup River watershed (1.5 in/yr; 43,000 acre-ft/yr).

Groundwater discharge to streams was quantified from discrete synoptic streamflow measurements from 2007 to 2015 and from hydrograph separation. Groundwater discharge from unmeasured parts of the AMA was not quantified because synoptic streamflow measurements and hydrograph separation estimated groundwater discharge for only part of the AMA (75 and 57 percent, respectively). The base flow estimated by hydrograph separation (701,000 acre-ft/yr) was greater than the groundwater discharge measured by synoptic streamflow measurements (361,000 acre-ft/yr), despite the smaller proportion of the AMA within the hydrograph separation area. This discrepancy partly reflects differences in the time during which groundwater discharge is quantified. Whereas groundwater discharge measured by synoptic streamflow measurements was quantified during summer and early-autumn low-flow conditions, hydrograph separation was used to quantify groundwater discharge during the entire year including low-flow and high-flow conditions.

Other natural discharge (including groundwater discharge to rivers and springs not accounted for by hydrograph separation or synoptic streamflow measurements, springs, and Puget Sound) was estimated as the difference between groundwater recharge and the sum of groundwater discharge to streams and groundwater withdrawals. Springs were estimated to contribute 2.9 in/yr (80,300 acre-ft/yr) to the Puyallup River watershed (Welch and others, 2015) and the 3.5 in. (80,000 acre-ft/yr) to the Chambers-Clover Creek watershed (Savoca and others, 2010). These estimates, however, did not account for many unmeasured springs and some spring discharge might be accounted for in groundwater discharge to streams; streamflow in Clarks Creek, for example, consists mostly of spring discharge. Additionally, sub-marine groundwater discharge to Puget Sound was not directly measured and is not well quantified.

Mean basin recharge estimated from January 2005 to December 2015 by the SWB model was similar in magnitude to mean basin recharge estimated for the Chambers-Clover Creek and Puyallup River watershed groundwater-budget areas by Savoca and others (2010) and Welch and others (2015), despite different spatial areas and time periods over which recharge was averaged. Mean basin recharge from September 2006 to August 2008 was estimated to be 20 in/yr (455,000 acre-ft/yr) for the Chambers-Clover Creek watershed groundwater-budget area and 21 in/yr (538,000 acre-ft/yr) for the Puyallup River watershed groundwater-budget area from January 2011 to December 2012. Groundwater recharge from precipitation estimated by the SWB model for the AMA was similar in magnitude to the previous estimates for the Chambers-Clover Creek and Puyallup River watershed groundwater-budget areas (21.9 in/yr; 1,037,717 acre-ft/yr; table C6). In addition to recharge from precipitation, 0.3 in/yr (13,500 acre-ft/yr) of groundwater recharge from groundwater-return flow originated as anthropogenic sources and 0.2 in. (9,400 acre-ft/yr) recharged from seepage from Lake Tapps (Pacific Groundwater Group, 1999). Unlike estimates of groundwater recharge for the AMA, groundwater recharge within the Chambers-Clover Creek and Puyallup River watershed groundwater-budget areas was estimated using precipitation-recharge relations developed for western Washington (Bidlake and Payne, 2001). These precipitation-recharge relations accounted for the permeability of surficial materials, but did not explicitly account for surface-runoff, interception, or evapotranspiration like the SWB model. Instead, these terms were calculated within the Chambers-Clover Creek and Puyallup River watershed groundwater-budget areas by Savoca and others (2010) and Welch and others (2015) as the residual precipitation that was not accounted for by groundwater recharge. Combined surface runoff and evapotranspiration estimated for the AMA (25.3 in/yr; 1,196,000 acre-ft/yr) was similar to previous estimates for the Chambers-Clover Creek watershed (25 in/yr; 570,000 acre-ft/yr) by Savoca and others (2010) and for the Puyallup River watershed (31 in/yr; 847,000 acre-ft/yr) by Welch and others (2015).

