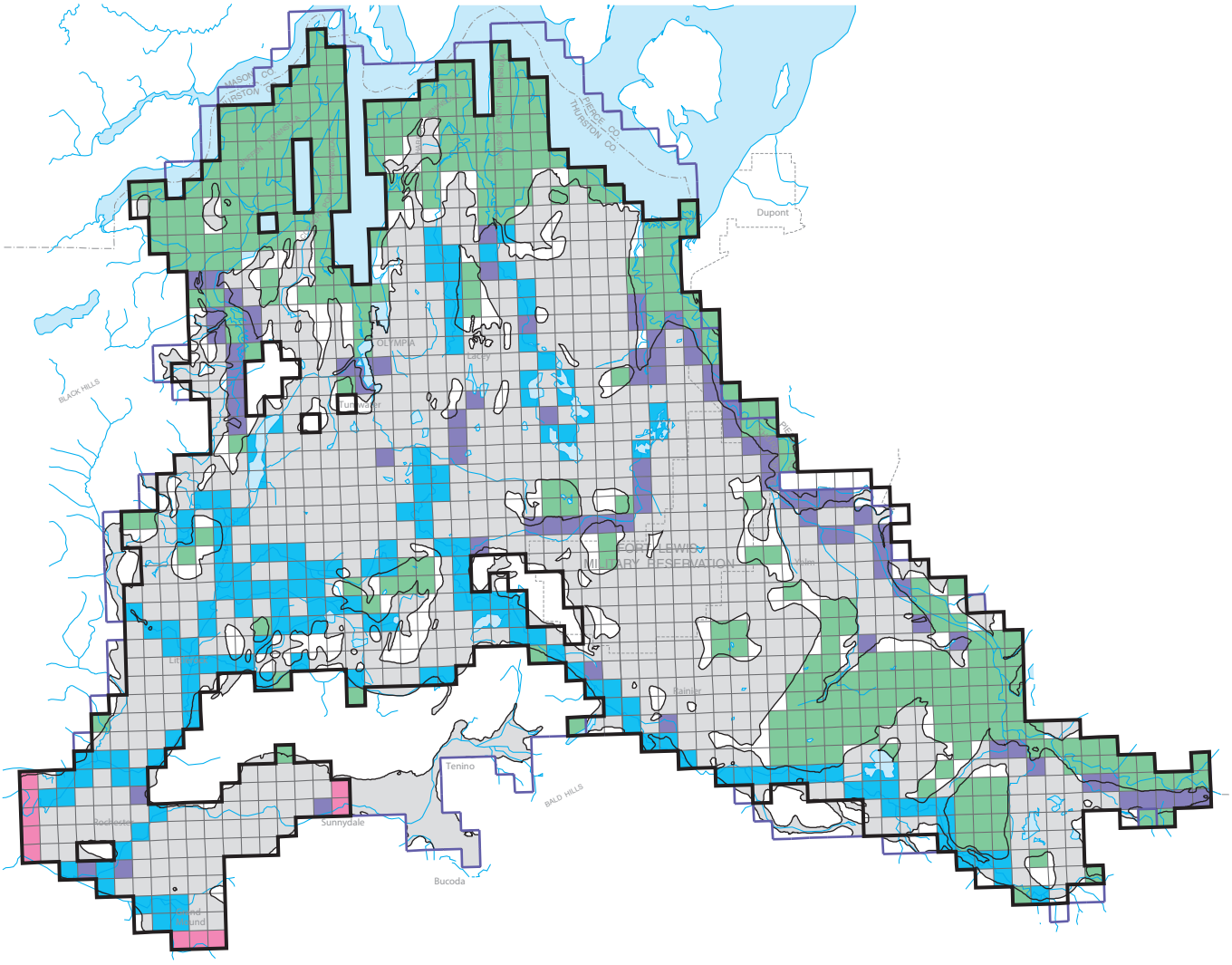
U.S. Department of the Interior
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Conceptual Model and Numerical Simulation of the Ground-Water-Flow System in the Unconsolidated Sediments of Thurston County, Washington

Water-Resources Investigations Report 99-4165



Prepared in cooperation with
Thurston County Health Department

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By B.W. Drost, D.M. Ely, and W.E. Lum, II

U.S. GEOLOGICAL SURVEY

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Tacoma, Washington
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CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch (in)	25.4	millimeter
foot (ft)	0.3048	meter
foot per day (ft/d)	0.0000035	meter per second
square foot per day (ft^2/d)	0.000001075	square meter per second
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
acre	4,047	square meter
	0.4047	hectare
acre-foot (acre-ft)	1,233	cubic meter
acre-foot per year (acre-ft/yr)	0.01427	cubic meter per second
gallon per minute (gal/min)	0.00006308	cubic meter per second
gallon per day (gal/d)	0.00000004381	cubic meter per second
cubic foot (ft^3)	0.02832	cubic meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Sea Level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

CONCEPTUAL MODEL AND NUMERICAL SIMULATION OF THE GROUND-WATER-FLOW SYSTEM IN THE UNCONSOLIDATED SEDIMENTS OF THURSTON COUNTY, WASHINGTON

By B.W. Drost, D.M. Ely, and W.E. Lum, II

ABSTRACT

The demand for water in Thurston County has increased steadily in recent years because of a rapid growth in population. Surface-water resources in the county have been fully appropriated for many years and Thurston County now relies entirely on ground water for new supplies of water. Thurston County is underlain by up to 2,000 feet of unconsolidated glacial and non-glacial Quaternary sediments which overlie consolidated rocks of Tertiary age. Six geohydrologic units have been identified within the unconsolidated sediments.

Between 1988 and 1990, median water levels rose 0.6 to 1.9 feet in all geohydrologic units except bedrock, in which they declined 1.4 feet. Greater wet-season precipitation in 1990 (43 inches) than in 1988 (26 inches) was the probable cause of the higher 1990 water levels.

Ground-water flow in the unconsolidated sediments underlying Thurston County was simulated with a computerized numerical model (MODFLOW). The model was constructed to simulate 1988 ground-water conditions as steady state.

Simulated inflow to the model area from precipitation and secondary recharge was 620,000 acre-feet per year (93 percent), leakage from streams and lakes was 38,000 acre-ft/yr (6 percent), and ground water entering the model along the Chehalis River valley was 5,800 acre-ft/yr (1 percent). Simulated outflow from the model was primarily leakage to streams, springs, lakes, and seepage faces (500,000 acre-ft/yr or 75 percent of the total outflow). Submarine seepage to Puget Sound was simulated to be 88,000 acre-ft/yr (13 percent). Simulated ground-water discharge along the Chehalis River valley was simulated to be 12,000 acre-ft/yr (2 percent). Simulated withdrawals by wells for all purposes was 62,000 acre-ft/yr (9 percent).

The numerical model was used to simulate the possible effects of increasing ground-water withdrawals by 23,000 acre-ft/yr above the 1988 rate of withdrawal. The model indicated that the increased withdrawals would come from reduced discharge to springs, seepage faces, and offshore (total of 51 percent of increased pumping) and decreased flow to rivers (46 percent). About 3 percent would come from increased leakage from rivers. Water-levels would decline more than 1 foot over most of the model area, more than 10 feet over some areas, and would be at a maximum of about 35 feet.

Contributing areas for water discharging at McAllister and Abbott Springs and to pumping centers near Tumwater and Lacey were estimated using a particle-tracking post-processing computer code (MODPATH) and a MODFLOW model calibrated to steady-state (1988) conditions. Water discharging at McAllister and Abbot Springs was determined to come from water entering the ground-water system at the water table in an area of about 20 square miles (mi^2) to the west and south of the springs. This water is estimated to come from recharge (both precipitation and secondary) and from leakage from Lake St. Clair and several other surface-water bodies. Southeast of Lacey, about 3,800 acre-ft of ground water were pumped from five municipal wells during 1988. The source of the pumped water was determined to be an area that covers about 1.1 mi^2. The water was estimated to come from recharge (both precipitation and secondary) and leakage from surface-water bodies. Along the lower Deschutes River nearly 3,900 acre-ft/yr of ground water were pumped during 1988 from 15 wells for

municipal and industrial use. The calculated source of this water was an area that covers about 1.3 mi^2. Within the calculated contributing area the pumped ground water comes from recharge (both precipitation and secondary) and leakage from the Deschutes River and several other surface-water bodies.

INTRODUCTION

Demand for water in Thurston County, Washington, has increased steadily in recent years because of rapid growth in population. Thurston County lies at the southern end of Puget Sound in western Washington, and is bounded at the north by a coastline of numerous inlets. The northern part of the county is underlain by thick sediments of mostly glacial origin, including widespread deposits of sand and gravel at land surface.

Because surface-water resources in the county have been fully appropriated for many years, Thurston County now relies almost entirely on ground water for domestic, public supply, agricultural, and industrial uses. Any additional development in the county imposes an additional stress on the ground-water system.

The U.S. Geological Survey (USGS) entered into a cooperative study with the Thurston County Health Department to characterize the ground-water system in the unconsolidated sediments that underlie northern Thurston County, including the designated Ground Water Management Area. The objectives of that study were to:

- Describe and quantify the ground-water system to the extent that existing or readily collectable data allow;
- Describe the general chemical characteristics of waters in the major aquifers and the areal patterns of any ground-water contamination;
- Provide guidelines for the establishment of networks to monitor ground-water levels and ground-water quality; and
- Determine the feasibility of constructing a three-dimensional ground-water-flow model for the area.

The results of the study (Drost and others, 1998) provided data on the ground-water system, described the chemistry of the ground water, and established a monitoring network for measuring water levels in wells. The study also indicated that existing data were sufficient to support the construction of a ground-water-flow model to use as a tool to increase the understanding of the regional-scale ground-water-flow system. Accordingly, the Thurston County Health Department entered into another agreement with the USGS to construct a model. The objectives of the modeling study were to construct and use a ground-water-flow model to:

- Gain a better understanding of the ground-water-flow system and to quantify components of the ground-water budget in the study area;
- Identify probable areas of ground-water recharge and discharge, and;
- Simulate ground-water-flow paths using a particle-tracking post processor with the flow model.

The project was designed such that the completed model would be available for Health Department personnel to use to qualitatively address management concerns, including:

- Determination of where sanitary sewers could be installed to decrease the potential for degradation of ground-water quality by on-site sewage disposal systems (septic systems);
- Evaluation of the effects of agriculture on water quality;
- Determination of areas where degradation of ground-water quality will have a long-term effect on the quality of ground water where it is currently used or may be used in the future; and
- Estimation of the effects of large-scale increases in ground-water withdrawals on ground-water levels and the quality of ground water.

One of these management concerns, estimating the effects of large-scale increased withdrawals, is evaluated in this report.

Purpose and Scope

The purpose of this report is to summarize the findings of the modeling study. The topics covered in this report include the geometry and hydraulic characteristics of the aquifers and confining beds; the conceptual model of the ground-water flow system; the numerical model used to simulate the ground-water flow system; the model-derived ground-water budget; simulations of increased ground-water withdrawals; identification of areas contributing to ground-water flows at selected locations; sensitivity testing of the model; and limitations of the model.

Description of the Study Area

The study area includes all of Thurston County where unconsolidated sediments are at land surface (510 square miles; fig. 1). The study area includes the designated Ground Water Management Area (GWMA, fig. 1), which covers 232 square miles (mi^2) in the northern part of Thurston County. The GWMA is bounded on the east by the Nisqually River, on the north by the various marine inlets of Puget Sound, on the west by the Black Hills, and on the south by an arbitrary boundary based partly on township and section lines, geologic contacts, and the Fort Lewis military reservation (fig 2). The GWMA, where most of the people in Thurston County reside, was investigated intensively. The remainder of the study area was investigated at a reconnaissance level, placing greater emphasis on data from previous studies.

The topographic surface of the study area is largely the result of erosion and deposition during and since the Vashon Stade of the Fraser Glaciation (during the last 15,000 years). For the most part, the land surface is a low-lying, drift-covered glacial plain that ranges in altitude from 200 to 400 feet above sea level. Relief on the plain is generally low, but the plain terminates in steep bluffs along the shorelines of Puget Sound. Parts of the relatively flat plain where trees are absent are referred to locally as “prairies”. The plain has been dissected by rivers and streams of small to medium size, but local closed depressions, some of which are occupied by lakes, ponds, and wetlands, are common. In particular, an area of terminal moraine in the vicinity of Lake St. Clair contains numerous kettle lakes which are of glacial origin (see Flint, 1971, p. 212-213). Four major peninsulas at the northern edge of Thurston County extend northward into Puget Sound. In this report, the four peninsulas will be referred to informally, from west to east, as the Griffin, Cooper Point, Boston Harbor, and Johnson Point peninsulas (fig. 2). The physiography of Thurston County is further described by Wallace and Molenaar (1961).

The climate of Thurston County is of the mid-latitude, West Coast marine type, characterized by warm, dry summers and cool, wet winters. Moist air masses reaching the county originate over the Pacific Ocean, and this maritime air has a moderating influence in both winter and summer (Phillips, 1960). Prevailing winds are from the south or southwest in fall and winter, gradually shifting to the northwest or north in late spring and summer.

The long-term mean annual air temperature at Olympia is 49.6°F; July is the warmest month and January the coldest (63.0°F and 37.2°F, respectively; National Oceanic and Atmospheric Administration, 1982). Afternoon temperatures are usually in the 70's in summer and from the upper 30's to lower 40's in winter.

During the wet (winter) season, rainfall is usually of light to moderate intensity and continuous over extensive periods of time. The long-term mean annual precipitation is about 51 inches at Olympia (National Oceanic and Atmospheric Administration, 1982), but ranges from about 35 inches in the northeastern part of the county to about 65 inches in the northwestern and southeastern parts of the county (U.S. Weather Bureau, 1965). The areas of greater precipitation are largely a result of the lifting and cooling of moist maritime air by higher landforms.

Seventy-nine percent of the precipitation at Olympia falls during the 6 months from October to March. July receives the least mean monthly precipitation and December the greatest (0.76 and 8.70 inches, respectively). Precipitation during the 3 driest months (June, July, and August) totals less than 7 percent of the annual total.

The study area is drained by four prominent rivers— the Nisqually, Deschutes, Chehalis, and Black Rivers—and by numerous smaller streams such as McAllister, Woodland, Woodard, Percival, Salmon, Spurgeon, and Eaton Creeks (fig. 2). None of the drainages of the four principal rivers is completely enclosed within the study area. The principal lakes in the study area are Black, Capitol, Hewitt, Hicks, Lawrence, Long, Offutt, Pattison, St. Clair, Scott, and Ward Lakes (fig. 2); they are described by Bortleson and others (1976).

The native vegetation is largely dependent on the moisture-holding capacity of the soil. Poorly drained, fine-grained soils support mostly firs, cedars, alder, and madrona. Beneath these trees is a lush understory of huckleberry, Oregon grape, and salal. On the well-drained prairies, underlain by coarse-grained outwash, the vegetation consists chiefly of wild grasses, bracken fern, Scotch broom, blackberry, and isolated patches of firs and oaks.

The 1988 population of the study area, which includes the cities of Olympia, Lacey, and Tumwater, is estimated to be about 147,000 (Thurston Regional Planning Council, 1989), or 98 percent of the county population. On the basis of the distribution of



Figure 1. Location of the study area.

residences in Thurston County, approximately 38 percent of the study-area population resides within the boundaries of those three cities. The population of the GWMA was about 124,000 in 1988. Many people who work in or near the urban core of northern Thurston County live outside the urban core in rural environments or in the smaller cities and towns of Yelm, Rainier, Tenino, Rochester, Grand Mound, and Littlerock (fig. 2). The population of Thurston County, and most likely the study area and GWMA as well, has more than tripled from 1950 to 1988 (Thurston Regional Planning Council, 1989).

Because Olympia is the capital city of Washington, the economy of Thurston County and the study area is dominated by State government. In 1987, State government accounted for 30 percent of the employment in the study area; by contrast, manufacturing and agriculture accounted for only 7 and 3 percent, respectively. Within Thurston County there are only eight manufacturers with more than 100 employees, and only one, a brewery, with more than 400. Agricultural pursuits in the study area include dairy cattle, tree farms, wholesale nurseries, egg and poultry production, strawberries, mushrooms, and oyster harvesting.

Site-Numbering System

In Washington, wells are assigned numbers that identify their location within a township, range, section, and 40-acre tract. For example, well number 18N/01W-12J02 (fig. 3) indicates that the well is in township 18 North (N) and range 1 West (W) of the Willamette base line and meridian. The numbers immediately following the hyphen indicate the section (12) within the township; the letter following the section gives the 40-acre tract of the section, as shown on figure 3. The two-digit sequence number (02) following the letter indicates that the well was the second well in that 40-acre tract entered into the USGS data base. For springs, the sequence number is followed by the letter "S". If a well has been deepened or significantly reconstructed, the sequence number is followed by the letter "D" and a number indicating the sequence of deepenings or reconstructions. A "P" following the sequence number indicates that the site is a piezometer. Outcrops are indicated by an "O" following the sequence number.

Acknowledgments

The authors wish to acknowledge the cooperation of the many well owners, tenants, water-system managers, consultants, and government agencies who supplied information and allowed access to their wells. Appreciation is due in particular to the Cities of Olympia, Lacey, and Tumwater, and Mr. Gerald Petersen of the South Sound Utility Company for providing well and water-use data; Mr. James Mathieu of Pacific Ground Water Group for providing reports on aquifer tests; Mr. Robert Palmquist of AGI Technologies for providing data on Lake St. Clair sediment cores; Ms. Susan Davis of the Thurston County Environmental Health Division for providing flow data for Eaton Creek; Mr. Linton Wildrick of the Washington State Department of Ecology for providing long-term water-level data: and Mr. Mark Swarthout of the Thurston County Waste Management Division for providing long-term lake stages for Ward Lake. Mr. Robert Mead of Thurston County Environmental Health Division reviewed a draft of this report and provided suggestions resulting in significant improvements to the final version.

GEOHYDROLOGIC SETTING AND CONCEPTUAL MODEL

Many studies have contributed to our current understanding of the geologic framework of the study area. Detailed descriptions of geologic conditions in Thurston County, its environs, and the Puget lowland in general are provided by Bretz (1910, 1911, 1913), Mundorff and others (1955), Snavely and others (1958), Crandell and others (1958 and 1965), Crandell (1965), Noble and Wallace (1966), Thorson (1980), Easterbrook and others (1981), Lea (1984), Gower and others (1985), Jones (1996), and Drost and others (1998). The brief summary that follows is taken largely from the work of Noble and Wallace (1966). In this section, the geologic units in the study area will be described. In a later section (Geohydrologic Units), the geohydrologic units will be described.

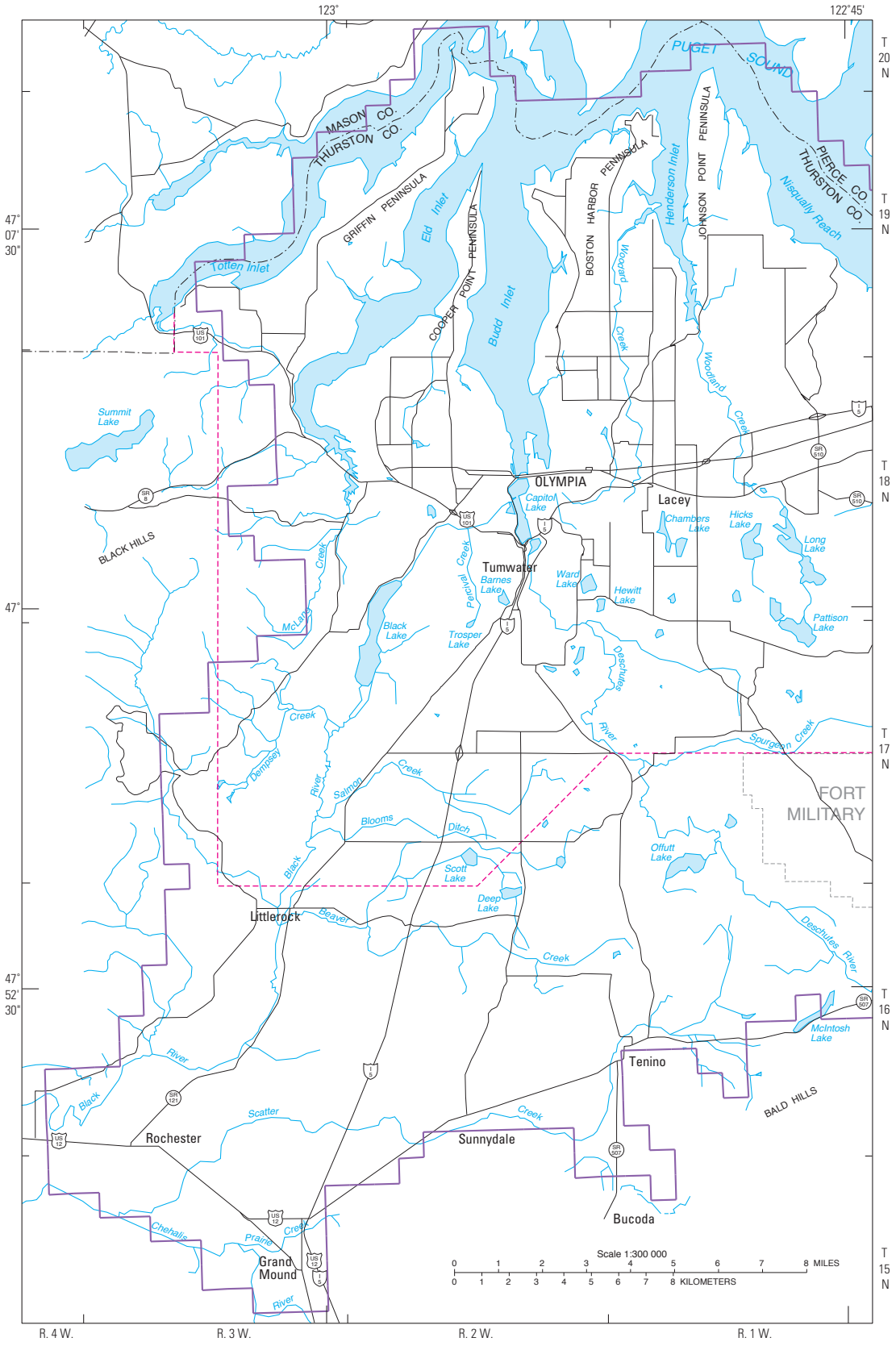


Figure 2. Locations of physiographic and cultural features of the study area.

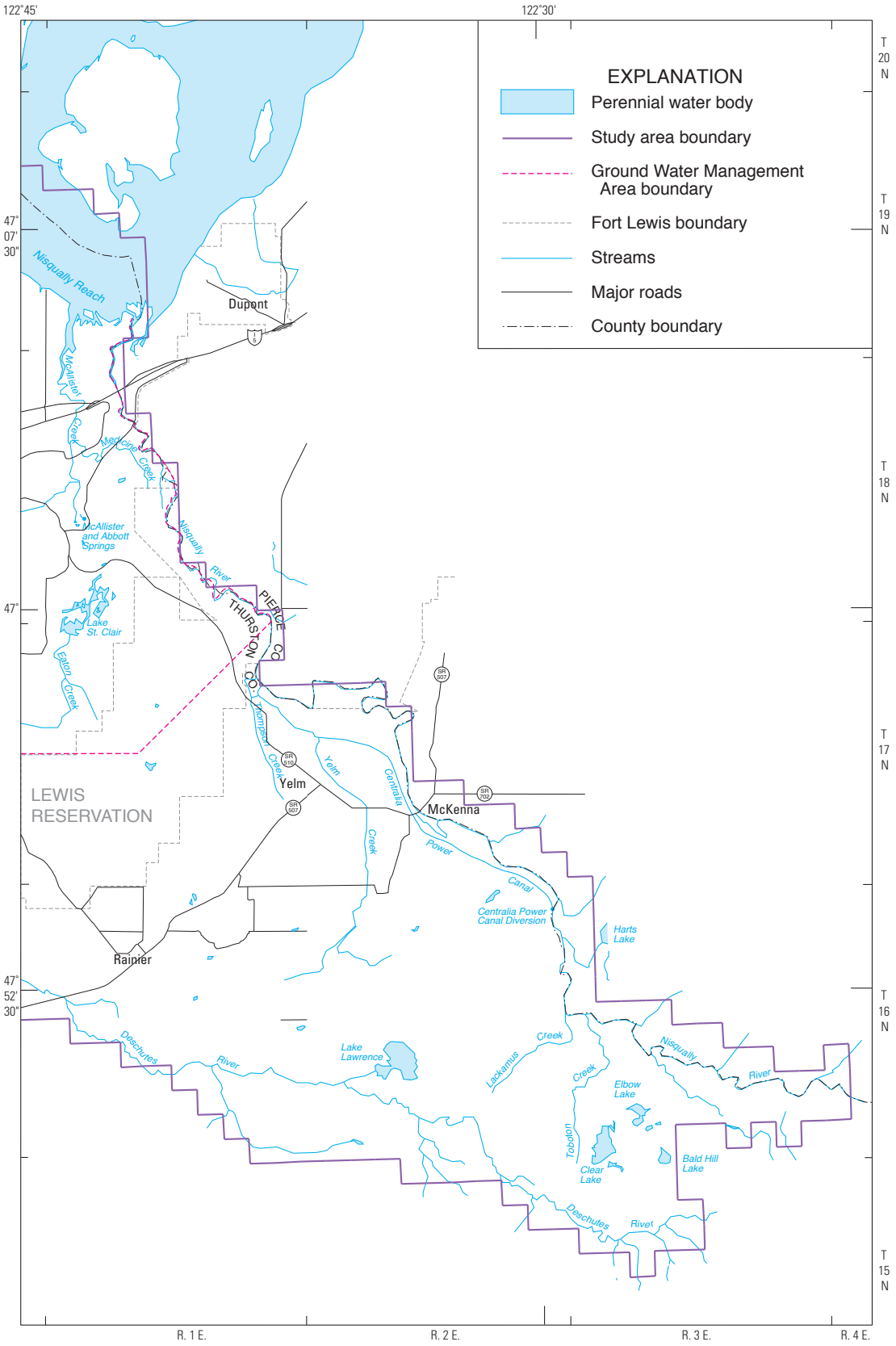


Figure 2. continued.

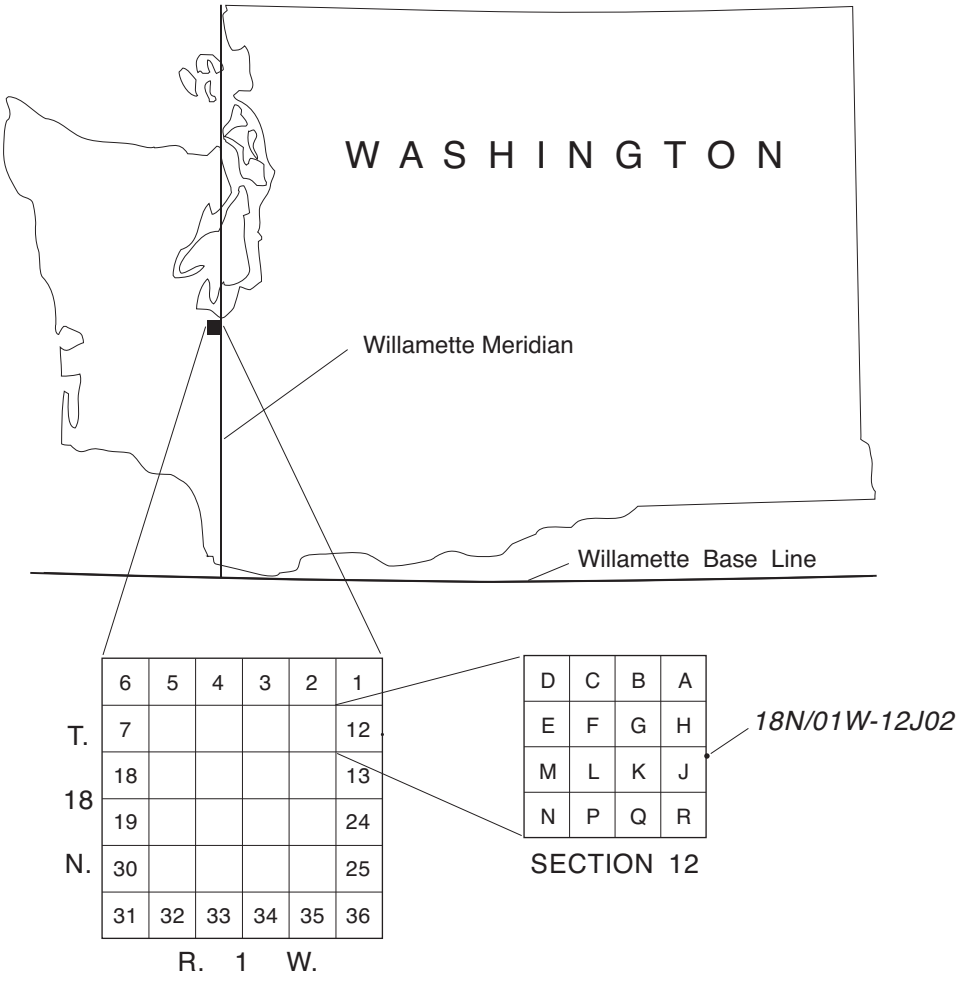


Figure 3. Site-numbering system in Washington.

Geologic Setting

Continental glaciers advanced into Thurston County at least twice during the Pleistocene Epoch. The most recent glaciation of the study area, referred to as the Vashon Stade of the Fraser Glaciation, began about 15,000 years ago when the climate cooled and a great continental ice mass formed in British Columbia, Canada. The glacier moved slowly southward, blanketing the entire Puget Sound basin. The southern part of Thurston County, near Tenino (fig. 4), is generally regarded as the southernmost extent of continental glaciation in western Washington. Previous investigators have postulated that the southern advance of the glacier(s) was halted at this approximate location because of the configuration of bedrock at land surface.

As the Vashon glacier advanced southward, rivers and streams that once flowed northward, including the Nisqually and Deschutes Rivers, were blocked, and a large lake formed in front of the ice. This lake received runoff from both the blocked rivers and the advancing glacier. Eventually, the rising lake breached its temporary basin and established drainage channels westward and southwestward into the valley of the Chehalis River, which drains to the Pacific Ocean. The Vashon Glacier remained at its maximum southern extent for a relatively short time. As the climate warmed, about 13,500 years ago, the glacier began retreating northward and drainage to the north through the Puget lowland to the Strait of Juan de Fuca eventually was re-established. This most recent glaciation, however, left behind a characteristic sequence of glacial drift. Glacial sediments are of two general types,

outwash (moderately to well-sorted sands and gravels deposited by streams) and till (unsorted sand, gravel, and boulders in silt and clay matrix deposited by ice).

As a result of the events described above, the study area is underlain by unconsolidated deposits of the Pleistocene Epoch that are of both glacial and nonglacial origin (table 1). Beneath these unconsolidated deposits, which are as much as 2,000 feet thick, are consolidated rocks of Eocene to Miocene age, which are referred to in this report as bedrock.

The youngest geologic unit in the study area consists of alluvial and deltaic sand and gravel of Holocene age. The alluvium is generally found along the valley bottoms of the principal streams and is of limited areal extent.

The Vashon recessional outwash is the next youngest unit and consists of poorly to moderately well-sorted sand and gravel laid down by streams emanating from the melting and receding glacier. A large part of the study area is mantled with this unit. Included in this unit is the glacial drift that was deposited at the terminus of the stationary or slowly retreating ice mass and labeled Vashon end moraine by Noble and Wallace (1966). Areas underlain by end moraine are characterized by hummocky terrain in which kettle lakes are common. Extensive areas of kettled-lake terrain are present north and southeast of Lake St. Clair and southwest of Black Lake (Qvrm on fig. 4). A close examination of the bathymetric map of Lake St. Clair (Bortleson and others, 1976, p. 181-184) indicates that the lake basin most likely is formed of coalescing kettles within the end moraine. Numerous other lakes in Thurston County, such as Hewitt and Ward Lakes, are situated in closed depressions that are also kettles. Some of the smaller kettles are above the water table and therefore contain no ground water.

In most places beneath the Vashon recessional outwash is Vashon glacial till, commonly referred to as "hardpan" or "boulder clay," which consists of unsorted deposits of sand, gravel, and boulders encased in a matrix of silt and clay. The till is compact in nature where it was laid down beneath the heavy mass of glacial ice and relatively noncompacted where it formed by glacial melting. Till is exposed extensively at land surface in the northern, eastern, and south-central parts of the study area (fig. 4).

Some materials that are found at or near the surface in the study area and resemble Vashon till may actually be part of an older till, the "penultimate till" of Lea (1984). Lea mapped this older till near Tenino. In the southeastern part of the study area, there are indications in some drillers' logs of a sequence of two (or more?) tills alternating with outwash. These till sequences may represent multiple Vashon tills or the deeper tills may represent older tills associated with glacial sequences prior to the Vashon.

As the Vashon Glacier advanced southward into Thurston County, large quantities of stratified sand and gravel were deposited by meltwaters at the front and sides of the ice mass. This Vashon advance outwash typically consists of fine- to coarse-grained glacially derived sand and subordinate gravel grading upward to poorly to moderately sorted, well-rounded gravel in a sandy matrix, interbedded with lenses of sand. Surface exposures of Vashon advance outwash are not common, but the unit is found at depth over most of the study area.

Beneath the advance outwash is a generally fine-grained assemblage of clay and silt with minor amounts of sand, gravel, peat, and wood. In many locations, this deposit is most likely the Kitsap Formation described by previous investigators. Surface exposures of this unit are found in several places along shorelines where it typically occurs as high vertical bluffs above peninsular beaches. The Kitsap Formation is thought to have been deposited in shallow lakes and swamps and is probably nonglacial in origin.

Situated directly below the Kitsap Formation (table 1) is a deposit of pre-Vashon glacial origin. This unit consists of coarse stratified sand and gravel that is commonly stained with iron oxides to a yellowish brown or reddish brown color. Noble and Wallace (1966) referred to this deposit as the Salmon Springs(?) Drift. However, Easterbrook and others (1981) and Lea (1984) have suggested that the Salmon Springs Drift at its type locality is much older than previously assumed, and further, that it should not be correlated to more distant locations. Noble (1990) also recommended that use of the term should be discontinued in Thurston County. The unit is at the surface in several shoreline locations and in the southern part of the study area.

Beneath the Salmon Springs(?) Drift is a sequence of fine- and coarse-grained sediments extending to bedrock. These sediments are the "unconsolidated and undifferentiated deposits" of Quaternary and Tertiary ages in table 1. Little is known about the lithologic character of these unconsolidated sediments, but they probably are both glacial and nonglacial in origin and may be similar in nature to the overlying sequence of sediments.

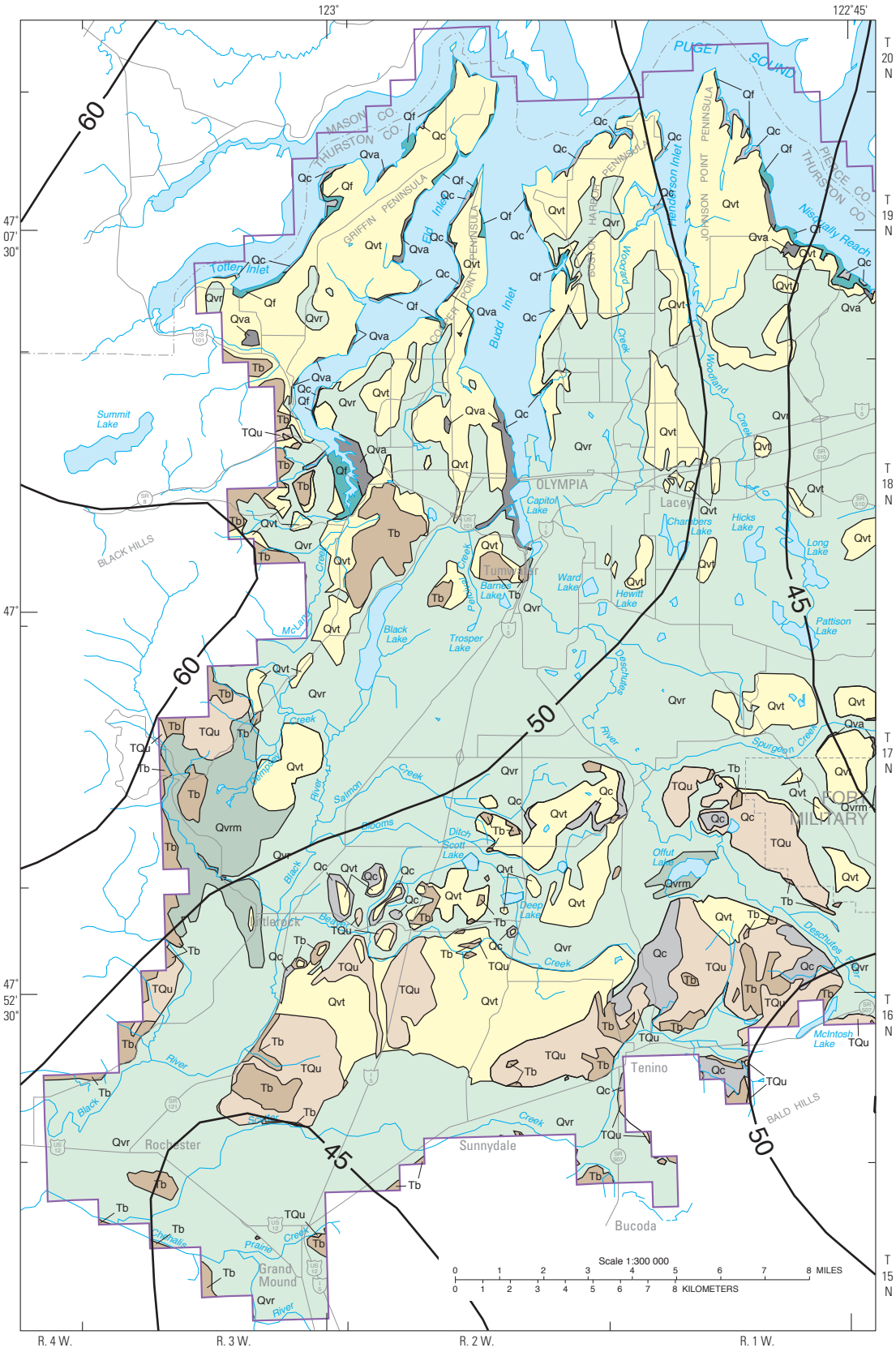


Figure 4. Mean annual precipitation and surficial extents of geohydrologic units of the study area.

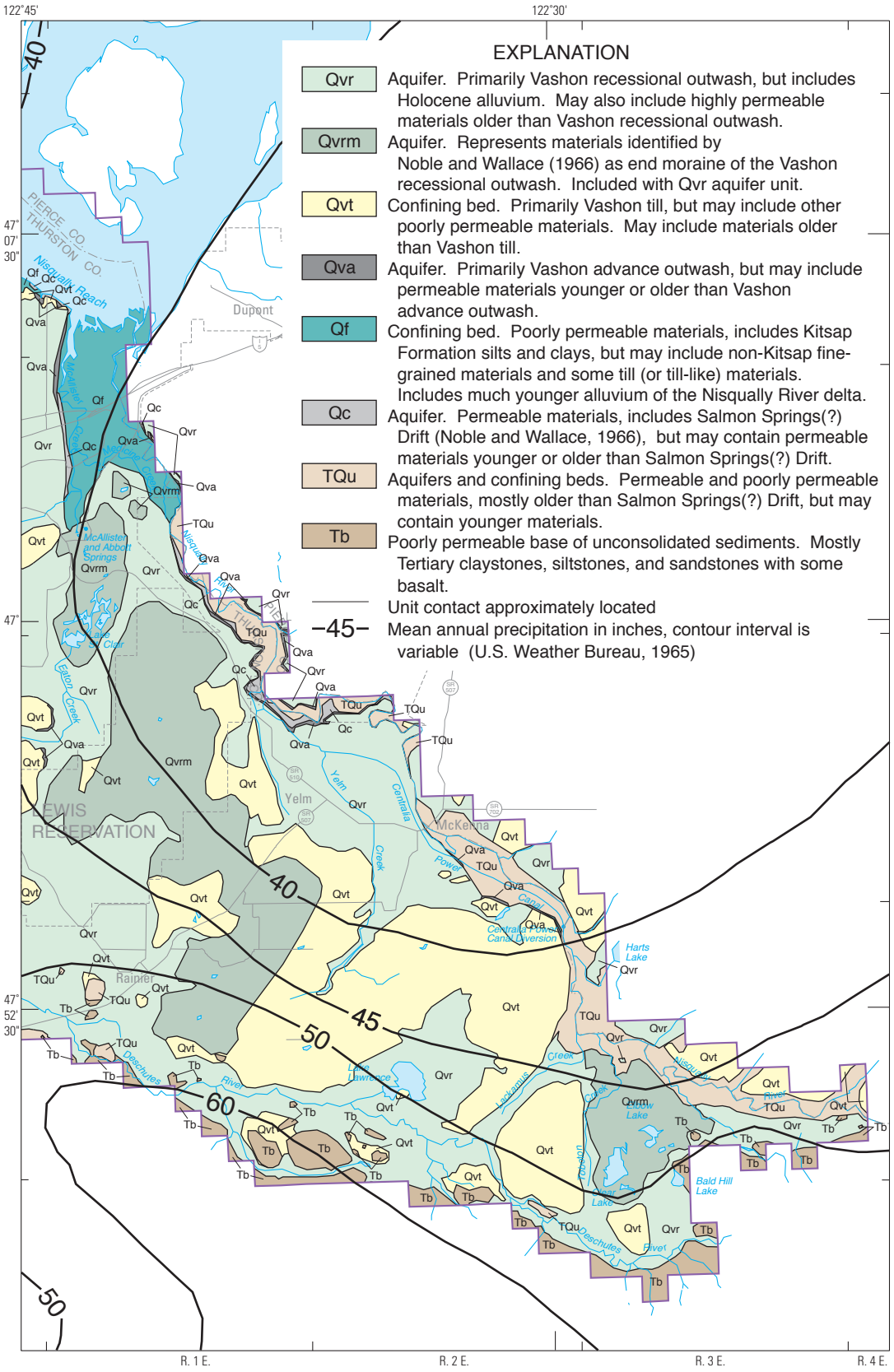


Figure 4. continued.

Table 1. Lithologic and hydrologic characteristics of geohydrologic units in the study area

System	Series	Geologic unit		Geohydrologic unit, in this report[1]	Typical thickness (feet)	Lithologic characteristics	Hydrologic characteristics
Quaternary	Holocene		Alluvium	Qvr Qvrm	10-40	Alluvial and deltaic sand and gravel along major water courses. Moderately to well-sorted glacial sand and gravel, including kettled end moraine	An aquifer where saturated. Groundwater is mostly unconfined. Perched conditions occur locally.
	Pleistocene	Vashon Drift	Recessional outwash and end moraine				
			Till	Qvt[2]	20-55	Unsorted sand, gravel, and boulders in a matrix of silt and clay.	Confining bed, but can yield usable amounts of water. Some thin lenses of clean sand and gravel.
			Advance outwash	Qva	10-45	Poorly to moderately well-sorted, well-rounded gravel in a matrix of sand with some sand lenses.	Ground water, mostly confined. Used extensively for public supplies near Tumwater.
		Kitsap Formation		Qf[3]	20-70	Predominantly clay and silt, with some layers of sand and gravel. Minor amounts of peat and wood.	Confining bed, but in places yields usable amounts of water.
		Salmon Springs(?) Drift (Noble and Wallace, 1966) / Deposits of "penultimate" glaciation (Lea, 1984)		Qc	15-70	Coarse sand and gravel, deeply stained with red or brown iron oxides.	Water is confined. Used extensively for industrial purposes near Tumwater.
		Unconsolidated and undifferentiated deposits		TQu	Not known	Various layers of clay, silt, sand, and gravel of both glacial and nonglacial origin.	Contains both aquifers and confining beds. Water probably confined.
Tertiary	Miocene and Eocene	Bedrock		Tb	Not known	Sedimentary rocks consisting of claystone, siltstone, sandstone, and minor beds of coal. Igneous bodies of andesite and basalt.	Poorly permeable base of unconsolidated sediments. Locally an aquifer, but generally unreliable. Water contained in fractures and joints. Well yields relatively small. Numerous abandoned wells.

[1]The identification of geohydrologic units in this report is a "best estimate" based on drillers' logs and existing surficial geology maps.

[2]Includes "late Vashon lake deposits" (Washington State Department of Ecology, 1980). May include till of "penultimate" glaciation (Lea, 1984).

[3]Includes alluvium younger than Kitsap Formation in Nisqually River delta. May include some Vashon till (where multiple tills are present). May include till of "penultimate" glaciation (Lea, 1984).

The consolidated rocks that make up the bedrock consist largely of Tertiary sedimentary claystone, siltstone, sandstone, and some beds of coal (Snavely and others, 1958). Associated with these sedimentary rocks are igneous bodies of andesite and basalt. In the Black Hills and near Tumwater, the bedrock is predominantly basalt. Bedrock is exposed in the southern and western parts of Thurston County, near Tumwater, and near the head of Eld Inlet. The bedrock slopes downward to the northeast beneath an increasing thickness of unconsolidated deposits. Beneath the northeastern boundary of the study area, the top of bedrock is probably more than 2,000 feet below sea level (fig. 5; Jones, 1996).

Ground-Water Hydrology

The bulk of the data used in this study to describe and quantify the ground-water system in the Quaternary deposits came from information associated with approximately 1,320 wells and springs that were inventoried in the field during a previous study (Drost and others, 1998). Because the study area for the current investigation extends farther to the southeast, south, and southwest than the previous study, information on approximately 180 sites (wells, springs, and outcrops) in the extended area were added to the previous data base. These additional sites were either field inventoried during earlier studies (Schlax, 1947; Mundorff and others, 1955; Wallace and Molenaar, 1961; Sinclair and Hirschey, 1992; and Pacific Groundwater Group, 1996b) or field inventoried during December 1997 for this study. Data for all 1,500 inventoried sites are presented in table A1 of Appendix A. The inventory process included locating the site in the field; determining its latitude, longitude, and approximate land-surface altitude; measuring the water level in the well where practical; compiling, analyzing, and interpreting the information incorporated on the driller's report of the well construction, lithology, and testing; and then entering the information into a computerized data base.

Conceptual Model of the Ground-Water-Flow System

A generalized conceptual model of the ground-water-flow system beneath northern Thurston County shows the general nature of ground-water flow through the unconsolidated geohydrologic units. Part of the precipitation falling on the inland glacial-drift plains infiltrates the land surface, percolates past the plant root zone, and recharges the ground-water system. Ground water in recharge areas moves vertically and horizontally to discharge areas such as springs, streams, and Puget Sound. The directions of ground-water movement (flowpaths) within the system are shown with arrows on figure 6. Movement is generally horizontal in aquifers and vertical in confining beds. The amount of time required for an individual particle of water to complete its journey through the system is roughly proportional to the length of the flow path and the hydraulic conductivity of the material through which it passes. Generally, water particles with a relatively short travel path from recharge point to discharge point may be in the ground-water system for only a few weeks or months; particles with relatively long flow paths may be in the system for years or centuries.

Ground water in the study area occurs in aquifers under two different conditions. If water only partly fills an aquifer, the upper surface of the saturated zone (the water table) is free to rise and fall with changes in recharge and discharge. In this situation, the ground water is said to occur under unconfined or "water-table" conditions. The position of the water table is represented by water levels in shallow wells.

If water completely fills an aquifer that is overlain and underlain by a confining bed, such as clay or bedrock, ground water is said to occur under confined or "artesian" conditions. Wells that tap a confined aquifer encounter water that rises in the well to a height corresponding to the potentiometric surface or "head" of the confined ground water at that point. If the head is sufficient to raise the water above land surface, the well will flow and is called a flowing artesian well. Confined ground water has a potentiometric surface analogous to a water table in an unconfined aquifer. The potentiometric surface, like the water table, fluctuates in response to changing recharge and discharge.

The series of aquifers and confining beds in the study area (fig. 6) comprises a system in which water flows horizontally within and vertically between layers. A stress (for instance, pumping) in one aquifer can produce responses (water-level changes) in other aquifers.

More-detailed descriptions of the recharge, movement, and discharge of water in the ground-water system of the study area are given in later sections of this report.

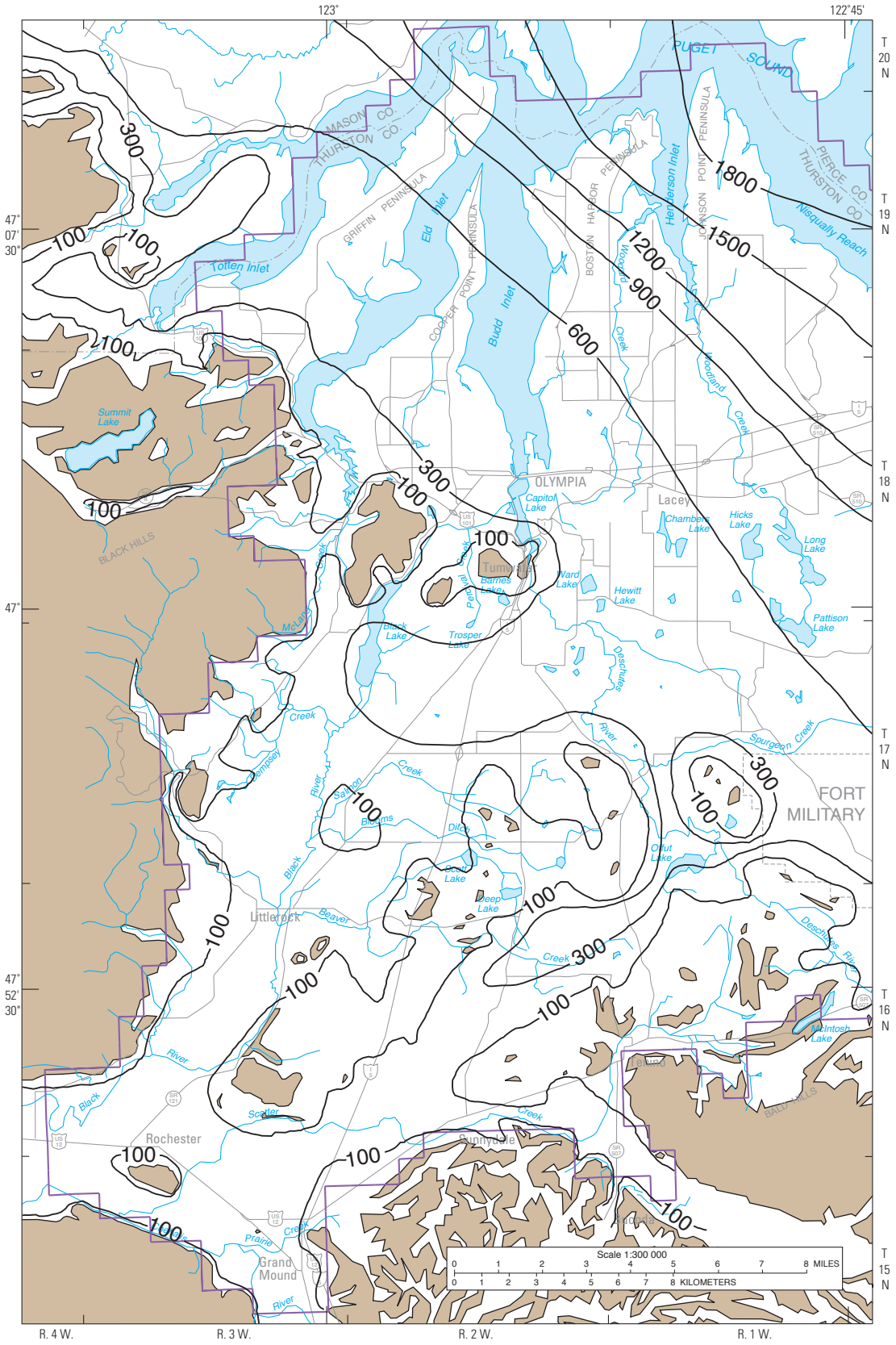


Figure 5. Thickness of unconsolidated sediments in the study area (modified from Jones,1996).