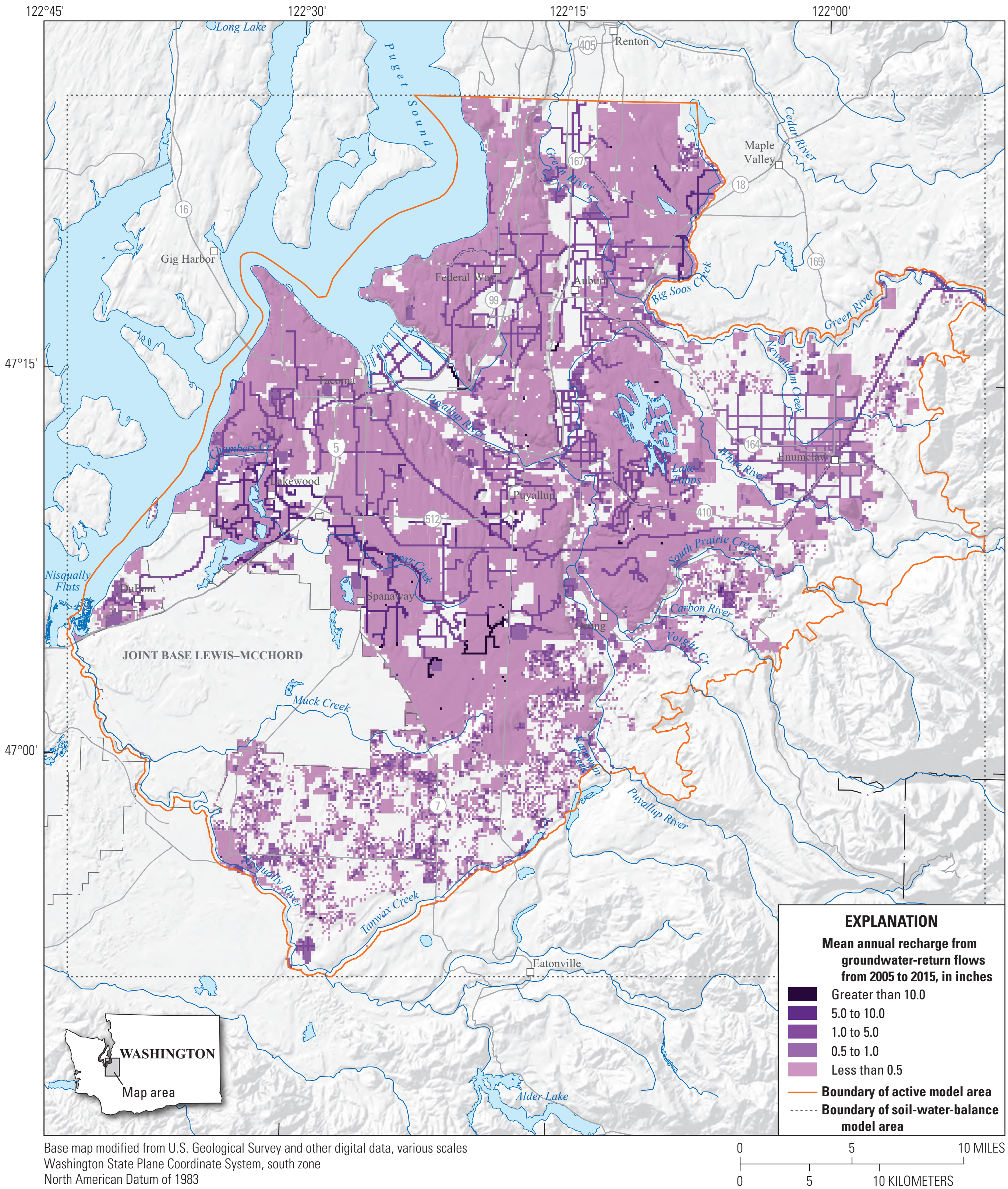


Figure C10. Distribution of mean annual recharge from groundwater-return flows in the active model area, near the southeastern part of Puget Sound, Washington, 2005–15.

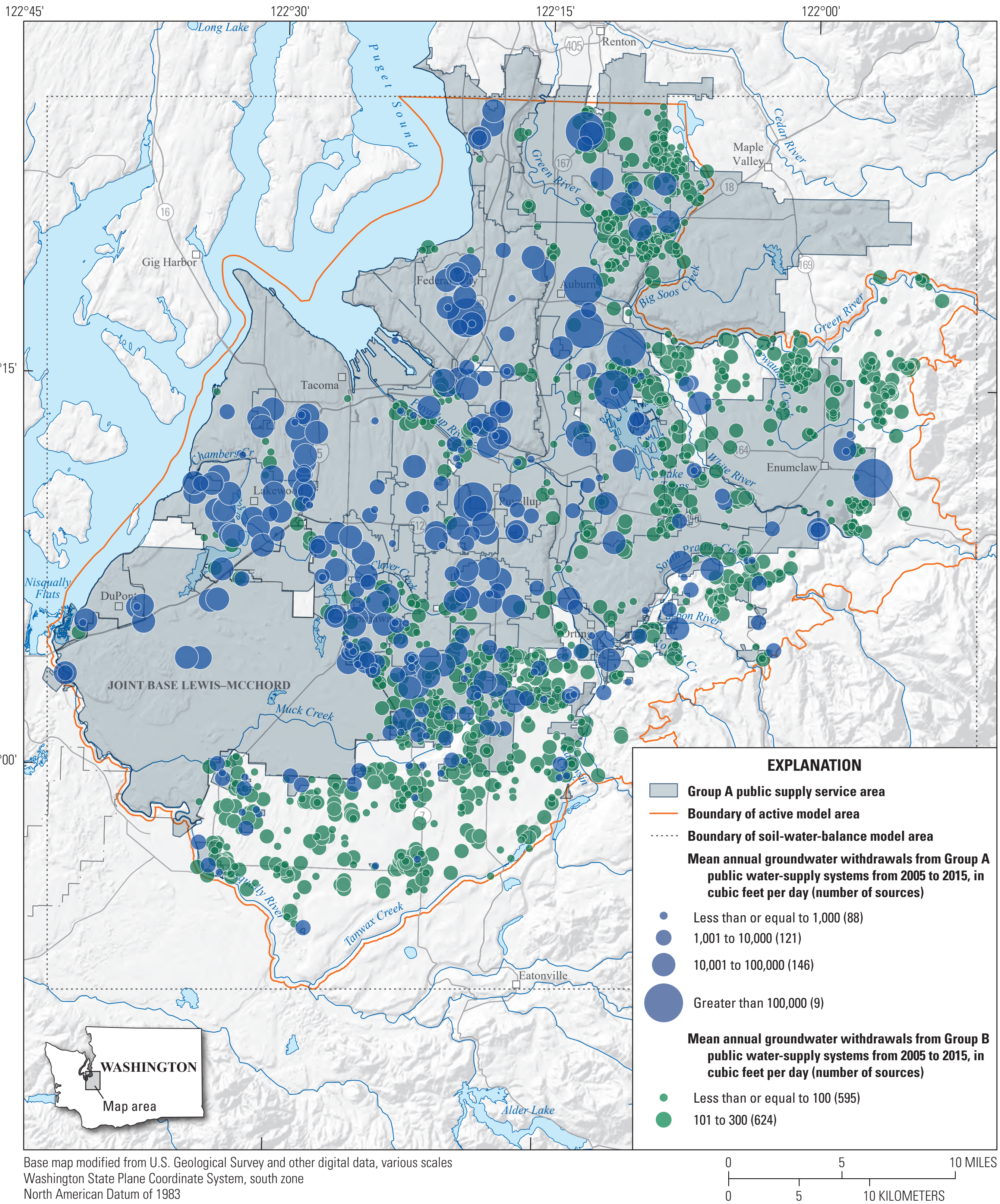


Figure C11. Distribution of mean annual groundwater withdrawals from Group A and B public water-supply systems in the active model area, near the southeastern part of Puget Sound, Washington, 2005–15.