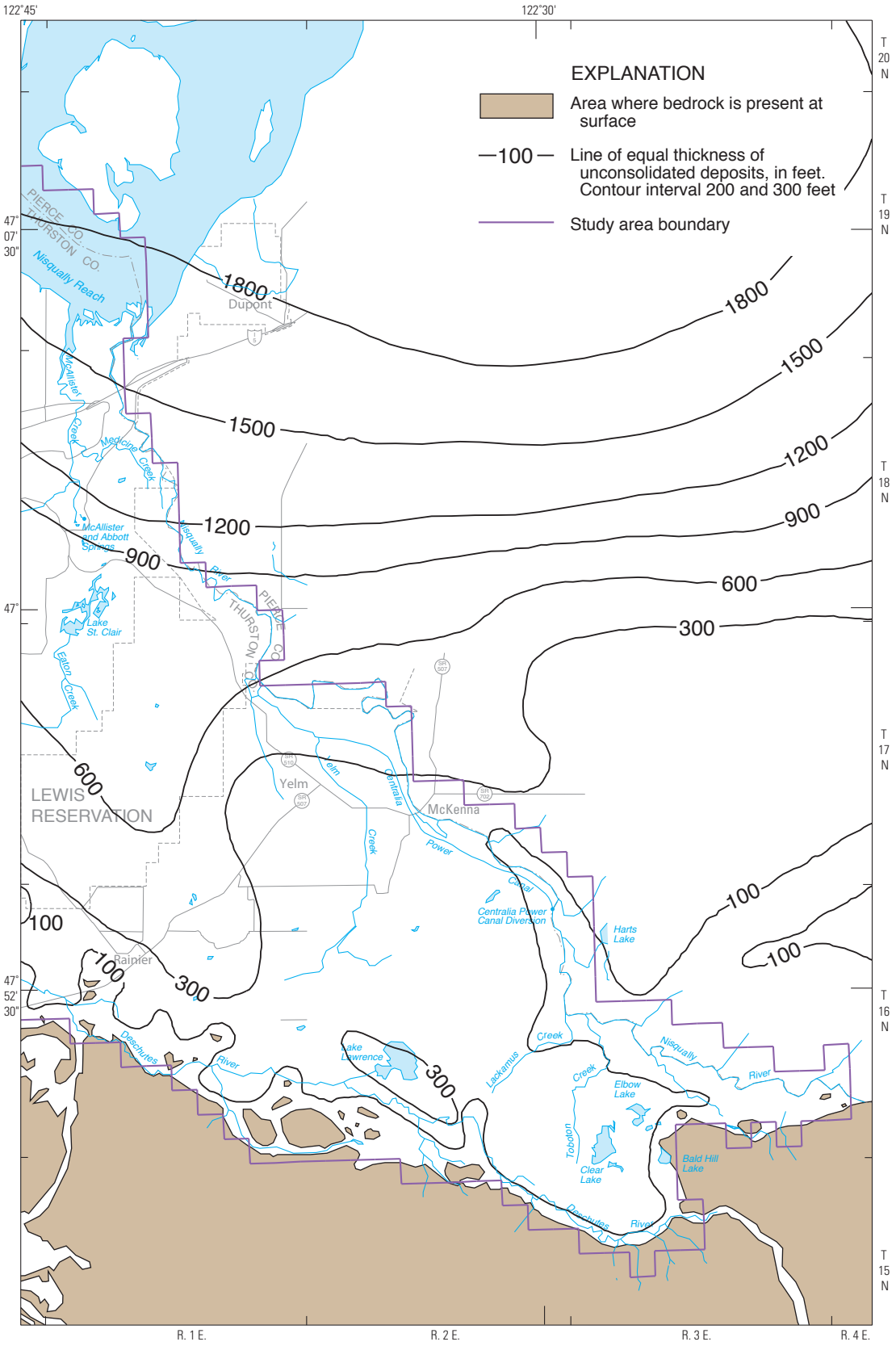


Figure 5. continued.

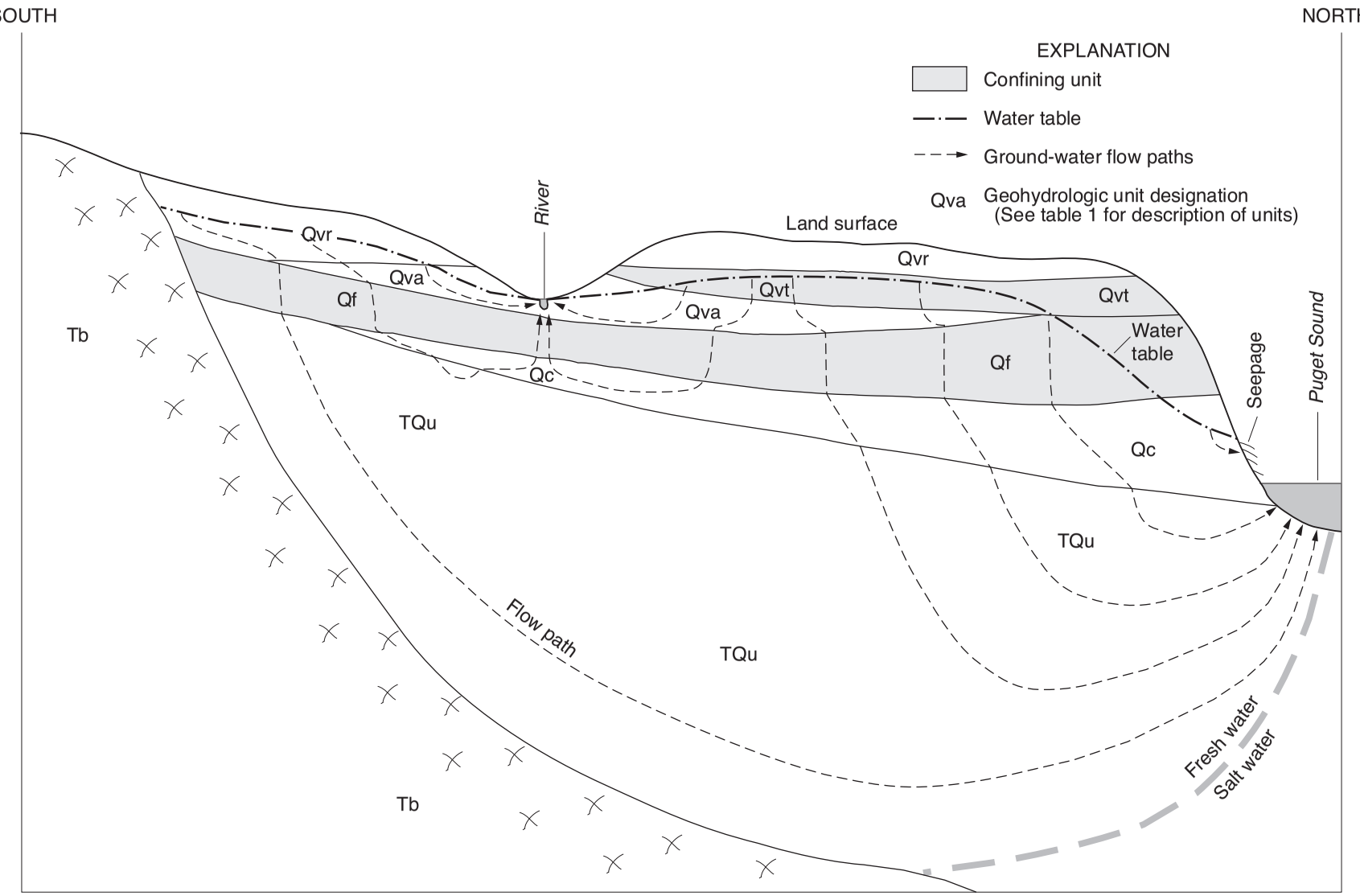


Figure 6. Conceptual model of the ground-water system beneath the study area.

Vertical scale greatly exaggerated

Geohydrologic Units

The geologic units described previously were differentiated into aquifers and confining beds using lithologic, water-level, and well-yield data for the approximately 1,500 inventoried sites (Appendix A, table A2). The aquifers and confining beds thus defined are referred to as "geohydrologic" units in this report because they were identified on the basis of a combination of geologic (primarily grain size and sorting) and hydrologic (hydraulic conductivity and unit geometry) properties. In making the differentiation, it is important to keep in mind the heterogeneity of the sediments involved. A glacial aquifer may be composed predominantly of sand and (or) gravel, but in the small scale it will probably also contain relatively thin and discontinuous lenses of clay or silt. Conversely, a confining layer, composed predominantly of silt and (or) clay, may also contain local lenses of coarse sand or gravel. As a consequence, the general occurrence and movement of ground water may be influenced locally by these small-scale variations in lithology.

In a previous study (Drost and others, 1998), approximately 1,140 drillers' logs were used to delineate seven major geohydrologic units (table 1), six of which are in the unconsolidated deposits. Five geohydrologic sections, considered typical of the study area, can be seen on plate 1c of the report for the previous study. An examination of those sections indicates a great deal of variation in the thickness of individual units, and that not all seven units are necessarily present at any given location. Approximately 170 additional drillers' logs were used to extend the interpretation of the geohydrologic units into the expanded study area. In the course of this expansion, some reinterpretation of the previously defined geohydrology resulted in modifications of the geohydrology that was presented in Drost and other (1998).

Because the relatively undisturbed Vashon Drift is located at or near land surface, it has been more carefully studied than other, older drifts. Accordingly, previously accepted and published nomenclature associated with the Vashon Drift was used for three geohydrologic units—-the Vashon advance outwash (Qva), Vashon till (Qvt), and Vashon recessional outwash (Qvr).

Because of their lithologic similarities, Holocene alluvium and Vashon recessional outwash were combined as a single geohydrologic unit (Qvr). A large part of the study area is mantled by unit Qvr (figs. 4 and 7). This coarse-grained unit can be a productive aquifer, and is important locally as a water supply. Throughout most of the study area, however, few wells withdraw water from Qvr because the unit is thin or it lies above the water table and is unsaturated. This is especially true where the underlying till, which retards downward percolation, is absent (fig. 8). About 80 inventoried wells tap Qvr and most are in the southern part of the study area. In the Qvr, ground water occurs under water-table (unconfined) conditions, and wells tapping the unit produce moderate yields for domestic purposes. Locally, perched ground-water conditions (local zones of saturation above the regional water table) may exist within the Qvr because of the low vertical permeability of the underlying till. Where present, Qvr is generally between 10 and 40 feet thick, but locally may be greater than 150 feet thick (fig. 7).

The Vashon till, and possibly some older tills, make up geohydrologic unit Qvt. In some shoreline locations, "Late Vashon lake deposits" (Washington State Department of Ecology, 1980) were correlated with the Qvt because they tend to act as confining beds and occur at the same stratigraphic position as the Vashon till. The Qvt is generally a poor source of water and is considered a confining bed. About 30 inventoried wells tap thin layers of relatively clean sand and (or) gravel that are irregularly distributed within the unit. The unit is broadly distributed (fig. 8) and exists at land surface throughout a large part of the study area (fig. 4). At one time, dozens of shallow dug wells produced water from the upper, less compact part of the unit (Wallace and Molenaar, 1961). As reported by Noble and Wallace (1966), perched ground water is present near the top of the unit, and many of the shallow wells tapping the till occasionally go dry in late summer. Where present, Qvt is generally between 20 and 55 feet thick, but locally may be greater than 175 feet thick (fig. 8).

The Vashon advance outwash is represented as geohydrologic unit Qva, which is an important aquifer in northern Thurston County. It is present throughout a large part of the study area, mostly in the subsurface. Qva is tapped extensively in the Tumwater area, where it yields relatively large quantities of water to municipal and industrial wells. It is not developed extensively in the extreme northern parts of the study area, where it is relatively thin (fig. 9). Nearly 500 of the inventoried wells tap unit Qva. Ground water in this aquifer typically is confined by the overlying Qvt and the underlying Qf. Where present, the unit is generally between 10 and 45 feet thick, but locally exceeds 100 feet thick (fig. 9).

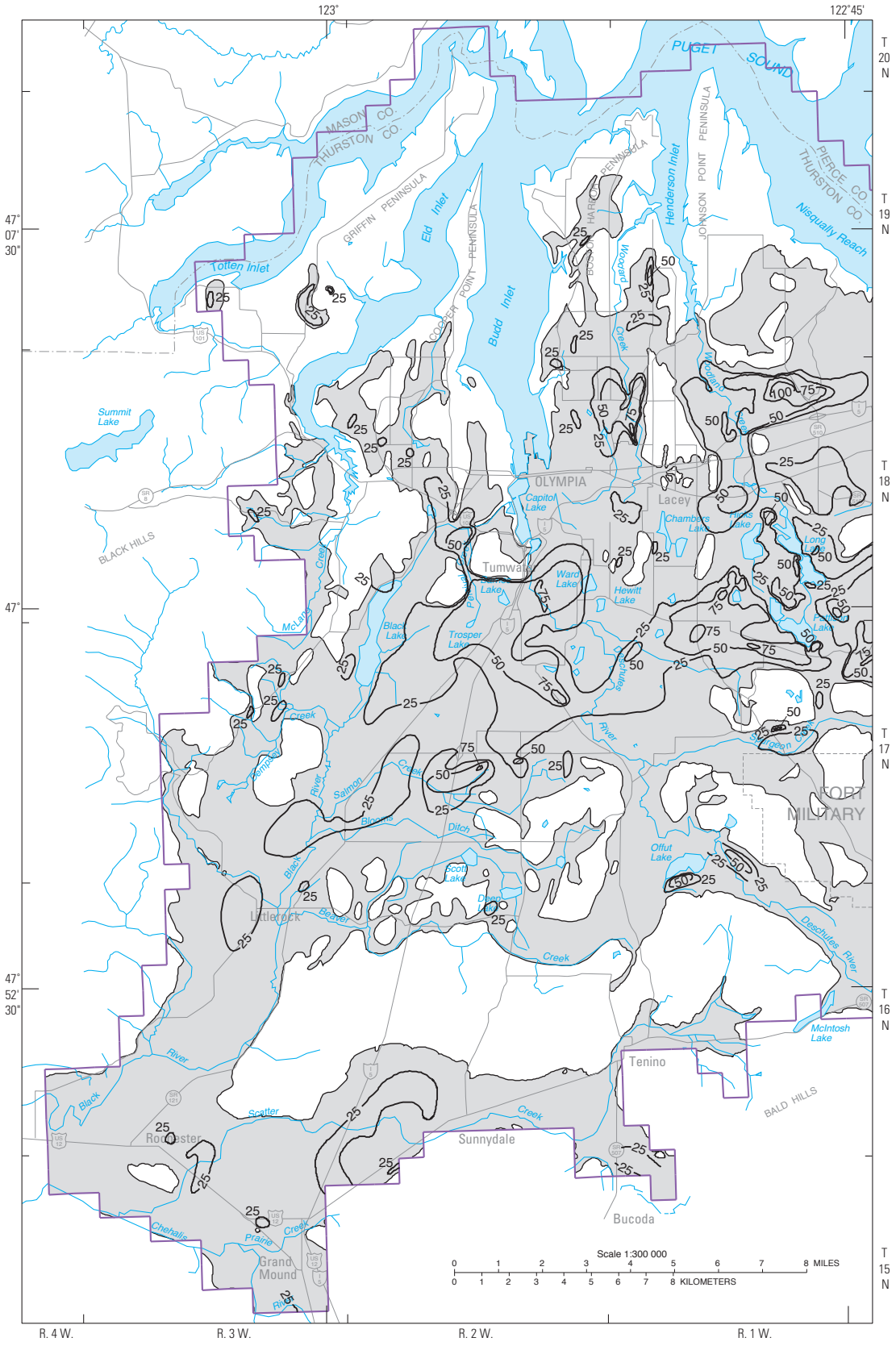


Figure 7. Areal extent and thickness of geohydrologic unit Qvr in the study area (modified from Drost and others, 1998).

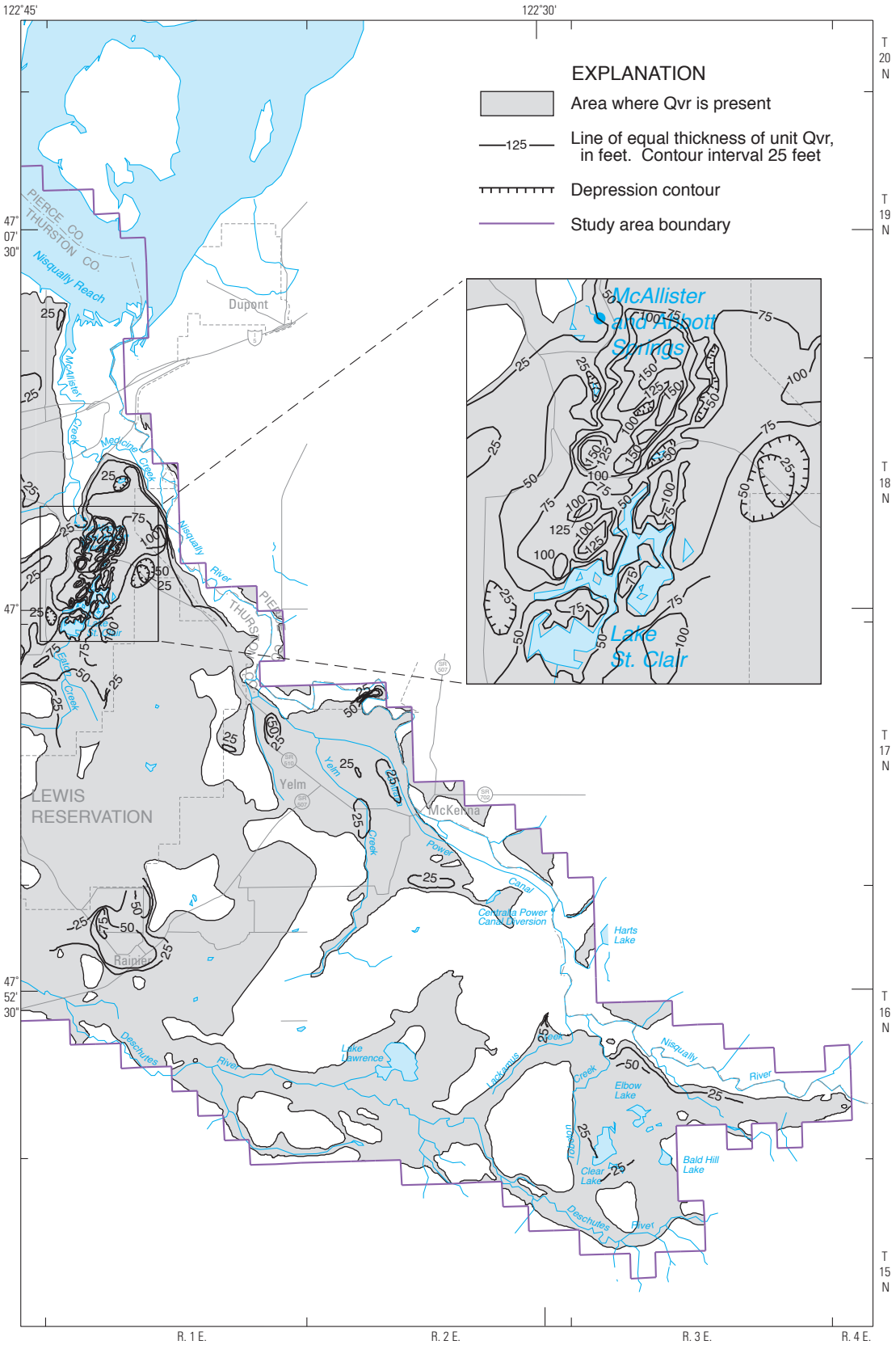


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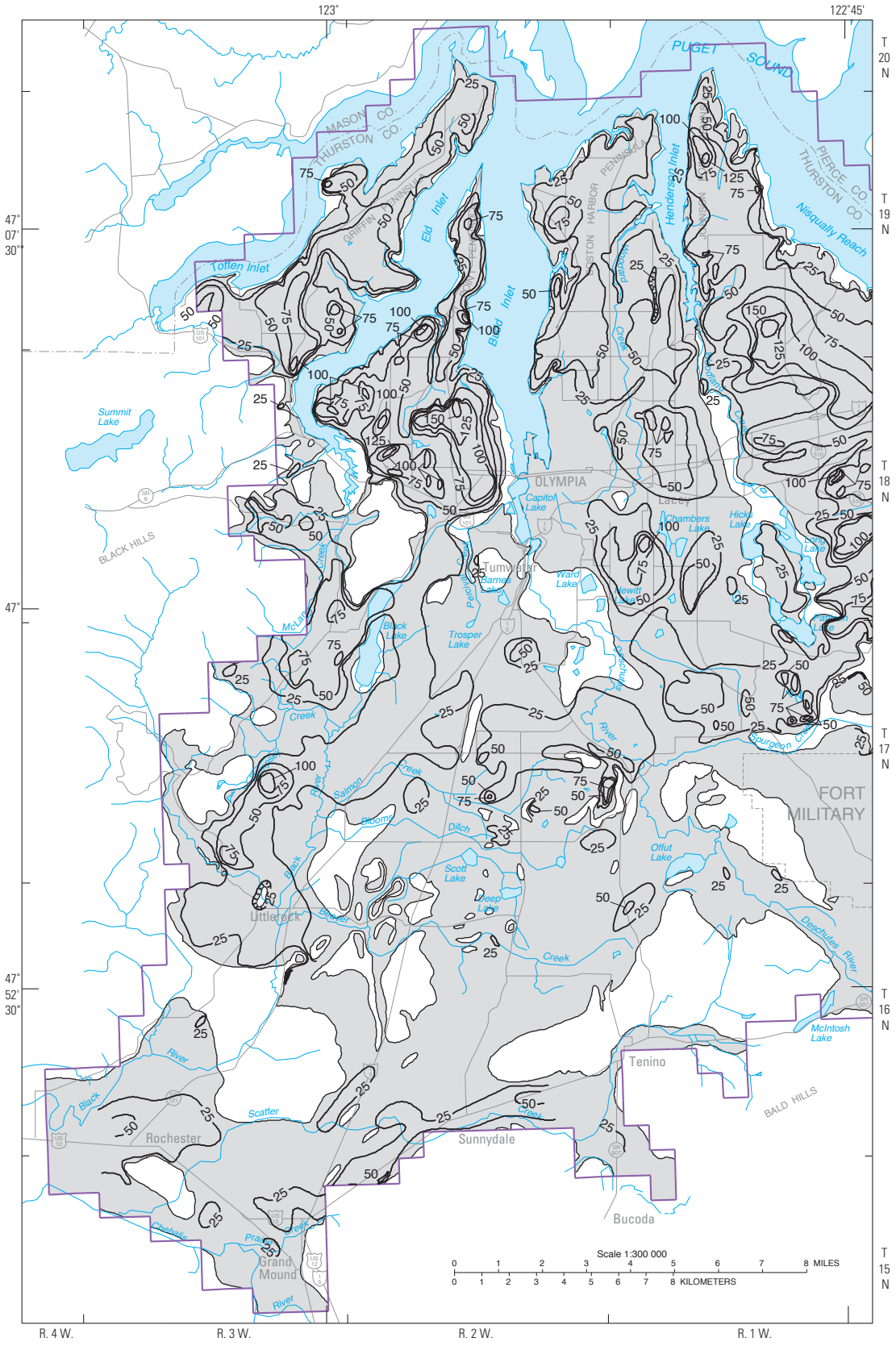


Figure 8. Areal extent and thickness of geohydrologic unit Qvt in the study area (modified from Drost and others, 1998).

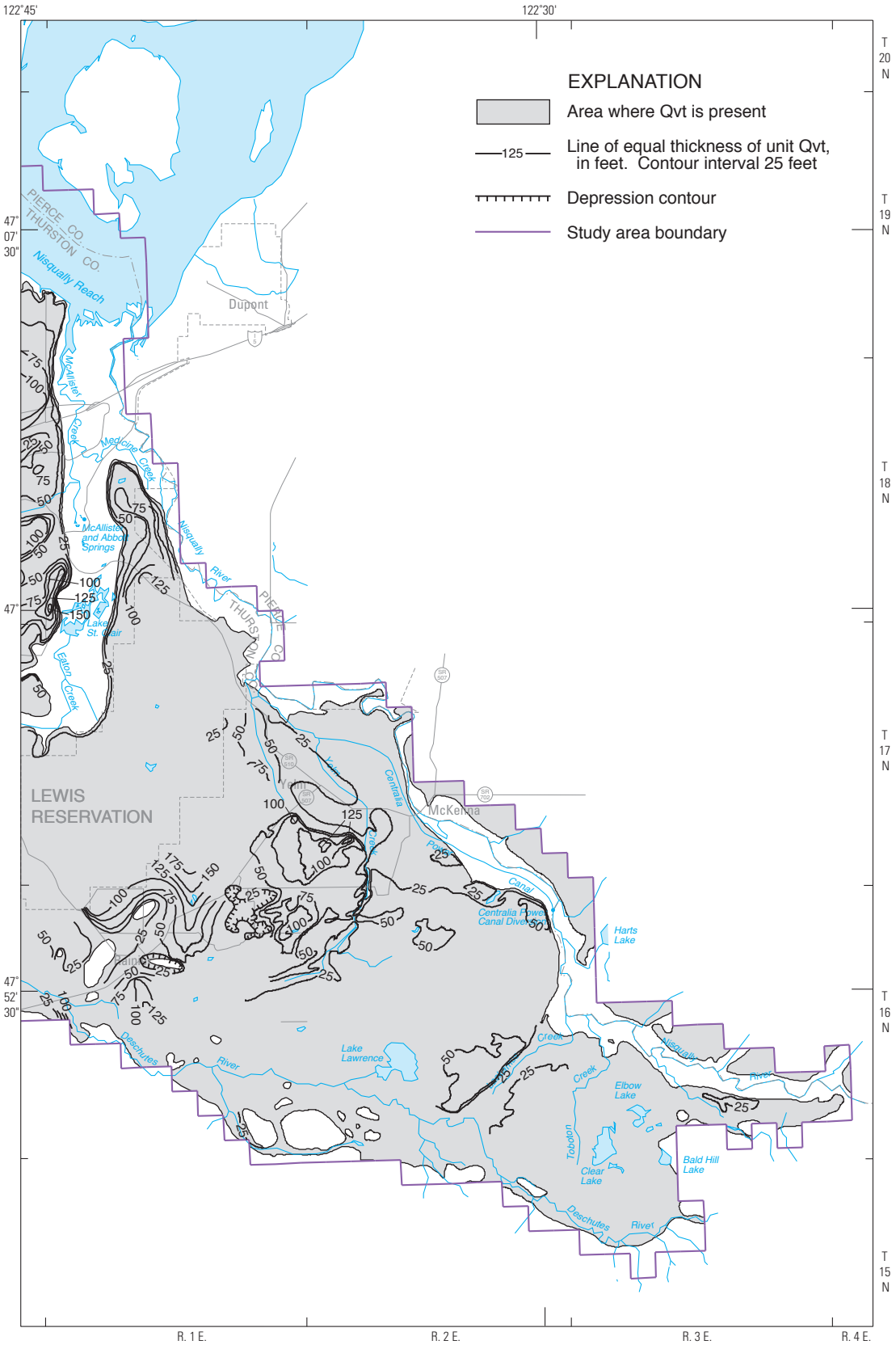


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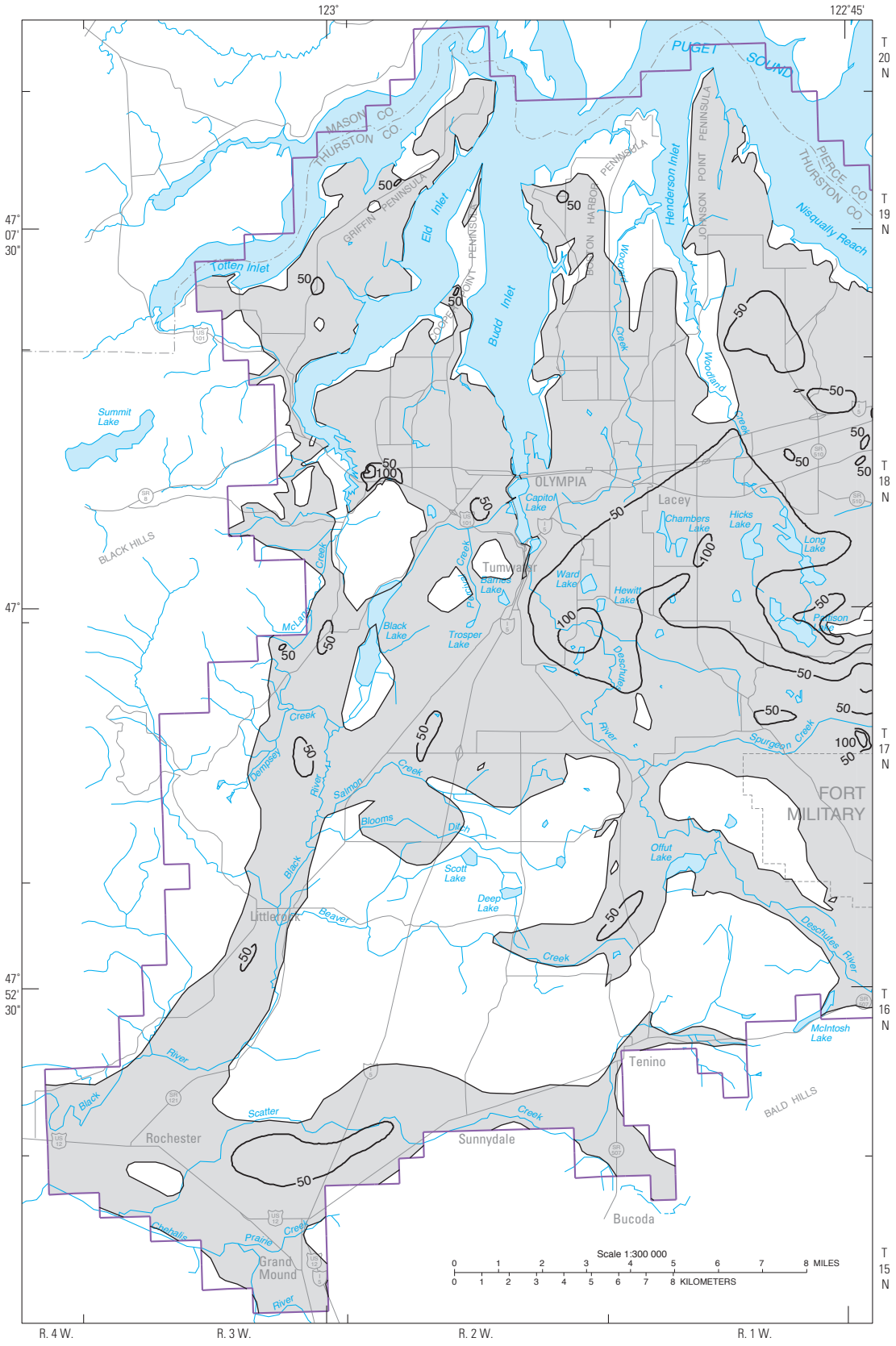


Figure 9. Areal extent and thickness of geohydrologic unit Qva in the study area (modified from Drost and others, 1998).

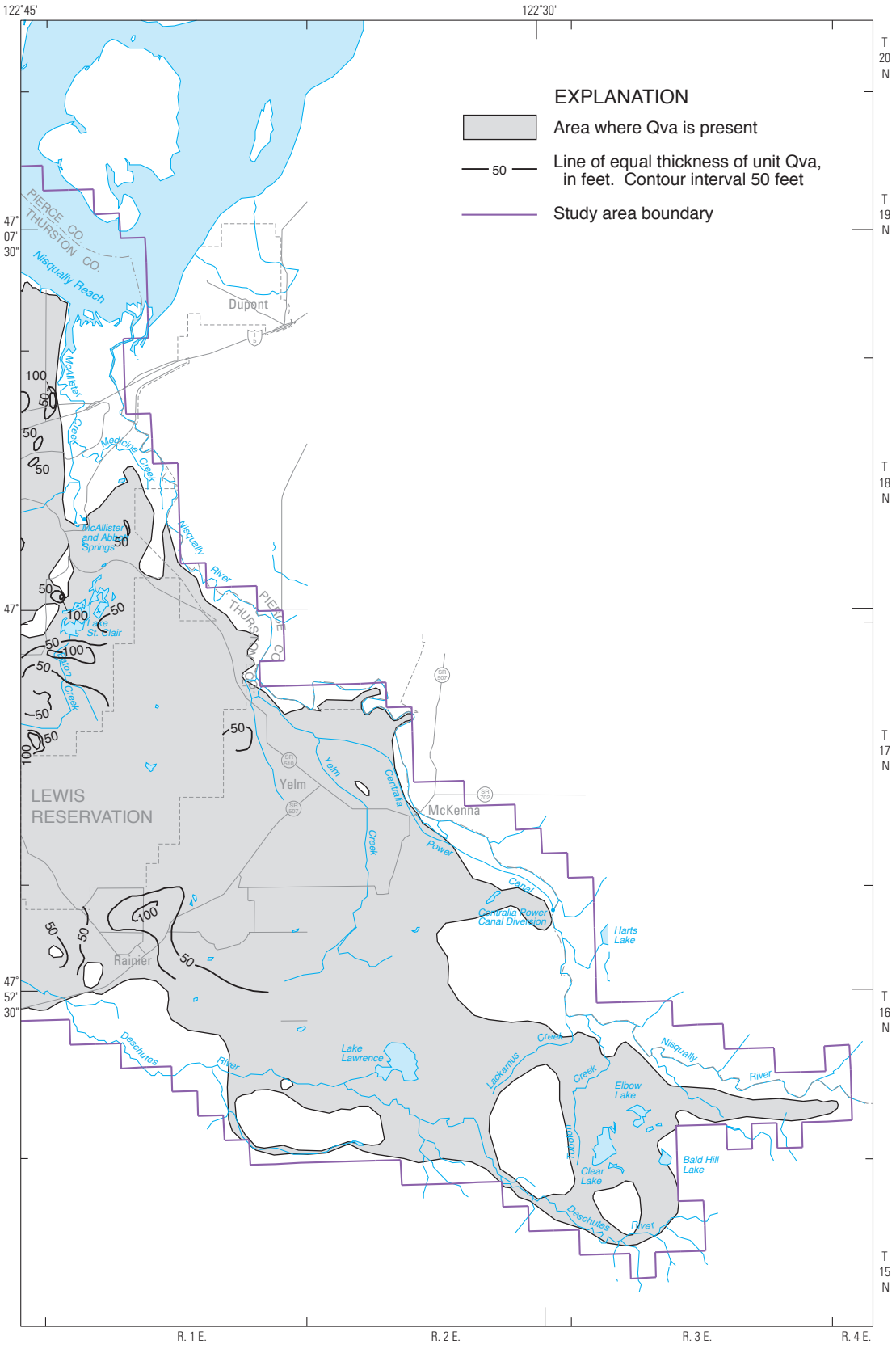


Figure 9. continued.

The top of the Qva generally occurs between 50 and 400 feet above sea level (fig. 10). In the vicinity of McAllister Springs, the large thickness of coarse-grained sediments was divided somewhat arbitrarily into Qvr, Qva, and Qc. That part identified as Qva was selected to be laterally continuous with Qva identified to the west and south, although its geologic identity is unknown.

The Kitsap Formation and other poorly permeable materials occurring beneath the Qva are represented as geohydrologic unit Qf. Included in Qf are the fine-grained deposits underlying the delta at the mouth of the Nisqually River. These deposits are undoubtedly much younger than the Kitsap Formation. The upper surface was mapped as Quaternary alluvium by Noble and Wallace (1966). They were included in Qf because they are of similar lithology and are, at least in part, horizontally continuous with the other Qf materials adjacent to the Nisqually River delta. Also included in Qf, but not correlative with the Kitsap Formation, are some till units. Where multiple tills were observed, generally the uppermost was assigned to the Qvt and the lower tills to the Qf. Unit Qf confines ground water in the coarse-grained glacial deposits both above and below it. The unit is not made up solely of fine-grained materials; about 45 inventoried wells tap local, thin lenses of sand or gravel that yield relatively small quantities of water suitable for domestic use. Qf is generally absent in the southwestern part of the study area. Where the unit is present (fig. 11), Qf is effective in retarding the downward percolation of ground water into Qc (described below), and in causing vertical head gradients between the Qva and Qc aquifer units. Where present, Qf is generally between 20 and 70 feet thick, but locally is greater than 150 feet thick (fig. 11).

The coarse-grained Salmon Springs(?) Drift, penultimate deposits, and other deposits are represented as geohydrologic unit Qc. Qc constitutes one of the most widely used aquifers in the study area. Nearly 500 of the inventoried wells tap unit Qc. The unit is present throughout most of the study area (fig. 12). Ground water in this aquifer occurs primarily under confined conditions. Where the entire thickness of Qc has been penetrated, it is observed to be generally between 15 and 70 feet thick, with a maximum observed thickness of more than 200 feet. In some locations, such as near McAllister Springs where the overlying confining bed (Qf) is absent, Qc merges with the lithologically similar Qva above it to form a single thick and productive aquifer. The top of the unit ranges from more than 100 feet below sea level to more than 600 feet above sea level and is commonly between 50 feet and 400 feet above sea level (fig. 12).

The undifferentiated unconsolidated sediments beneath Qc are designated as geohydrologic unit TQu. More than 200 of the inventoried wells tap this heterogeneous unit. These wells tap several different water-bearing layers that are irregularly distributed both horizontally and vertically. Ground water in these layers is generally confined. TQu is an important aquifer in the study area. Deeper untapped water-bearing layers may exist within this unit, especially in the northern part of the study area where the unit is relatively thick. The unit has not been more extensively developed because sufficient quantities of ground water can usually be found at shallower depths. Few wells penetrate the entire assemblage of unit TQu in the northernmost part of the study area, and the maximum thickness of the unit in that area, therefore, is uncertain. The best estimate of maximum thickness in the study area is somewhat in excess of 2,000 feet. Layering in TQu may be similar to that of the Vashon Drift.

The consolidated rocks of Tertiary age that constitute the bedrock are represented by geohydrologic unit Tb. This unit contains small quantities of water in fractures and joints that are more numerous near the top of the unit. In general, however, Tb is an unreliable source of ground water and many wells drilled into this unit in Thurston County have been subsequently abandoned because of insufficient yield or poor-quality water (Drost and others, 1998). About 75 inventoried wells tap bedrock. Most are domestic wells located in the southern and western parts of the study area and supply water for domestic use. Where the bedrock is exposed at land surface (fig. 4), the ground water is likely to occur under water-table conditions; where the bedrock is covered by a significant thickness of unconsolidated deposits, especially clays and silts, the ground water is likely to be confined.

The relative importance of each of the geohydrologic units as a source of ground water can be determined from the number of inventoried wells finished in each unit (fig. 13), and the relative quantities of water withdrawn from each unit (see section on Discharge and table 5). The resulting information indicates that units Qvr, Qva, Qc, and TQu are the principal sources (aquifers) of water for wells and springs in the study area, but usable quantities of ground water can also be obtained from units Qvt, Qf, and Tb. Even though units Qvt and Qf generally function as confining beds, wells

tapping these units can produce water from thin, local lenses of sand or gravel in these otherwise relatively poorly permeable deposits. In areas where two or more aquifers are combined, that is, where an intervening confining bed is absent, the units function together as a single aquifer.

John Noble (Robinson & Noble, Inc., personal commun., 1998) and Pacific Groundwater Group (1997b) have identified and described a locally important geohydrologic unit, the McAllister gravel aquifer. The visible discharge point of this aquifer is McAllister Springs, which is the largest public water-supply source in the study area. The McAllister gravel aquifer is composed of pebble-to-boulder-sized sediments that appear to be a channel fill deposited by the ancestral Nisqually River. At McAllister Springs, the unit extends to at least 250 feet below sea level, is very narrow, and probably continues to the north of McAllister Springs beneath the Nisqually River delta. The southerly extent of the unit is unknown, but there are indications that it might extend to the present course of the Nisqually River just north of Yelm. The McAllister gravel aquifer is in contact horizontally with units Qvr, Qva, and Qc. Because of this lateral connection, and the regional perspective of this study, the McAllister gravel aquifer was divided into layers and incorporated in units Qvr, Qva, and Qc. The division was done by horizontally projecting the adjacent Qvr, Qva, and Qc units through the McAllister gravel aquifer.

Hydraulic Conductivity

Horizontal hydraulic conductivity is a measure of a hydrologic unit's ability to transmit water horizontally. Horizontal hydraulic conductivity is the volume of water that will move in unit time under a unit gradient through a unit area (measured at right angles to the direction of flow). In this report, it is in units of cubic feet per square foot per day, simplified to feet per day. For unconsolidated materials, hydraulic conductivity depends on the size, shape, and arrangement of the particles. An estimate of the magnitude and distribution of horizontal hydraulic conductivity of each of the geohydrologic units is helpful in understanding the movement and availability of the ground water within the aquifer. Determinations of the horizontal hydraulic conductivity for each aquifer were computed from transmissivity values that were calculated from specific-capacity data. Transmissivity is equal to the product of an aquifer's horizontal hydraulic conductivity and its saturated thickness. Specific capacity is a measure of a well's productivity and is equal to the pumping rate divided by the resulting drawdown in the well. Horizontal hydraulic conductivities were calculated for all wells that have specific-capacity information (pumping rate and drawdown) and that are open to a single geohydrologic unit; 1,017 of the approximately 1,500 study area wells met these criteria.

Either of two methods was used to estimate hydraulic conductivity, depending on how the well was constructed. For wells with a screened or perforated interval, values of horizontal hydraulic conductivity were estimated from specific-capacity data with the Theis method for wells tapping water-table units and the Brown method for wells tapping confined units (both in Bentall, 1963). The specific-capacity data were obtained from well records and generally represent short-term (about 4-hour) pumping or bailer tests conducted by well drillers at the time the wells were originally completed. The Theis and Brown methods calculate transmissivity values. Therefore, these transmissivity values were subsequently divided by the length of the saturated open interval(s) in each well to obtain hydraulic conductivity. Using the assumption that the open interval of the well is equal to the total aquifer thickness assumes that all water flow within the unit toward the well was horizontal and limited to the open interval of the well. However, because there probably is some flow to the well from above or below the open interval, this computational method probably results in an overestimate of hydraulic conductivity. The amount of error caused by this assumption is probably small because layering within the geohydrologic units tends to make horizontal flow much easier than vertical flow. For wells having only an open end, and thus no vertical dimension to the open interval, horizontal hydraulic conductivity was estimated using Bear's (1979) equation for hemispherical flow to an open-ended well just penetrating a geohydrologic unit. When modified for spherical flow to an open-ended well within a unit, the equation becomes:

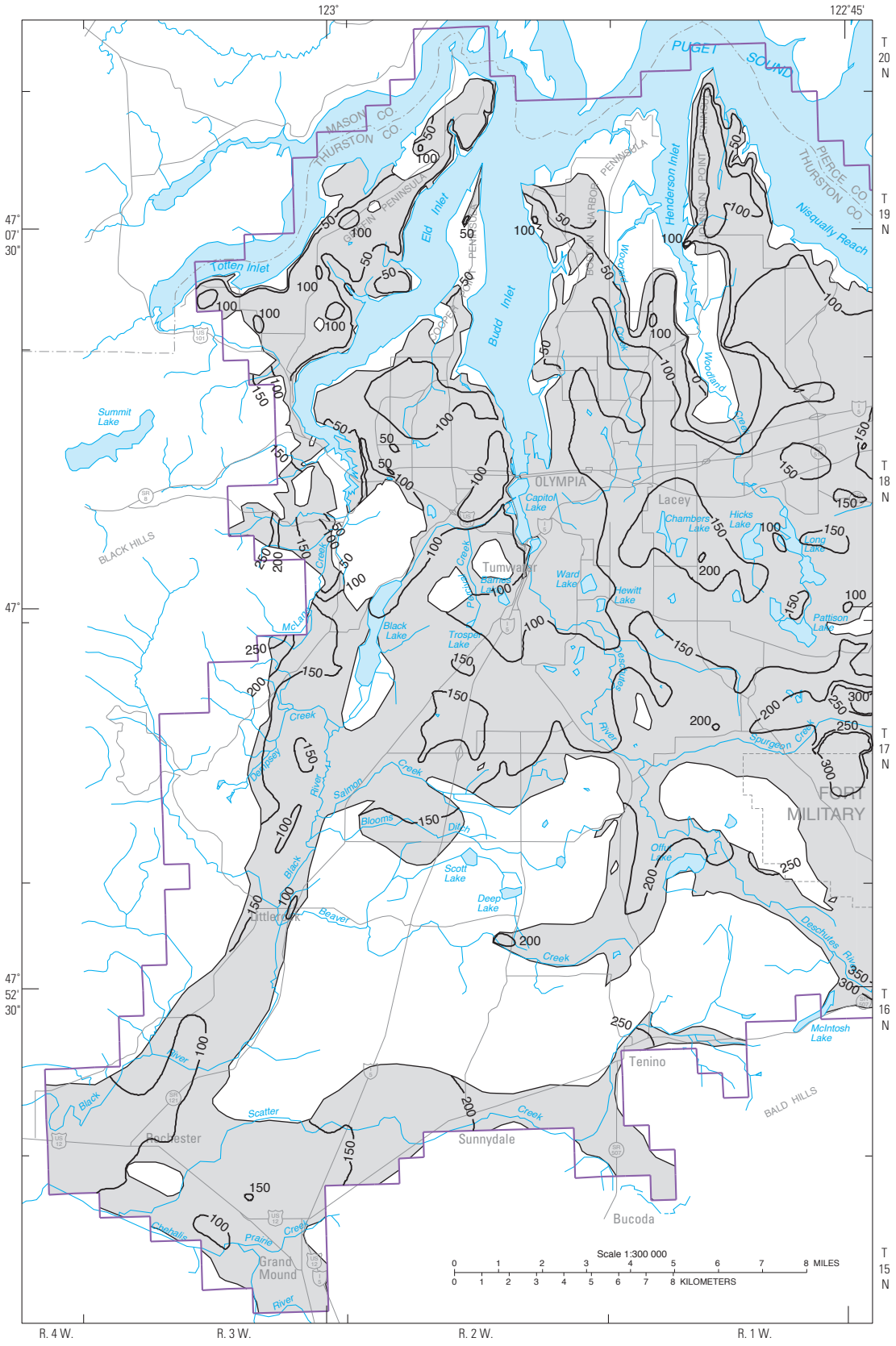


Figure 10. Altitude of the top of geohydrologic unit Qva in the study area (modified from Drost and others, 1998).

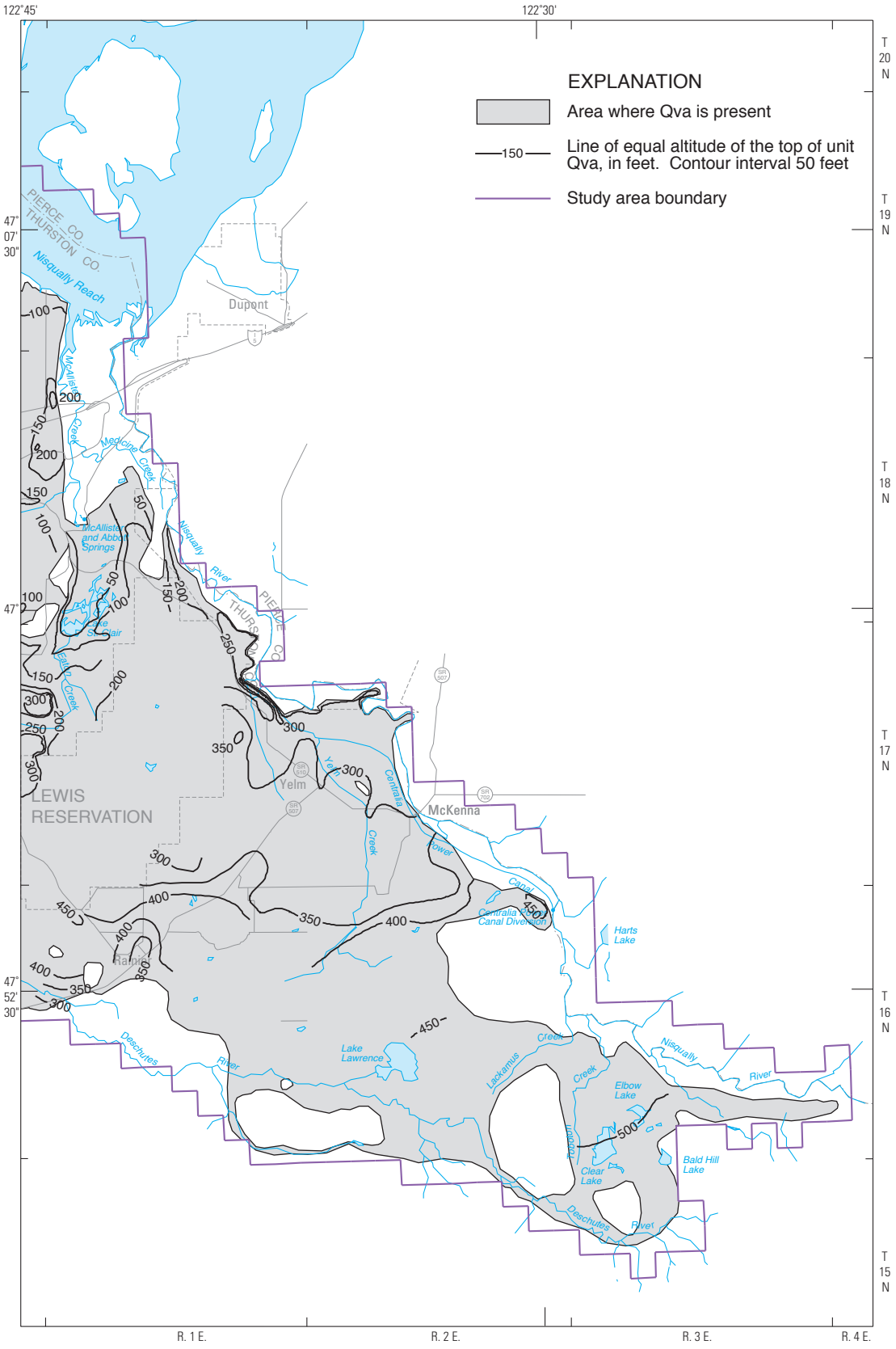


Figure 10. continued.