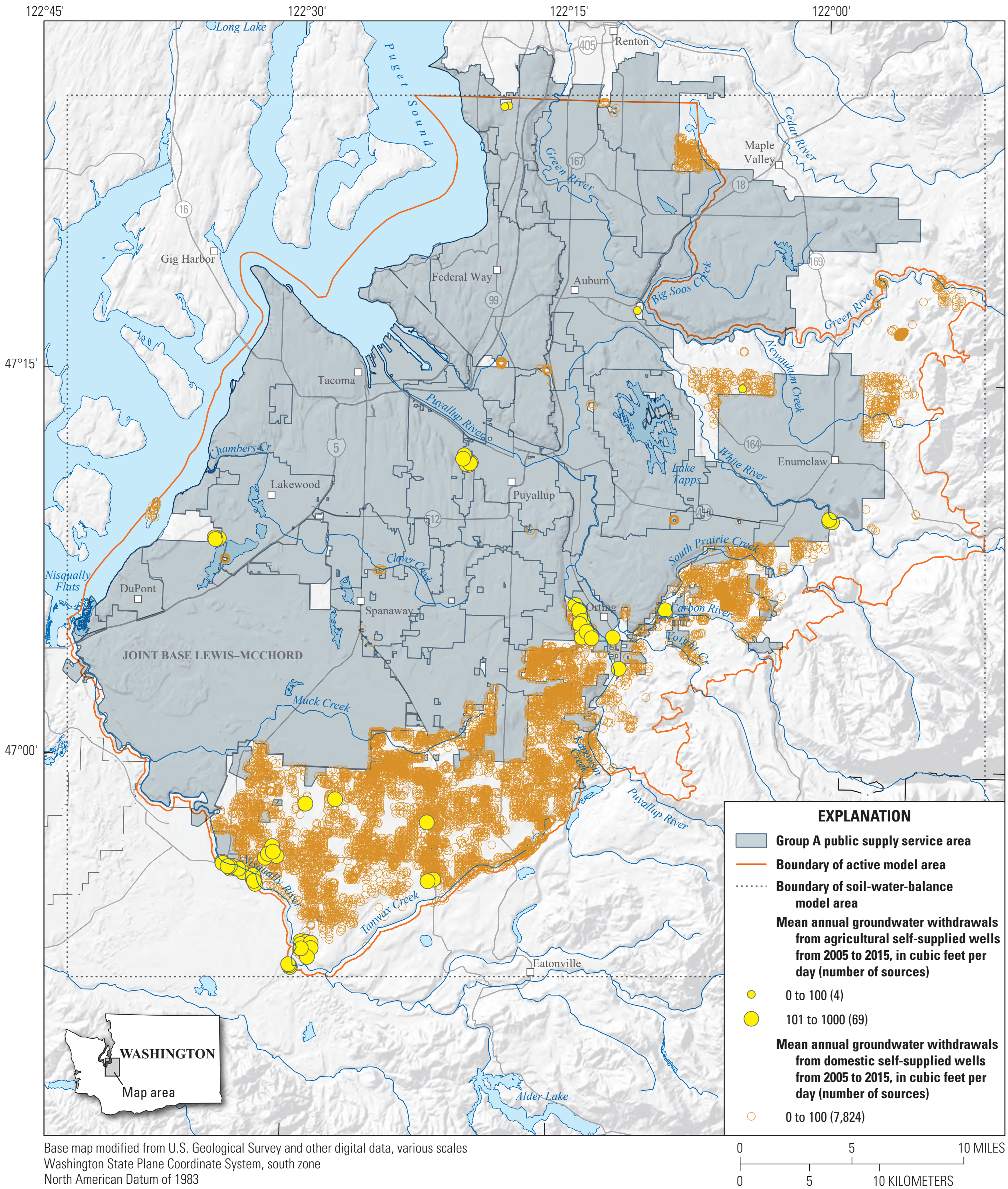


Figure C12. Distribution of mean annual groundwater withdrawals for agricultural irrigation outside Group A public-supply system boundaries and by self-supply users in the active model area, near the southeastern part of Puget Sound, Washington, 2005–15.

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