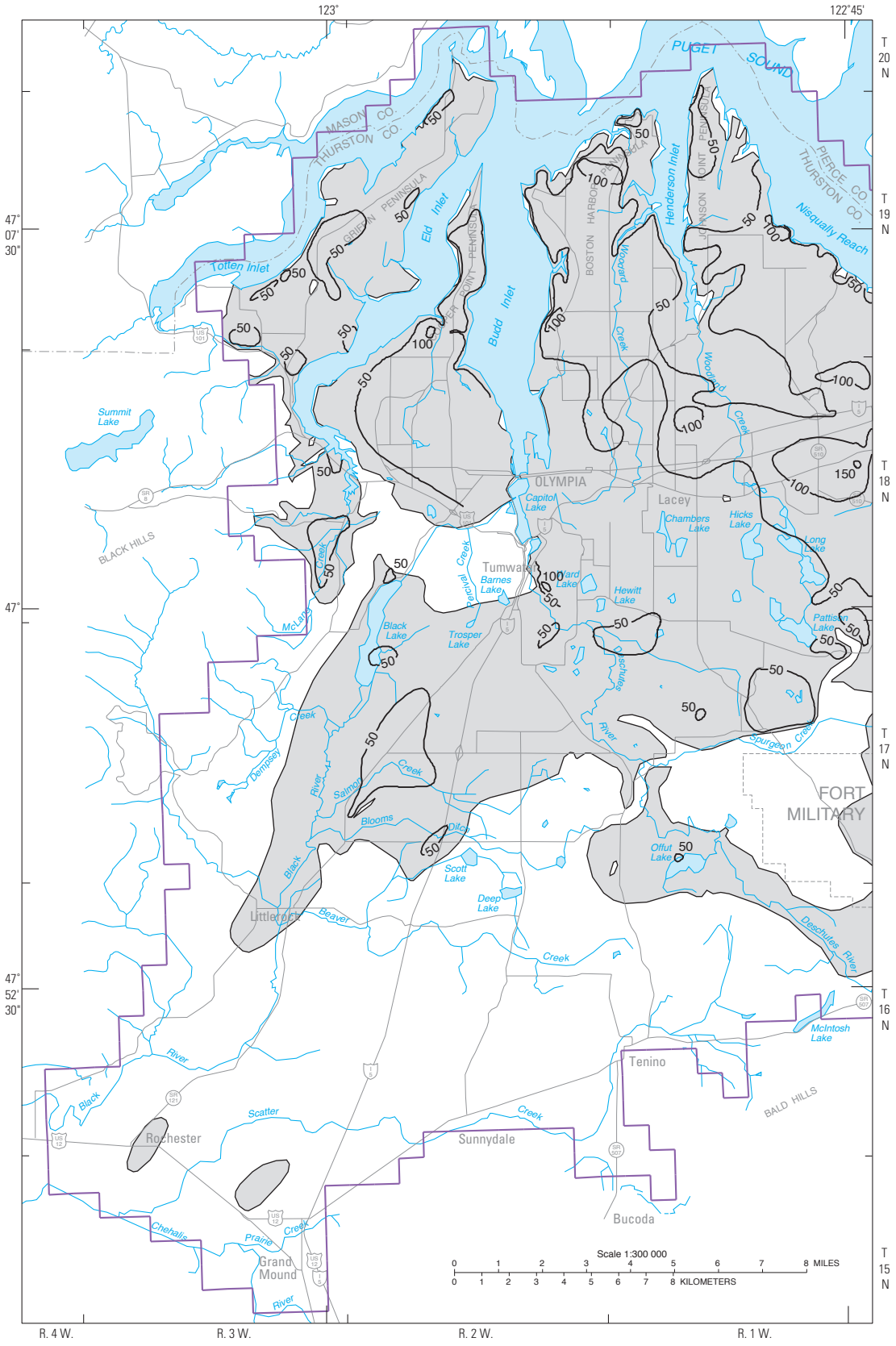


Figure 11. Areal extent and thickness of geohydrologic unit Qf in the study area (modified from Drost and others, 1998).

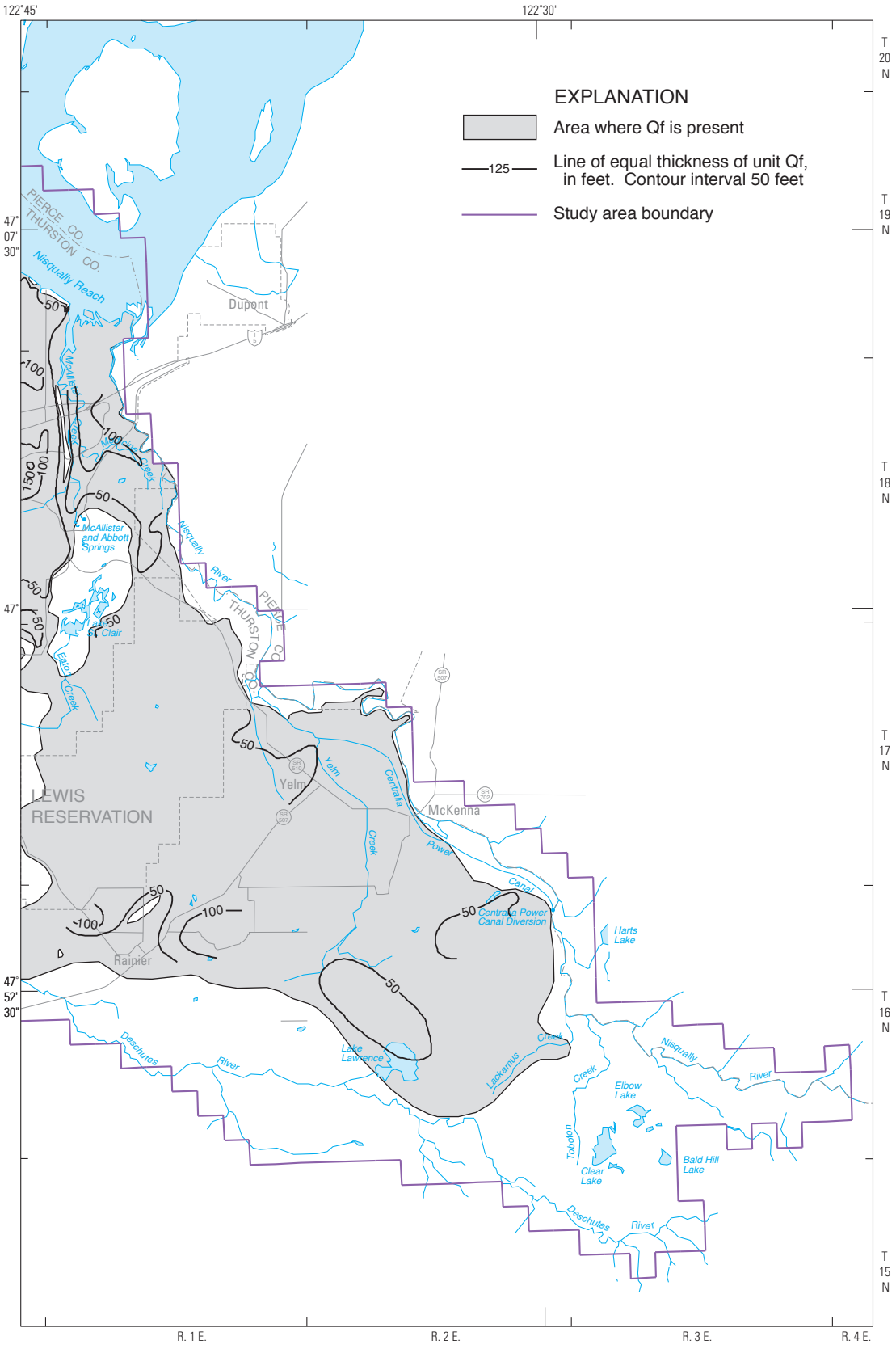


Figure 11. continued.

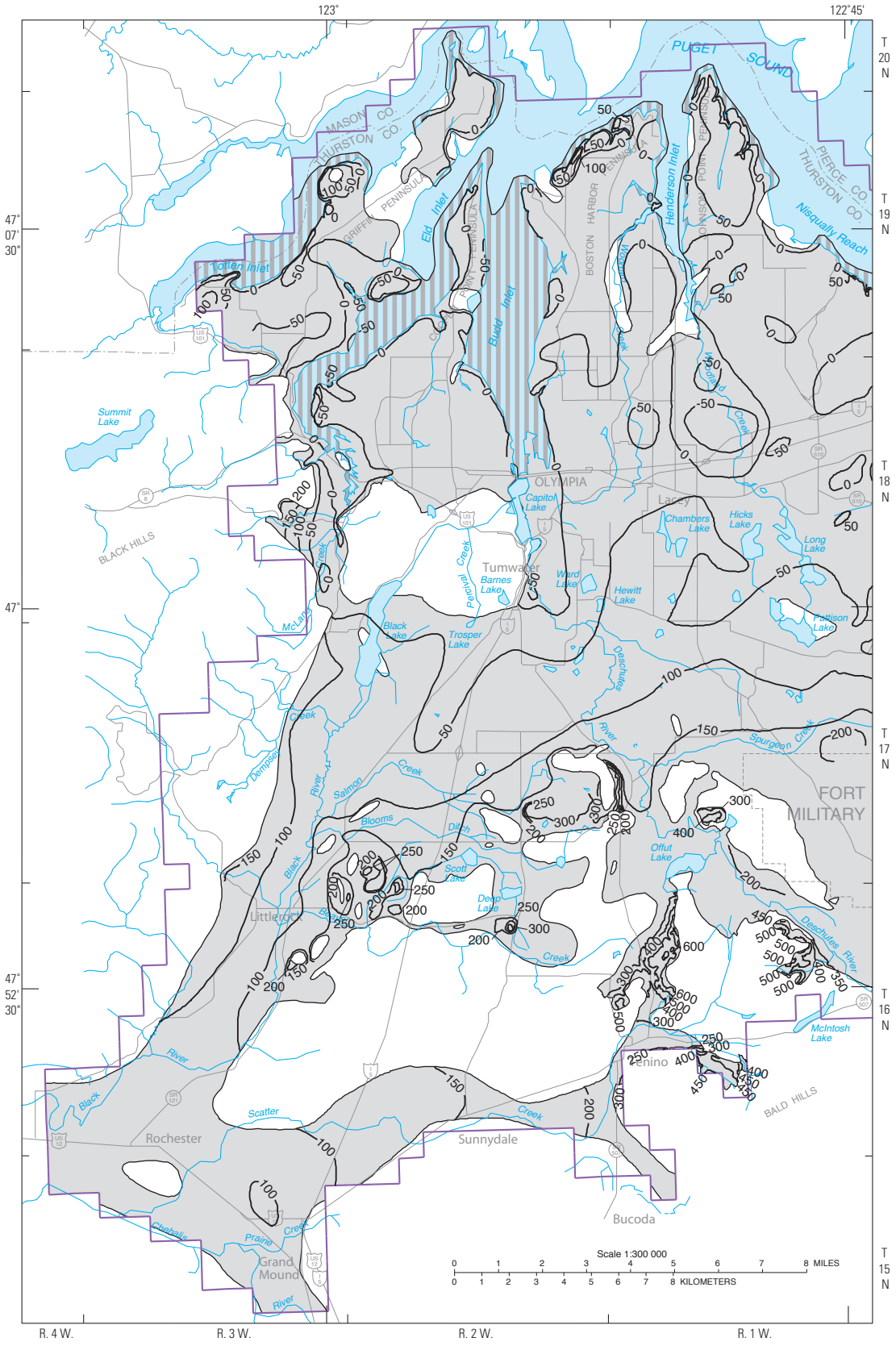


Figure 12. Areal extent and altitude of the top of geohydrologic unit Qc in the study area (modified from Drost and others, 1998).

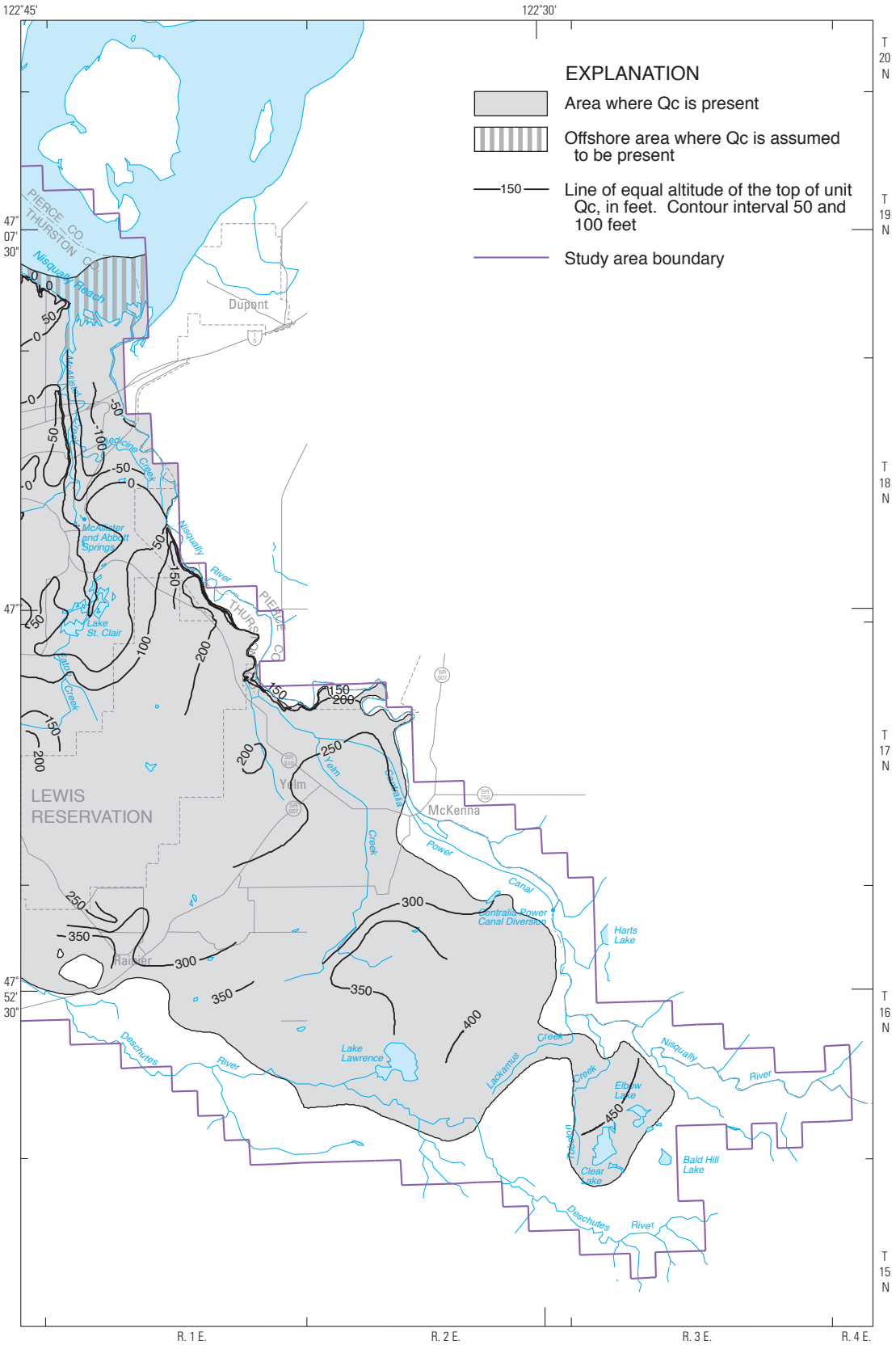


Figure 12. continued.

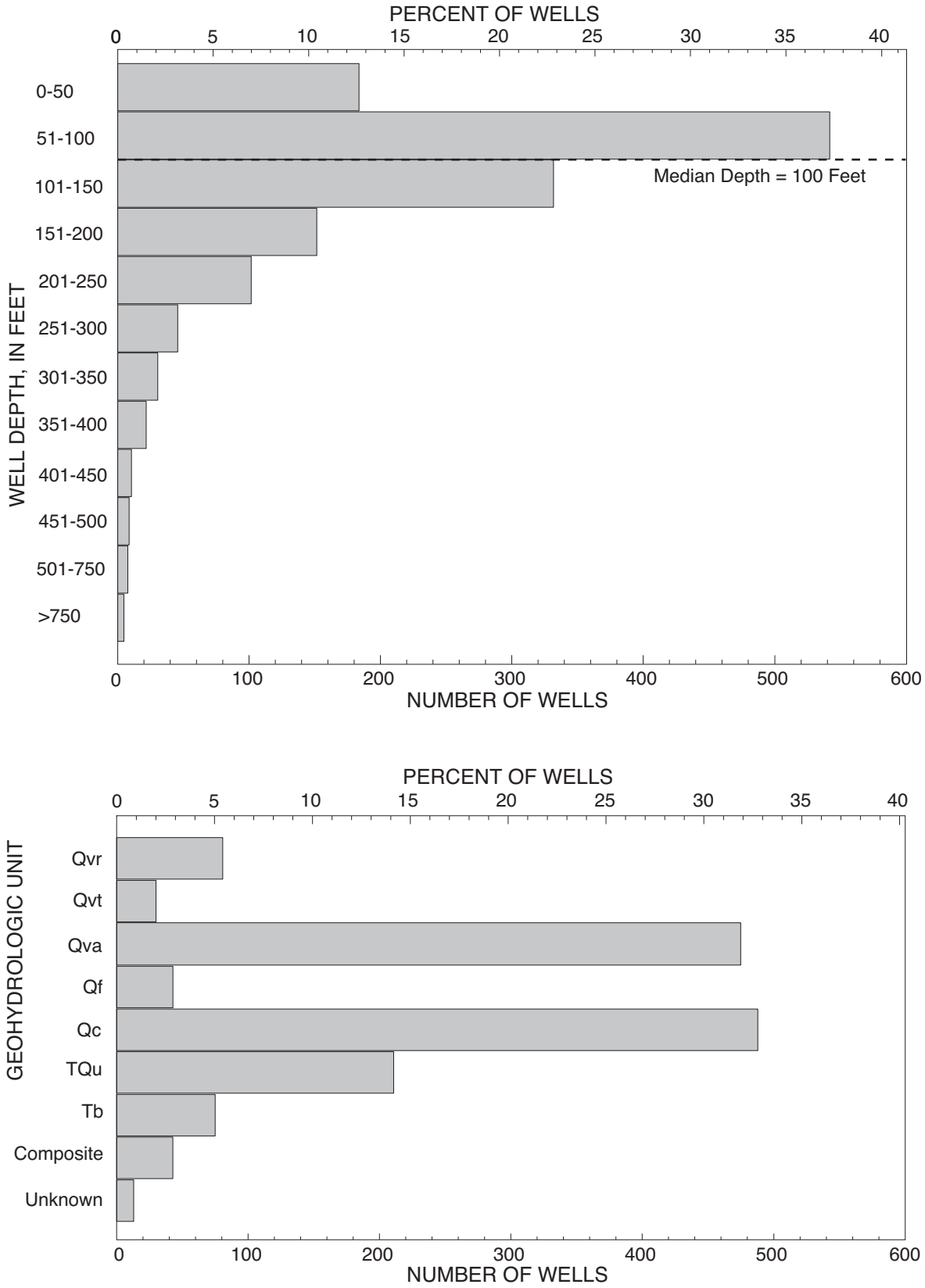


Figure 13. Frequency distributions of well depths and of geohydrologic units tapped by wells in the study area.

$$K_h = \frac{Q}{4\pi s r}, \quad (1)$$

where

K_h is horizontal hydraulic conductivity, in feet per day,

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

s is drawdown in the well, in feet, and

r is radius of the well, in feet.

Equation 1 is based on the assumption that horizontal and vertical hydraulic conductivities are equal, which is not likely for the deposits in the study area. Violating this assumption probably results in an underestimate of K_h by an unknown factor.

The horizontal hydraulic conductivities for all geohydrologic units were statistically analyzed so that medians, ranges, and differences between units could be determined. Hydraulic conductivities for those units with sufficient data (Qva and Qc) were examined to determine if there are distinct areal patterns of lower or higher values. Individual values of hydraulic conductivity can be found in the table of well data (Appendix A, table A1). A summary of horizontal hydraulic-conductivity data by unit is given in table 2. Of significance in table 2 is the fact that the median values for the three upper aquifers (Qvr, Qva, and Qc) are remarkably similar (from 150 to 180 feet per day (ft/d)). The available data for the two uppermost confining units (Qvt and Qf) also indicate similar median values (14 and 17 ft/d, respectively) and are approximately an order of magnitude less than the aquifers. However, the values for Qvt and Qf represent only the coarse-grained parts of these units because wells constructed in these units tap only the coarse-grained parts. True median values for these units, including the fine-grained portions, are probably much less than indicated by the available data. TQu represents a series of aquifers and confining beds and has a median value (78 ft/d) that is between the medians of the other aquifers and confining beds.

Table 2. Summary of horizontal hydraulic conductivity values estimated from specific-capacity data, by geohydrologic unit

Geohydrologic unit[1]	Number of wells tested	Hydraulic conductivity (feet per day)	
		Range	Median
Qvr	43	14 - 2,100	150
Qvt	22	5.2 - 89	14
Qva	370	6.8 - 130,000	180
Qf	41	.052 - 62	17
Qc	321	1.9 - 12,000	150
TQu	132	1.2 - 4,200	78
Tb	38	.0025 - 450	.88

[1]See table 1.

The validity of estimating hydraulic conductivities from specific-capacity data was checked using data from available multiple-well aquifer tests. Pacific Groundwater Group (1995, 1996a, 1997a, and 1997b) has conducted aquifer tests on three wells near Lacey and one well near McAllister Springs. The resulting hydraulic conductivities from these tests compare well with hydraulic conductivities estimated using the specific-capacity method:

Well number	Transmissivity from aquifer test (squared feet per day)	Aquifer	Aquifer thickness (feet)	Length of open interval (feet)	Hydraulic conductivity (feet per day)	
					Aquifer-test	Specific-capacity
18N/01W-24L02	24,000 to 120,000	Qc	110	20	220 to 1,100	320
18N/01W-24D04	270,000	Qc	92	32	2,900	4,700
18N/01W-24D05	380,000 to 430,000	Qc	104	40	3,700 to 4,100	3,500
18N/01E-29E02	370,000	Qc	>245	78	2,500	3,100

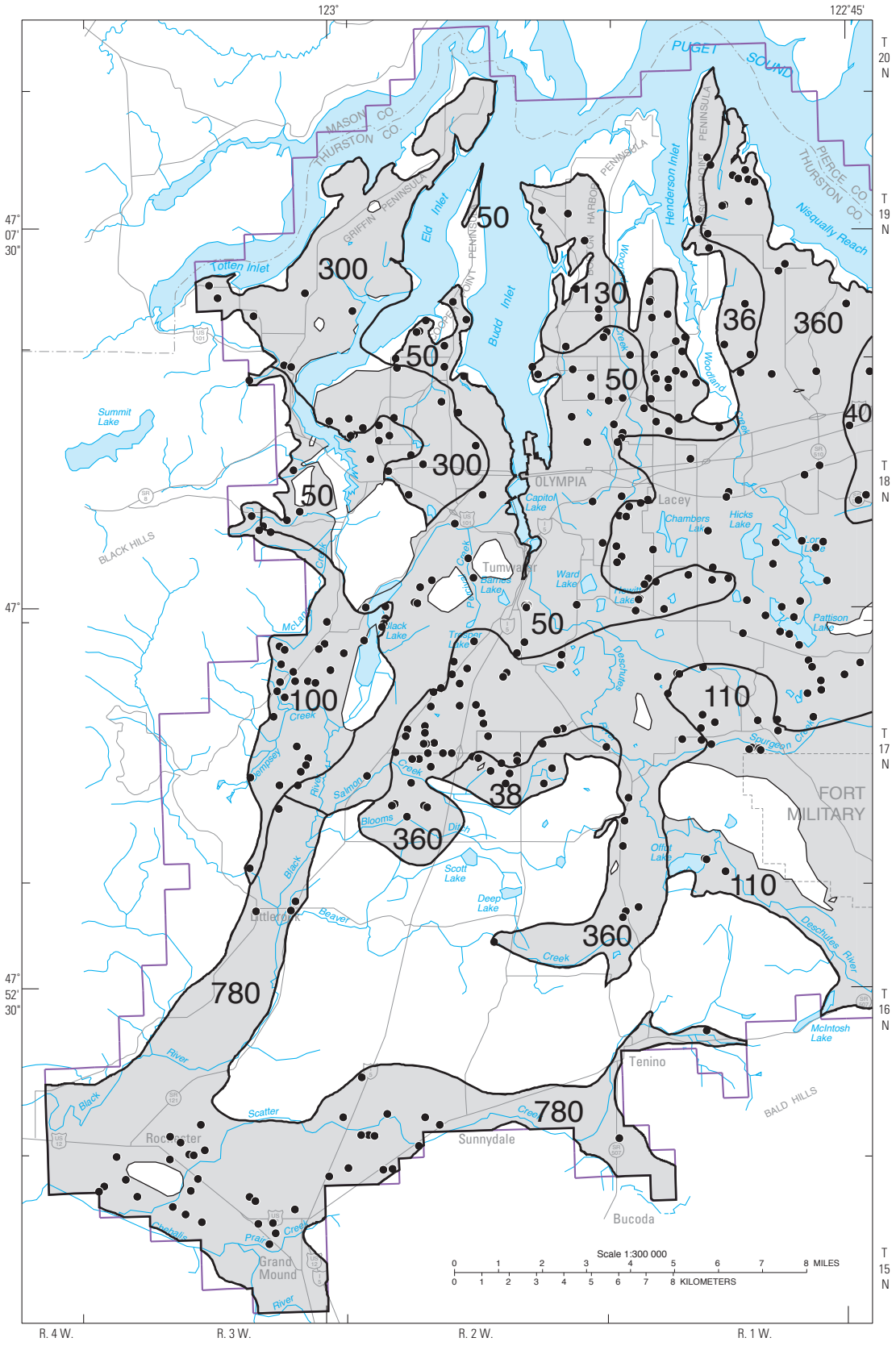


Figure 14. Areal distribution of horizontal hydraulic conductivity in unit Qva in the study area.

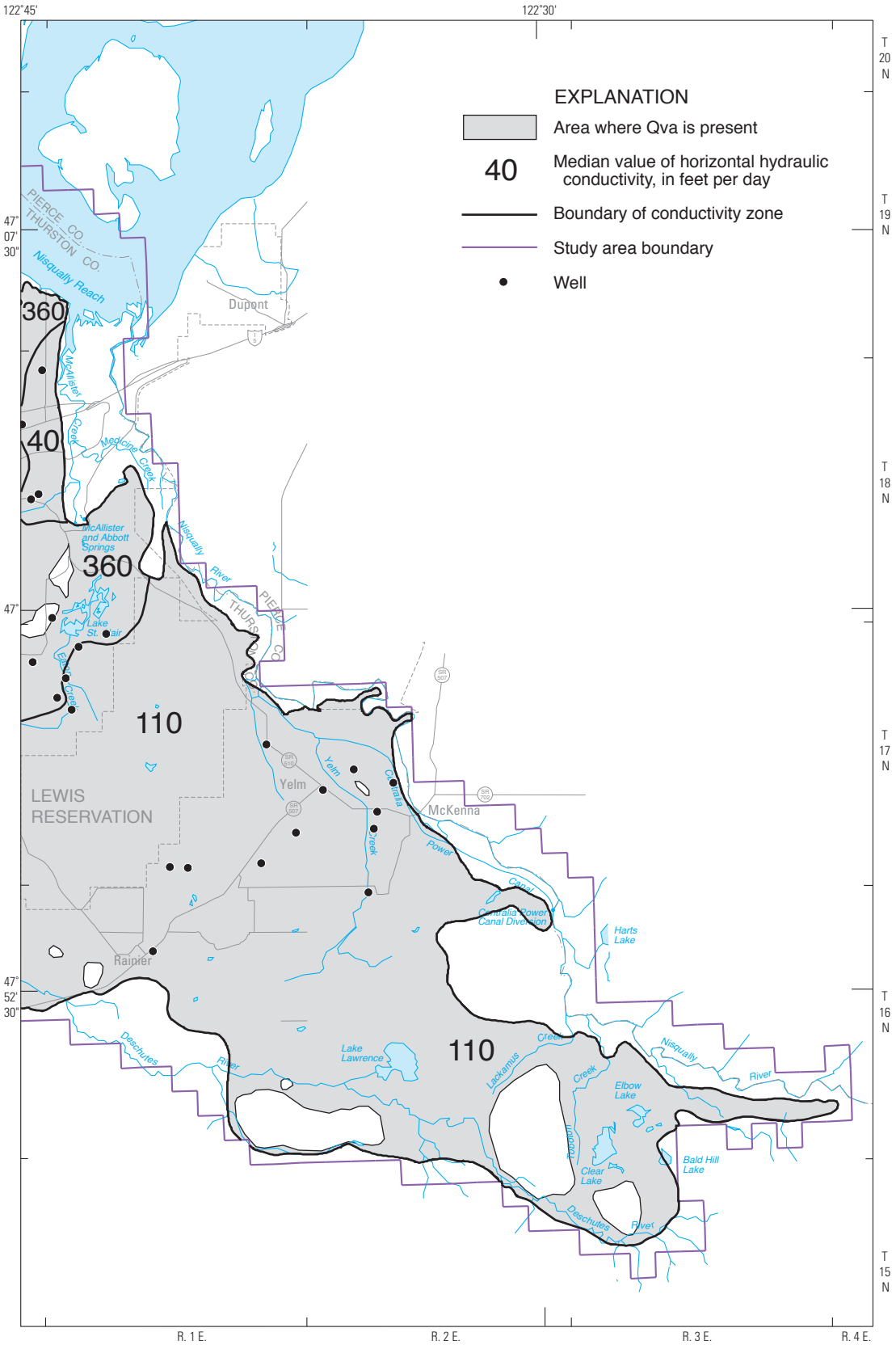


Figure 14. continued.

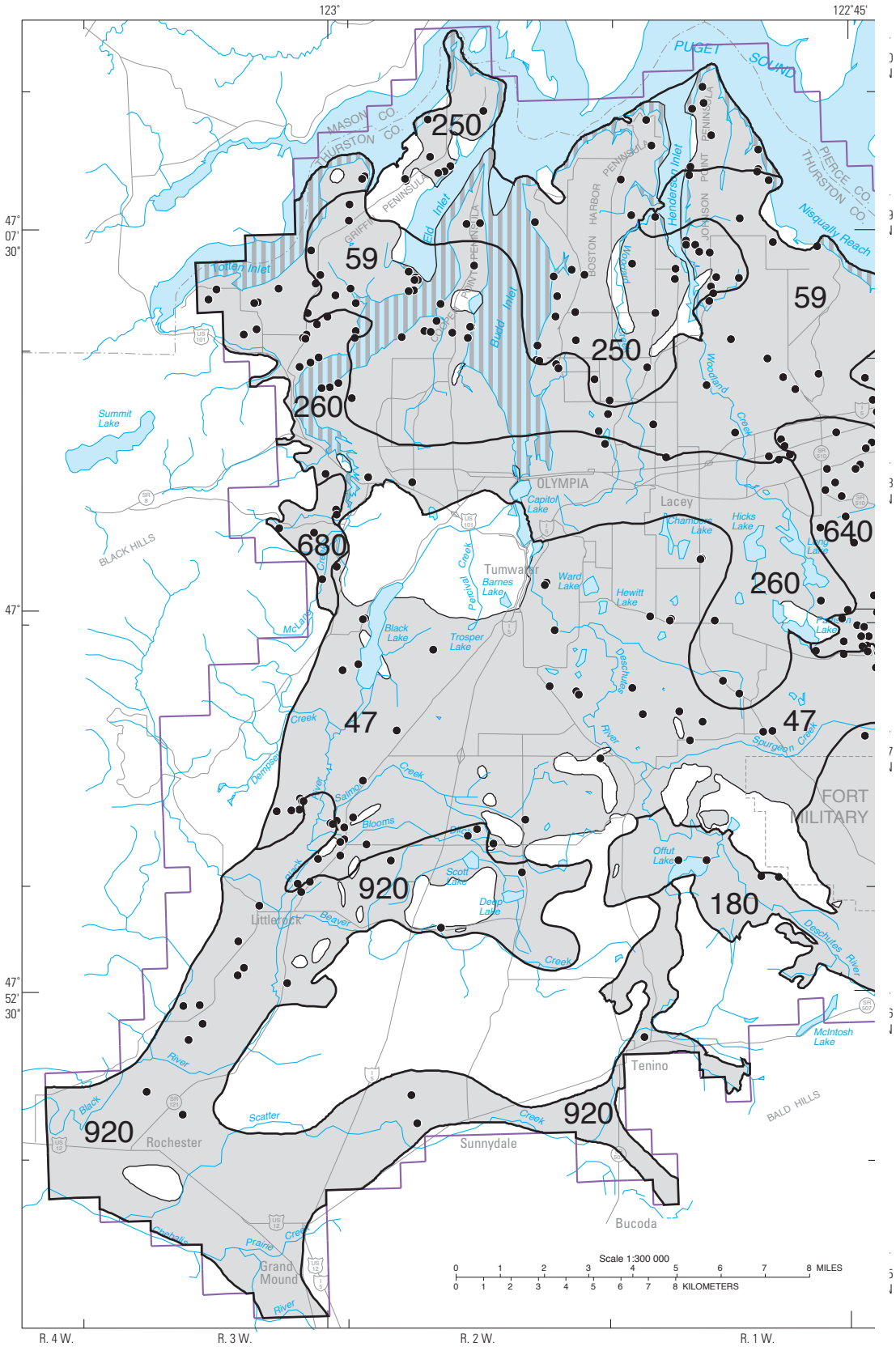


Figure 15. Areal distribution of horizontal hydraulic conductivity in unit Qc in the study area.

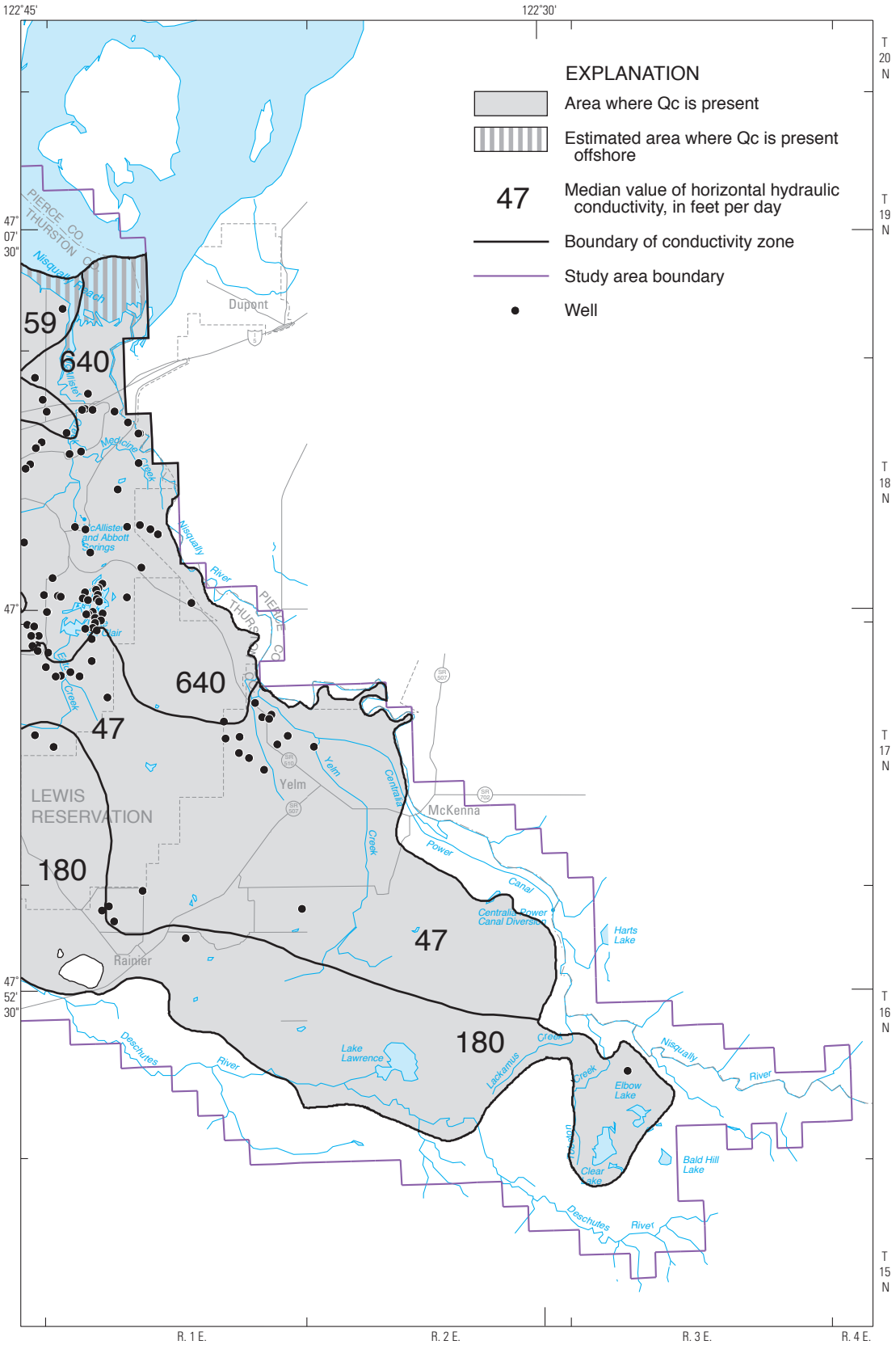


Figure 15. continued.

Sinclair and Hirschey (1992) reported that estimates of hydraulic conductivity from specific-capacity data resulted in values about one order of magnitude less than those obtained from multiple-well aquifer tests. However, Sinclair and Hirschey divided the transmissivity values estimated from the specific-capacity data by the full aquifer thickness rather than by the length of the open interval, as was done for this study. Sinclair and Hirschey estimated a hydraulic conductivity for well 16N/02W-29L02P1 of 69 ft/d (using an aquifer thickness of 105 ft), whereas the estimated value for this study is 1,400 ft/d (open interval length of 5 ft).

Identification of areal patterns of hydraulic conductivity is extremely difficult given the available data. The depositional nature of the units probably results in a network of "channels" of relatively coarse materials and therefore a three-dimensional distribution of hydraulic conductivity that is not readily discernible in a two-dimensional plot of the data. However, an attempt was made to see if general zones of similar hydraulic conductivities could be delineated for each unit. Some areal patterns in hydraulic conductivity were observed for Qva and Qc but not for units Qvr, Qvt, Qf, TQu, or Tb.

Ten zones of hydraulic conductivity were delineated for Qva (fig. 14), with median values ranging from 36 to 780 ft/d. Some of these zones are logical extensions of the conceptual model of the geohydrologic units. For example, the zone of relatively high hydraulic conductivity (780 ft/d) along the Black and Chehalis River valleys near Rochester is an area in which meltwater from the Vashon glacier was probably concentrated, resulting in the deposition of relatively coarse sediments. However, many of the zones do not have obvious correlations with the conceptual model.

Eight zones of hydraulic conductivity were delineated for Qc (fig. 15), with median values ranging from 47 to 920 ft/d. As was the case with Qva, Qc has a zone of relatively high hydraulic conductivity (920 ft/d) along the Black River valley. Some of the Qc zones correlate with the conceptual model and some have no obvious correlation.

The hydraulic-conductivity zones shown on figures 14 and 15 reflect adjustments made to the zone boundaries during model calibration. However, all zone-boundary adjustments were compatible with our conceptual model of the geohydrologic units, and the conductivity of each zone was calculated as the median of all values in that zone.

No data are available with which to estimate the vertical hydraulic conductivity of aquifers or confining layers. Estimates made in other areas within Puget Sound with similar deposits indicate that vertical hydraulic conductivity probably ranges from 0.0001 to 0.01 ft/d for the confining layers (Vaccaro and others, 1998).

Recharge

The bulk of the recharge to the ground-water system of the study area is derived from the infiltration and deep percolation of precipitation. Seepage from streams and lakes provides recharge to some parts of the study area. Some of the water that discharges from springs or is pumped from wells becomes a secondary source of recharge after it has been used. Secondary sources of recharge include seepage from septic systems, leakage from water and sewer lines, and deep percolation of irrigation water.

Recharge from precipitation occurs almost everywhere, with the possible exceptions of areas of ground-water discharge and areas covered by impermeable, man-made materials such as asphalt and concrete. However, impermeable materials at land surface may only delay and redistribute the recharge process; precipitation that runs off impermeable surfaces may seep into the ground where it encounters permeable materials. Throughout a large part of the greater Olympia area, precipitation runoff that might otherwise recharge the ground-water system is diverted through storm drains to Budd Inlet, resulting in less recharge beneath Olympia than in areas without storm drains. Similarly, there is little or no recharge from septic tank filter-field leachate in the Olympia area because domestic sewage there is diverted to central sewage-treatment facilities and then to Budd Inlet. Most of the precipitation recharge in the study area occurs in the 6-month period October–March, when precipitation greatly exceeds evapotranspiration.

The amount of precipitation recharge to the study area was first estimated by applying the precipitation–recharge relations derived for till and outwash units in nearby King County (Woodward and others, 1995) to similar units in the study area. These relations, graphically shown on figure 16, are based on the application to King County of a deep percolation (recharge) model developed by Bauer and Vaccaro (1987). Figure 16 also shows assumed precipitation-recharge relations for the kettled outwash. The kettled outwash was separated from the rest of the outwash on

the assumption that, having closed drainage, it would have somewhat greater recharge than outwash with open drainage to the sea. This incremental difference was assumed to be 10 percent. In addition, Qf was assumed to have the same recharge characteristics as Qvt because of their similar hydrologic properties.

The distribution of precipitation recharge in the study area was estimated on the basis of the areal distribution of long-term average precipitation (fig. 4), the surficial distribution of the geohydrologic units (fig. 4), and the precipitation-recharge relations shown on figure 16. The resulting recharge map (fig. 17) indicates that recharge rates range from 14 to 49 inches per year (in/yr). Summing the precipitation recharge for the recharge areas shown on figure 17 indicates that the ground-water system beneath the study area receives total precipitation recharge of about 670,000 acre-feet per year (acre-ft/yr) or an average annual rate of about 27 inches. During calibration of the ground-water model (see section on Model Calibration), estimated precipitation recharge was decreased by 10 percent.

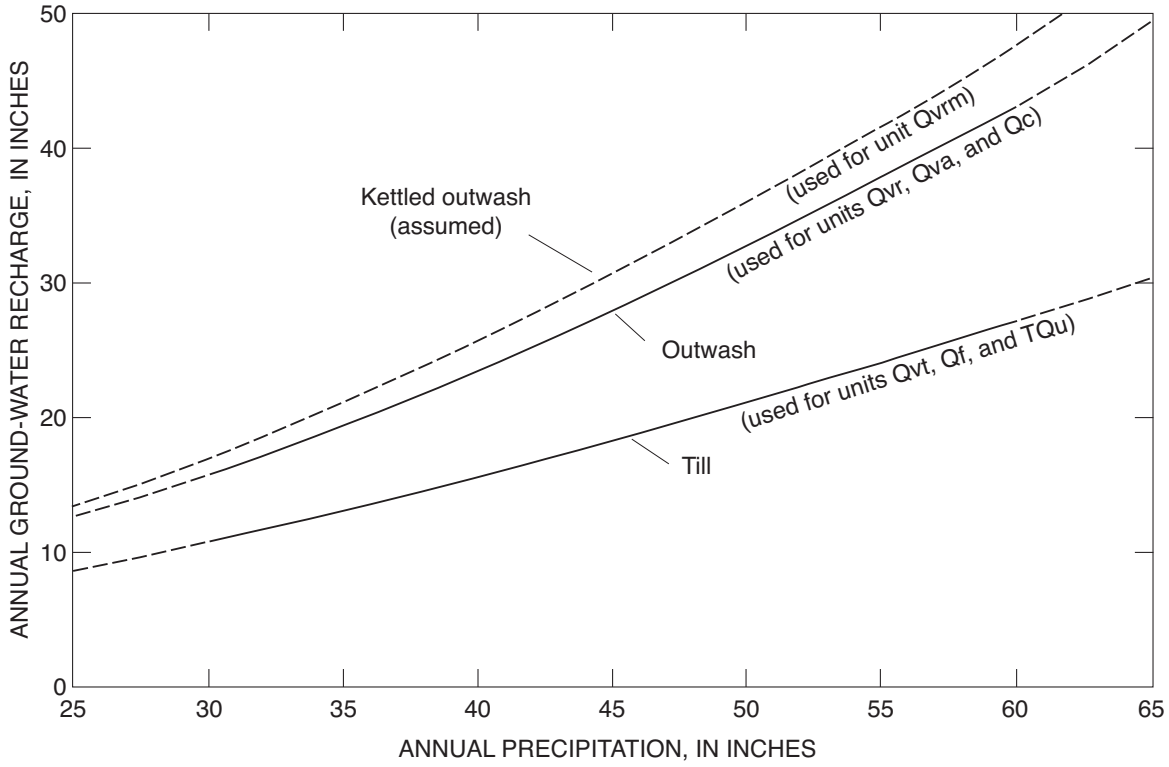


Figure 16. Precipation-recharge relations used to estimate recharge in the study area.

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A stream's rate of gain or loss of water from or to the ground-water system can be determined by a series of discharge measurements along the stream. This series of measurements is called a seepage study. Seepage studies on four rivers and three creeks (see Discharge section) indicate a ground-water recharge rate of 4.8 cubic feet per second (ft^3/s) (3,500 acre-ft/yr) from surface water. The seepage studies did not include all surface-water bodies in the study area. The recharge rate determined from the studies reflects only the conditions at the time the studies were conducted and therefore is not necessarily equal to the long-term average recharge rate.

Lake St. Clair also provides recharge to the ground-water system. A water budget for the lake indicates a net flow to the ground-water system of approximately 4,000 acre-ft/yr. Water-budget calculations for this lake are given in Appendix B. Most of the other major lakes in the study area probably have net gains from ground water. However, this has not been specifically investigated for each of the lakes. Combining the recharge from Lake St. Clair with the results of the seepage studies yields a total of approximately 7,500 acre-ft/yr of identified ground-water recharge from lakes and streams.

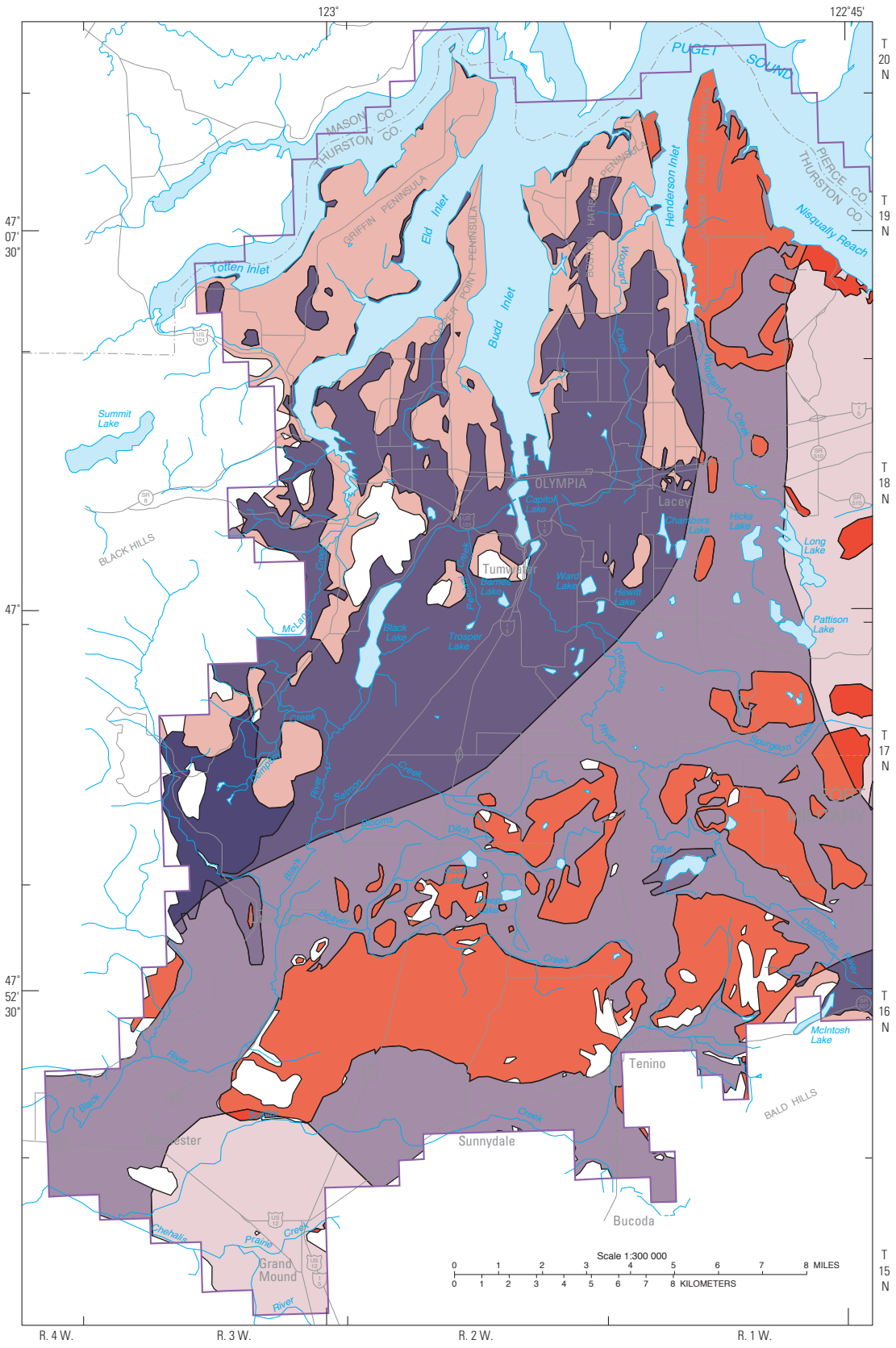


Figure 17. Areal distribution of recharge from precipitation in the study area.

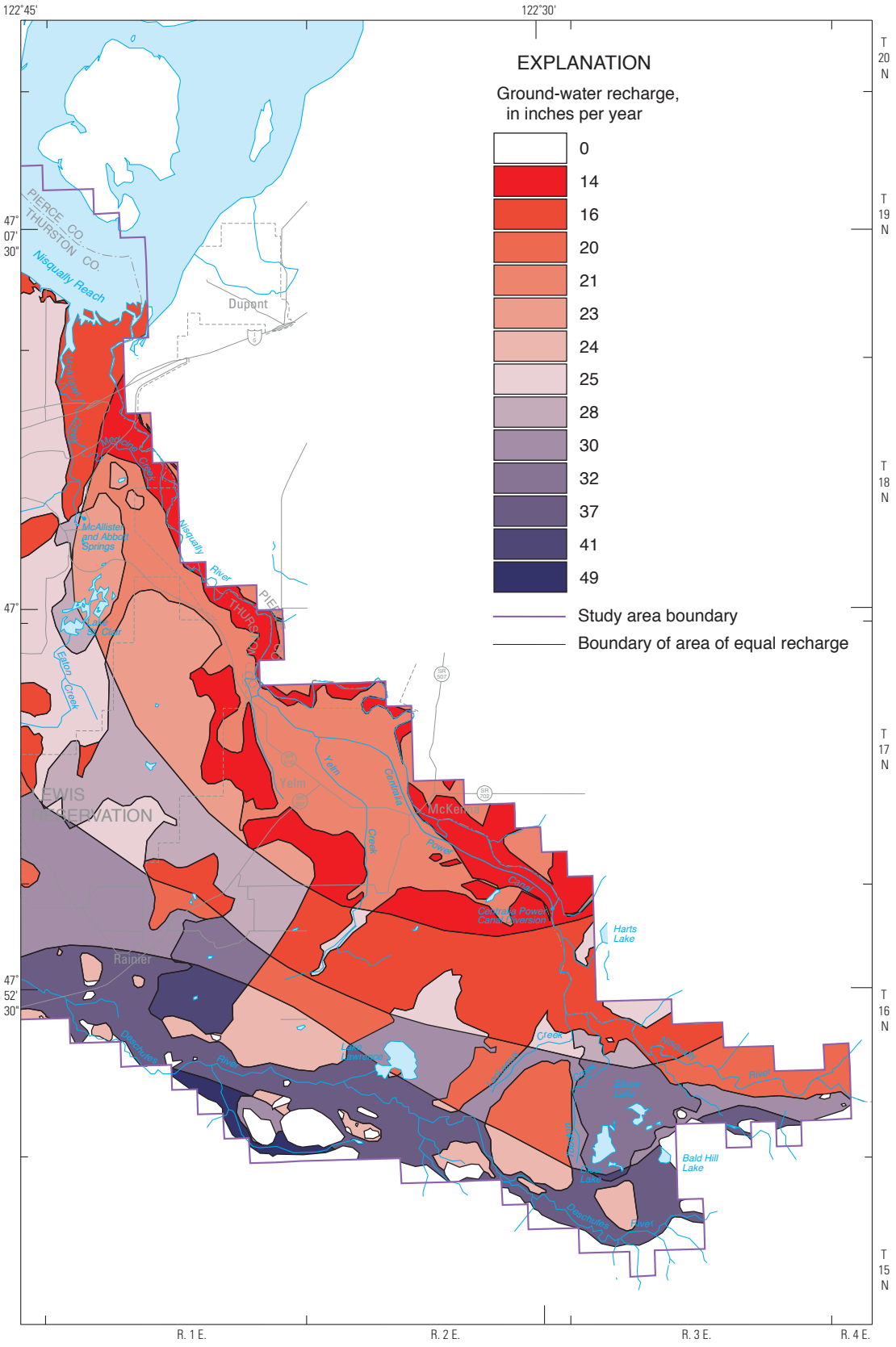


Figure 17. continued.

Secondary sources of recharge (for example, septic systems and irrigation) total 63,000 acre-ft/yr, and will be discussed with ground-water withdrawals (see section on Discharge). The factors used to estimate secondary recharge are shown in Appendix B (table B1).

Ground-Water Flow

The ground-water flow system is depicted in part by maps showing the potentiometric surface for the two principal aquifers (figs. 18 and 19). The water-level maps were constructed by extending the maps of Drost and others (1998) using water-levels from approximately 150 wells in the extended area. The water levels in the extended area include both measured and reported water levels and represent a wide time range. Therefore, the water-level contours in the extended part of the study area represent only generalized conditions and do not reflect any one point in time. Inferred horizontal directions of ground-water flow within aquifers Qva and Qc are shown with arrows on figures 18 and 19. Flow is from areas of higher head to areas of lower head and, in general, is perpendicular to the contours of equal head.

Ground water in Qva generally moves toward marine water bodies and to major streams; local mounds on the potentiometric surface occur beneath each of the major peninsulas (fig. 18). Contours along the lower reach of the Deschutes River indicate that ground-water flow is generally toward the river and that, as a result, river discharge probably increases in that area. Contours in the McKenna area indicate that ground-water flow in the Qva discharges to the Nisqually River.

The configuration of the potentiometric surface for Qc (fig. 19) is similar to that for Qva. Ground-water mounds are present on all four major peninsulas. Flow directions near Lake St. Clair and McAllister Springs are similar to those in Qva. As in unit Qva, it appears that the lower reach of the Deschutes River and the Nisqually River downstream of McKenna are areas of discharge from ground water to the rivers.

There are significant uncertainties in the observed patterns of water-level distribution (figs. 18 and 19). The accuracy of the observed water-level altitudes is limited by the accuracy of available land-surface altitudes at each site (generally +/-10 feet and poorer in some cases). The inaccuracy is due to most land-surface altitudes being estimated from topographic maps; very few of the study-area wells have been surveyed. This results in uncertainty about some of the features of the water-level distributions as depicted on figures 18 and 19. In particular, the apparent ground-water divide in unit Qc, which runs north from near Spurgeon Creek, between Olympia and Lacey, and out onto the Boston Harbor Peninsula, may not be an accurate representation of the actual ground-water system. The same applies to the apparent ground-water mound in unit Qva east of Lacey.

Beneath the upland areas, water levels in Qva are generally higher than in Qc, indicating that water flows downward, passing through Qf, where present. The areas of largest head difference coincide with ground-water mounds within Qva and with areas where the intervening fine-grained unit Qf is thickest. These areas of largest water-level differential are not necessarily areas of greater downward flow nor areas of greater aquifer vulnerability from surface contamination.

Discharge

Ground water in northern Thurston County discharges as seepage to lakes, streams, springs, and coastal bluffs; as evaporation and transpiration of shallow ground water; as submarine seepage to marine waters; as withdrawals from wells; and as ground-water outflow along the Chehalis River valley downstream of Rochester. Ground water discharges to some reaches of the principal streams in the study area, augmenting streamflow and producing what is usually referred to as a gaining reach. Ground-water discharge sustains the late-summer and early-fall flows of numerous streams in the study area. Seepage studies were conducted by the USGS on Woodland Creek (August 11, 1988), the Deschutes River (August 12, 1988), Eaton Creek (August 1, 1989), and the Nisqually River (October 8 and 9, 1991); by Sinclair and Hirschey (1992) on the Chehalis River (August 24, 1987) and Scatter Creek (August 18, 1989); and by Pickett (1994) on the Black River (July and August, 1992). A total of approximately 200 ft^3/s (140,000 acre-ft/yr) of ground water discharged to these creeks and rivers during the seepage studies (table 3). Discharge data for the seepage studies and locations of measuring sites are shown in Appendix B (table B2 and fig. B1, respectively). Because the seepage studies were not conducted on all streams in the study area, and the calculated ground-water discharges are not necessarily equal to the average annual discharge rate, total ground-water discharge

to streams may be significantly different than that measured by the seepage studies.

The total discharge of the principal springs in the study area is approximately 85 ft^3/s (62,000 acre-ft/yr; table 4). There are, in addition, probably hundreds of smaller springs of various types scattered throughout the study area. The total spring discharge in the study area is unknown. McAllister Springs (18N/01E-19Q01S) is by far the largest in the study area in terms of both discharge and surface area. Over the period 1979–88, the annual mean discharge of McAllister Springs has ranged from 21.2 to 25.6 ft^3/s (Andrew W. Hoiland, City of Olympia, written commun., 1990) and averaged 23.6 ft^3/s. From July 1988 through December 1989, the discharge of the spring was below the long-term average (fig. 20) and it was above the long-term average from January through July 1990. Approximately 24,000 of the 87,000 acre-ft/yr of spring discharge was used for household supply, commercial-industrial supply, aquaculture, or livestock supply (table 5 and Appendix B, table B3). Approximately 14,000 of the 24,000 acre-ft/yr became secondary recharge (septic systems, leakage from aquaculture ponds, etc.)(See Appendix B, table B1.)

Ground-water withdrawals from wells was approximately 65,000 acre-ft in 1988 (table 5 and Appendix B, table B3). After being used, approximately 49,000 acre-ft/yr of the withdrawn ground water became secondary recharge (septic systems, deep percolation of applied irrigation water, etc.).

Evapotranspiration from ground water in the study area occurs where the water table is at very shallow depths. The total discharge by ground-water evapotranspiration is unknown in the study area, but is presumed to be insignificant in comparison to the other discharges.

Discharge occurs from the study area as submarine seepage to Puget Sound and as ground-water outflow along the Chehalis River downstream of Rochester. This form of discharge is not readily measurable, but will be estimated in the section of this report describing the ground-water model.

Water-Level Fluctuations and Trends

The configuration of the water table or potentiometric surface is determined by (1) the overall geometry of the ground-water system; (2) the hydraulic properties of the aquifer; and (3) the areal and temporal distribution of recharge and discharge. When recharge exceeds discharge, the quantity of water stored will increase and water levels will rise; where discharge exceeds recharge, the quantity of water stored will decrease and water levels will fall.

Previous studies in western Washington have shown that, in years of typical precipitation, ground-water levels in shallow wells generally rise during the wet season of October through March and fall during the dry season of April through September. Water levels in deep wells generally respond more slowly, and usually with less magnitude, than water levels in shallow wells. Near the coast, water-level fluctuations also occur in response to tidal changes; these fluctuations are superimposed on the seasonal and long-term changes that are related to changing recharge-discharge relations.

A monthly water-level-measurement network within the GWMA was started in November 1988 and wells were added gradually through June 1990. Water levels in most of these wells were measured for at least a full year (May 1989 through May 1990). Water levels were generally at their seasonal highest in February–May and lowest in October–December. Hydrographs of water levels in selected observation wells (Drost and others, 1998) indicate that the highs and lows occurred at approximately the same time in both shallow and deep wells, and that the magnitude of fluctuation was controlled by more than well depth alone.

During the period May 1989 through May 1990 (when the network was most complete), most wells experienced a net water-level rise, with a median rise of nearly 1 ft. At the start of this period, the study area had been experiencing a relatively dry period. Annual water-level fluctuations in the network ranged from 2.25 to 17.08 ft, with a median of 5.36 ft. The largest fluctuations took place in bedrock wells.

To investigate somewhat longer-term changes, water levels were measured during July 23, 1990, to August 2, 1990, in 607 wells in Thurston County (table A3, end of report) that were previously measured for the study by Drost and others (1998). Measurements reported by Drost and others were taken over a broader period, March 1988 to October 1989. To minimize the effects of seasonal changes on an analysis of change over a 2-year period, only those measurements made by Drost and others from June 11, 1988, to September 13, 1988, were used in the analysis. Comparisons were made only in those cases where static water levels were obtained in 1988 and again in 1990. Given these restrictions, there were 278 wells with comparable 1988 and 1990 water levels.

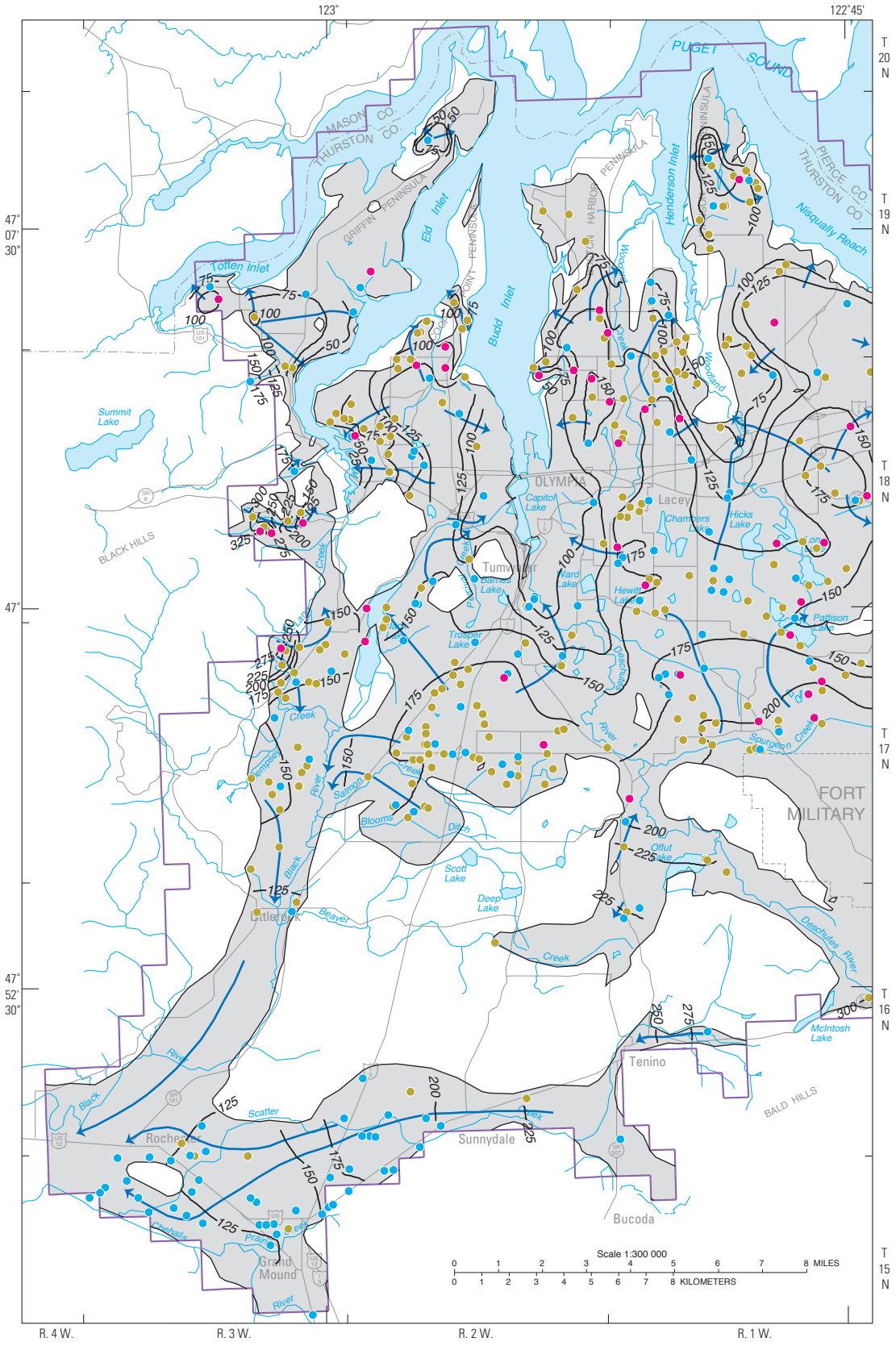


Figure 18. Water-level altitude and ground-water flow directions in unit Qva in the study area.

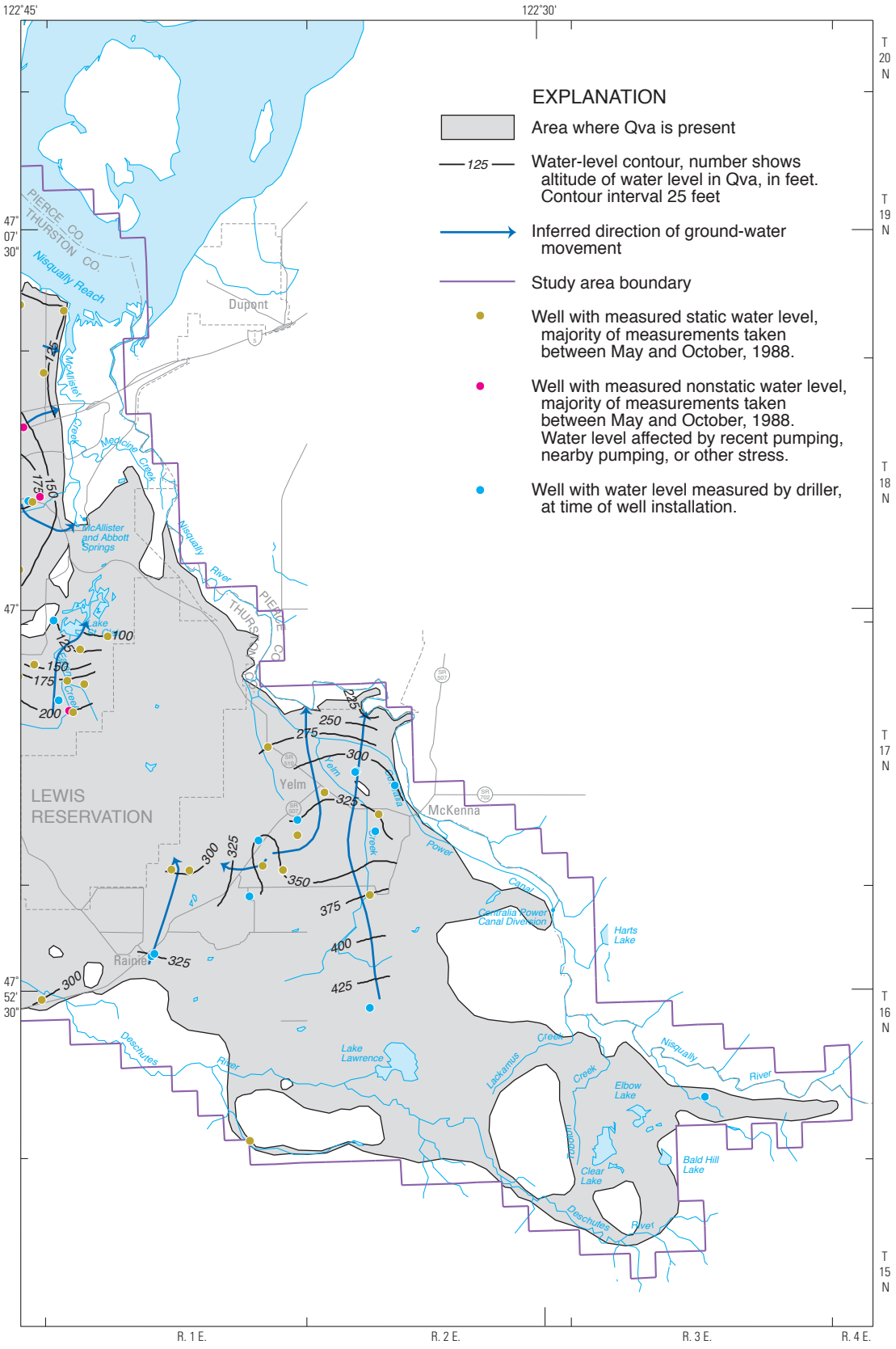


Figure 18. continued.

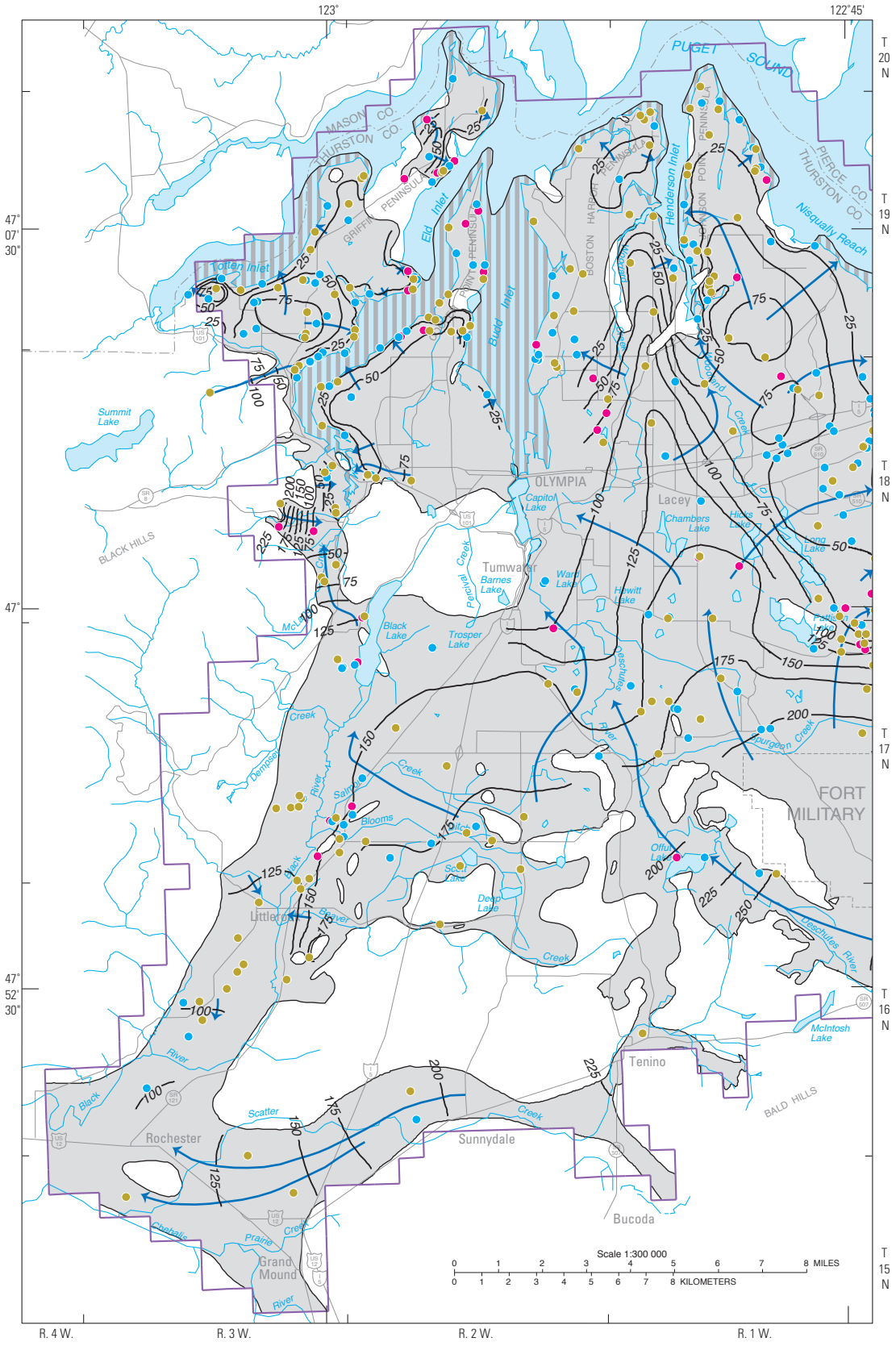


Figure 19. Water-level altitude and ground-water flow directions in unit Qc in the study area.

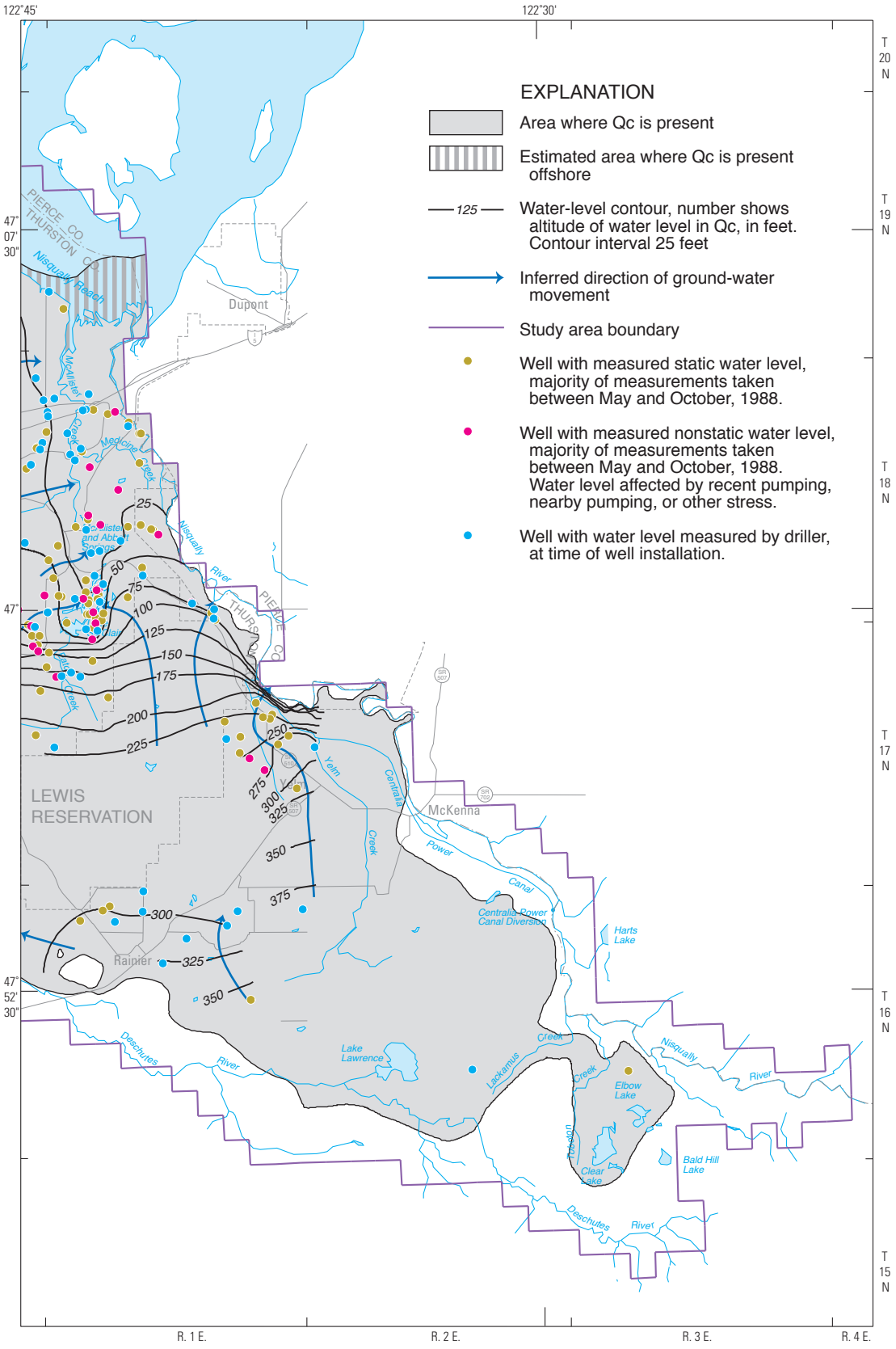


Figure 19. continued.

Table 3. Net flow from ground water to streams as determined from seepage studies

Site number and name (see Appendix 3, table B2, and figure B1)[1]	Change between sites (cubic feet per second)[2] Total gain	Total loss	Net change	Remarks
Woodland Creek				
1 at Pattison Lake inlet				--
8 at Pleasant Glade Road	8.4	3.2	+5.2	6.6 cubic feet per second from springs 18N/01W-15D01S and 18N/01W-16A01S
Eaton Creek				
At maximum upstream extent				
5 near mouth	3.8	0.6	+3.2	--
Deschutes River				
1 near Rainier (12079000)				--
14 at "E" Avenue	53	0	+53	1.1 cubic feet per second from spring 16N/01W-01N01S
Nisqually River				
1 at McKenna (12089500)				--
9 at Interstate 5 (12090240)	[3]92	0	+92	27 cubic feet per second from springs 17N/01E-11B01S, 17N/01E-11G01S, 17N/01E-11G02S, 17N/01E-12M01S, 17N/01E-12Q01S, 17N/01E-21C01S; 17N/02E-07N01S, 17N/02E-07N02S, 17N/02E-17C01S, 17N/02E-17D01S, 17N/02E-17J01S, 17N/02E-18M01S, 17N/02E-18K01S; and 18N/01E-35N01S
Black River				
1 at River Mile 15.2				--
6 at River Mile 9.3	25	0	+25	Average of two seepage studies; July 20, 1992 and August 18, 1992
Chehalis River				
1 near Grand Mound (12027500)				--
3 below Scatter Creek	16	0	+16	--
Scatter Creek				
1 at River Mile 4.6				--
4 at River Mile 1.5	4	1	+3	--
Totals	202.2	4.8	+197.4	

[1]Number in parentheses is U.S. Geological Survey gaging station number.

[2]"Gain" indicates flow from ground water to stream; "Loss" indicates flow from stream to ground water. Net change: +, indicates net gain; -, indicates net loss. Values do not include flow from identified springs (flows from identified springs are shown in "Remarks" section).

[3]Represents one-half of measured gain, based on assumption that one-half of gain comes from Thurston County and one-half from Pierce County.

Table 4. Principal springs in the study area

[See table 1 for description of geohydrologic units. Use: H, domestic; P, public supply; Q, aquaculture; S, livestock; T, institution; U, unused; ?, unknown; Discharge: N/A, not available; e, estimated; m, measured; r, reported; ft^3/s, cubic feet per second; <, less than]

Spring number	Owner (spring name)	Altitude (feet)	Use	Discharge (ft^3/s)		Discharge date	Geohydrologic unit
15N/03W-08D02S	Fosnacht, F.C.	120	U	N/A			Qvr
15N/03W-09F01S	Fox, J.R.	140	H	0.2	e	05-01-47	Qvr
15N/03W-09F02S	Hillis	140	H	0.1	e	05-02-47	Qvr
16N/01W-01N01S	Schoenbachler (Silver Spring)	295	U	1.1	m	08-12-88	Qvr
16N/02E-03E02S	Rieke, B.E.	445	S	N/A			Qvt
16N/02W-33H01S	Whitcomb, Roy A.	213	S	0.2	e	05-16-47	Qvr
16N/03E-30A01S	Unknown	390	U	1.7	e	12-03-97	Qvr
16N/03W-27N01S	Unknown	190	H	0.001	m	05-03-47	Qvr
17N/01E-02C01S	Unknown	110	Q	6-10	e	09-19-91	Qc
17N/01E-11B01S	Unknown	135	U	0.01	e	07-26-89	Qc
17N/01E-11G01S	Unknown	120	U	<1	e	07-26-89	Qc
17N/01E-11G02S	Unknown	140	U	1	e	07-26-89	Qc
17N/01E-12M01S	Unknown	120	U	1-3	e	10-09-91	Qc
17N/01E-12Q01S	Unknown	200	U	1.8	m	09-12-50	Qc
17N/02E-07N01S	Unknown	150	U	1.2	m	09-14-50	Qc
17N/02E-07N02S	Unknown	150	U	1.3	m	09-14-50	Qc
17N/02E-17C01S	Hutches	215	U	0.71	m	09-15-50	Qva
17N/02E-17D01S	Unknown	225	?	0.09	m	09-15-50	Qva
17N/02E-17J01S	Unknown	250	?	0.06	m	09-21-50	Qc
17N/02E-18K01S	Beckendorf, R. Sr. (Crystal Spring)	310	U	8.2	m	08-16-49	Qvr
				6.6	m	09-07-49	
17N/02E-18M01S	Beckendorf, R. Jr.	300	U	0.67	e	- -50	Qvr
17N/02E-28F01S	Unknown	300	?	8.9	m	06-02-50	Qva
				8.0	m	08-22-50	
				7.6	m	09-26-50	
17N/02E-32R03S	Unknown	380	S	0.45	m	05-26-50	Qvr
18N/01E-07F01S	Nisqually Trout Farm	100	Q	1.1	r	07-26-89	Qvr
18N/01E-07F02S	Nisqually Trout Farm	100	Q	0.6	r	07-26-89	Qvr
18N/01E-07P01S	Unknown	80	?	1.2	e	10-01-91	Qc
18N/01E-16M01S	Unknown	40	?	N/A			Qvr
18N/01E-18P01S	Unknown	15	U	N/A			Qc
18N/01E-19J01S	City of Olympia (Abbott Spring)	6.6	H	5-10	e	- -85	Qvr, Qva?, Qc?
18N/01E-19Q01S	City of Olympia (McAllister Springs)	6.5	P	[1]23.6	m	1979–88	Qvr, Qva?, Qc?
18N/01E-35N01S	Unknown	110	Q	2-3	e	09-19-91	Qc
18N/01W-15D01S	Nisqually Trout Farm (Beatty Spring)	75	Q	7.3	m	05-01-33	Qvr
				6.2	r	07-26-89	
18N/01W-16A01S	St. Martin's College	75	T	0.4	e	07-26-89	Qvr
18N/01W-34G01S	Unknown	165	U	0.19	m	08-11-89	Qvr
				1	e	07-26-89	
18N/02W-18L01S	City of Olympia (Allison Springs formerly Arnold Springs?)	10	Q	5	e	11-21-33	Qva
				3.1	r	06-17-88	
18N/03W-22H01S	Unknown	325	U	N/A			Qvr
19N/01W-25F01S	Unknown	125	U	N/A			Qvt
19N/02W-33G01S	Unknown	95	U	<1	e	07-27-89	Qva

[1]Annual average discharge 1979–88.

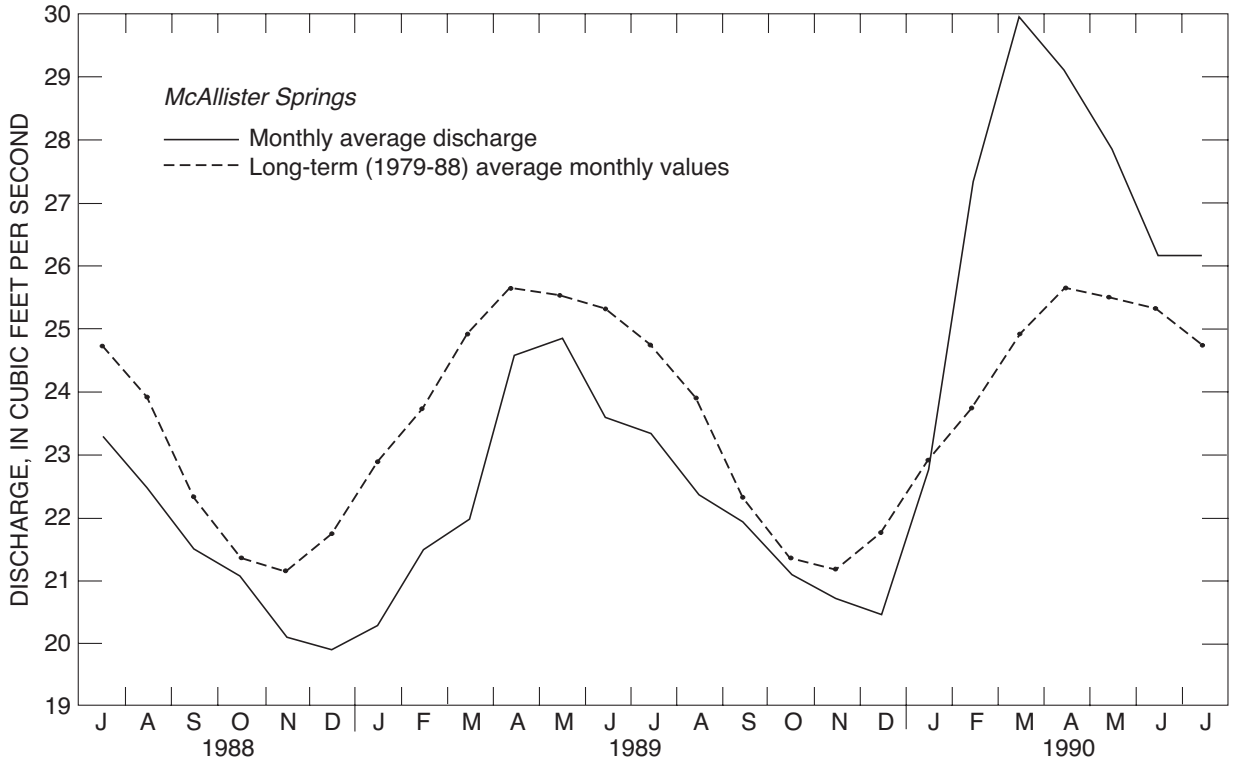


Figure 20. McAllister Springs discharge, monthly averages for July 1988 through July 1990, and long-term average monthly discharge.

Table 5. Summary of ground-water use in 1988 in the study area, by water-use category, source, and geohydrologic unit

[See table 1 for description of geohydrologic units; --, none or negligible]

Use category and source	Water use (acre-feet per year)[1]							
	Geohydrologic unit							
	Qvr	Qvt	Qva	Qf	Qc	TQu	Tb	Total
Household Use (Public and Domestic)								
Wells	580	110	7,500	20	5,200	1,400	54	15,000
Springs	[2]5,900	--	--	--	--	--	--	5,900
Commercial-Industrial								
Wells	310	16	2,300	370	2,300	530	--	5,800
Springs	[2]1,900	--	--	--	--	--	--	1,900
Irrigation								
Wells	840	39	4,700	15	2,000	520	38	8,200
Springs	--	--	--	--	--	--	--	--
Aquaculture and livestock								
Wells	--	--	16,000	--	20,000	--	--	36,000
Springs	5,700	--	2,200	--	7,600	--	--	16,000
Subtotal								
Wells	1,700	160	30,000	400	30,000	2,400	92	65,000
Springs	14,000	--	2,200	--	7,600	--	--	24,000
Total	16,000	160	32,000	400	38,000	2,400	92	89,000

[1]All values rounded to two significant figures.

[2]The discharge of McAllister Springs, attributed to Qvr, may actually also emanate from unit(s) Qva and(or) Qc.

An analysis of the difference in water levels (table 6) shows that from 1988 to 1990 there was a median rise of 0.6 to 1.9 ft in water levels in all units except Tb, where there was a 1.4 ft decline. It is not possible to determine the cause of the rise in water levels; it could be any combination of increased recharge and (or) decreased discharge. However, an analysis of precipitation over the typical recharge period (October through March) before each set of measurements may provide some insight into this rise in water levels. Approximately 26 inches of precipitation were recorded at Olympia for October 1987 to March 1988 and about 43 inches for October 1989 to March 1990, a 65-percent increase (National Oceanic and Atmospheric Administration, 1988, 1989, 1990, 1991). This greater precipitation probably caused more recharge before the 1990 measurements and may account for the higher water levels.

Table 6. Summary of water-level changes in wells, summer 1988 to summer 1990

Geohydrologic unit	Number of wells measured	Number of wells with water-level change		Median water-level change (feet)
		Down	Up	
Qvr	26	2	24	+1.9
Qvt	7	2	5	+0.7
Qva	121	15	106	+1.7
Qf	8	2	6	+1.6
Qc	78	14	64	+0.9
TQu	28	10	18	+0.6
Tb	10	8	2	-1.4

The detection of longer-term trends in ground-water levels generally requires the plotting and analysis of many years of water-level data. Those data are generally lacking in the study area. The water level in well 18N/02W-07R01, completed in unit Qva, was monitored from 1958–62, 1971–81, and 1988–99. The hydrograph of the data from that well (fig. 21) shows seasonal fluctuation of 2 to 12 feet and mean water levels during 1959–62 and 1972–80 of approximately 77.4 and 79.5 ft below land surface, respectively. The mean water level during 1989–98 was approximately 80.6 ft below land surface, 3.2 and 1.1 ft lower than during 1959–62 and 1972–80. Mean precipitation for the periods 1959-61, 1971–79 and 1988–97 were 53.3, 51.4, and 49.6 in/yr, respectively. The lower water levels observed in well 18N/02W-07R01 during 1988–99 may be due chiefly to the lower precipitation. The 3.7- and 1.8-in/yr decreases in precipitation during this period, assuming an effective porosity of 0.2, could account for 1.5 ft of the 3.2 ft of decline in water level (1958–61) and 0.75 ft of the 1.1 ft of decline (1972–80). However, the lower water level might reflect long-term drawdown due to nearby pumping or man-made changes in recharge. As development has increased, some areas have become sewered, resulting in decreased secondary recharge (compared with areas with septic systems). The increase in the amount of impervious surface with development may have also decreased recharge.

Two additional long-term hydrographs are shown on figure 21: 16N/01W-19G01 and 17N/02E-19M02. These two hydrographs also show seasonal responses to precipitation, but exhibit no obvious long-term trends. Both hydrographs, unfortunately, terminate during the early stage of rapid development in the study area.

Stage records for Ward Lake (fig. 21), which is formed by a kettle that intersects the water table, give some insight into long-term ground-water levels. During the period 1930–65 the mean lake stage was approximately 121.8 feet above sea level. During the period 1990–97 the mean stage was approximately 121.3 ft. Mean annual precipitation for 1929–64 and 1989–96 was 51.1 and 48.4 in., respectively. Assuming an effective porosity of 0.2, the decrease of 2.7 in/yr in precipitation during the 1989–96 period could more than account for the 0.5 ft decrease in lake level.

A recent study of the upper Chehalis River valley (Wildrick and others, 1995) reported that a network of ten observation wells (1977–92) in the Scatter Creek valley “indicate no apparent progressive year-to-year decline due to nearby ground-water pumping”. The available data, though not conclusive, seem to indicate that the ground-water system is in a state of dynamic equilibrium and therefore can be represented by a steady-state model.

Figure 21 (pages 52-54) can can be accessed by downloading files at http://pubs.usgs.gov/wri/wri994165.

MODEL CONSTRUCTION AND CALIBRATION

The preceding sections have developed qualitative and quantitative information that describes the ground-water system. A numerical model is used in the following sections to simulate the ground-water system. Numerical models are tools that increase an investigator's capability to formulate and test hypotheses about a ground-water system. If a reasonable match between observed and simulated conditions can be obtained, the model can provide useful information about ground-water movement and probable responses to further development or changes in hydrologic conditions.

Model Code

Ground-water flow in the unconsolidated deposits underlying Thurston County was simulated with a computer model consisting of data and a set of programs commonly known as MODFLOW (McDonald and Harbaugh, 1988). The data sets describe the geohydrologic units, recharge, discharge, and the conceptual model of the ground-water-flow system. MODFLOW uses finite-difference techniques to solve the mathematical equations describing ground-water flow.

The model will be given to the Thurston County Health Department for their use in water-resources planning. Therefore, in agreement with the County, commercial computer software (Visual MODFLOW, version 2.71; Waterloo Hydrogeologic, Inc.) that couples a graphic user interface with MODFLOW was used to construct the model and perform simulations.

Relationship Between Conceptual and Numerical Models

The purpose of the numerical model is to mathematically simulate flow in the ground-water system on the basis of the conceptual model formed during this project. The numerical model was designed to represent as much of the unconsolidated sediments in the study area as possible, but with emphasis on the GWMA. During calibration, some parts of the study area (such as the upstream part of the Scatter Creek valley) could not be successfully included, given the regional scale of this model. These areas were removed from the active portion of the model.

Model Grid and Layering

The MODFLOW program requires that the ground-water-flow system be subdivided, vertically and horizontally, into rectilinear blocks called cells. The hydraulic properties of the material in each cell are assumed to be homogeneous. The study area was subdivided by a horizontal grid into cells 3,000 feet per side and vertically into 8 layers having varying thicknesses (fig. 22).

The finite-difference grid chosen for the model (fig. 22) has 66 columns and 53 rows; cells are a uniform 3,000 feet on each side. The large cell size and uniform grid spacing were chosen to reflect the regional perspective of this study. The predominant flow direction in the study area is from south to north; therefore the grid is oriented similarly. Of the 27,984 cells within the model, 16,733 are inactive cells (no simulated ground-water flow), leaving 11,251 active cells. The extents of active cells in each layer are outlined on figures 23a-h.

Eight model layers were used to simulate the saturated unconsolidated sediments that overlie the Tertiary bedrock in the study area.

Geohydrologic unit	Model layer
Qvr	1
Qvt	2
Qva	3
Qf	4
Qc	5
TQu	6,7,8

The layers were delineated in the model by inputting land-surface altitude and the altitudes of the bottom of each layer as interpreted from the more than 1,300 well logs listed in table A2. Visual MODFLOW uses these data to estimate altitudes of the tops and bottoms of each layer at each cell in the entire model. Visual MODFLOW uses an inverse distance squared method to calculate these altitudes. For this model, the number of nearest points to use for the interpolating was set at 3. The surfaces and thicknesses constructed by Visual MODFLOW were compared with those

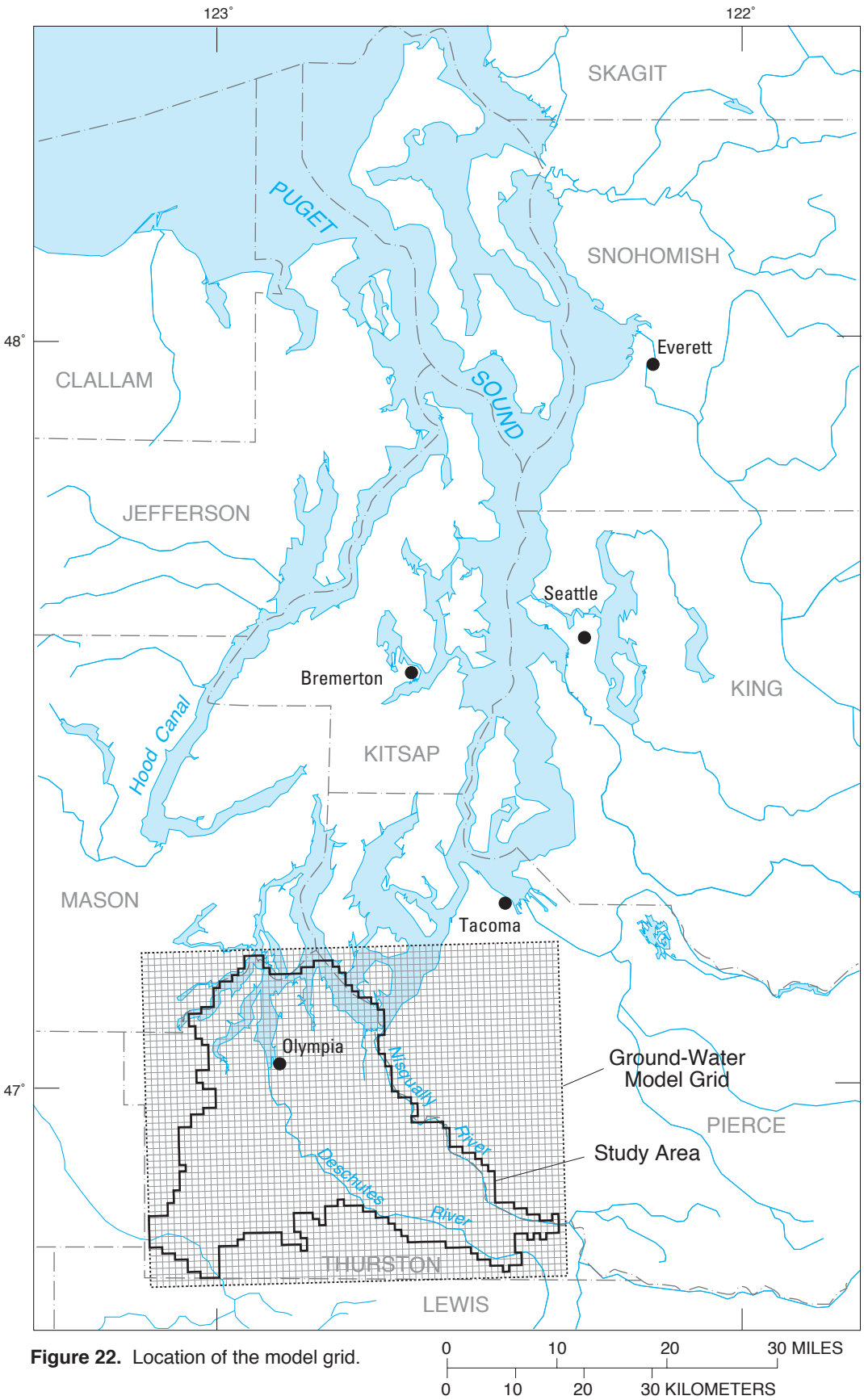


Figure 22. Location of the model grid.

shown on figures 7 through 12 and were adjusted where necessary to arrive at a reasonable model representation of the unit extents and thicknesses shown on figures 7 through 12.

All layers in the model were simulated as confined due to (1) limited data on the position of the water table where unconfined conditions exist, and (2) numerical instabilities that would occur in the model where relatively thin saturated thicknesses could not be accurately simulated because of the regional nature of the model. Adjustments were made to unit Qvr to account for large unsaturated thicknesses in some locations. These adjustments were accomplished by decreasing the horizontal hydraulic conductivity to result in a transmissivity representative of the saturated thickness.

Unit TQu is subdivided into three model layers. The layered sediments within this unit represent earlier glacial and interglacial periods and consist of unconsolidated sediments. The areal and vertical distribution of these materials are poorly known and can only be estimated. For the purposes of this model, it was assumed that the uppermost layer in TQu (model layer 6) is a fine-grained unit. In the process of designing the geohydrologic units, the bottom of unit Qc and top of TQu were generally identified as being at the contact between coarse and fine sediments. Thickness of layer 6 was set at 50 feet, an estimate based on the available data. It was further assumed that a coarse-grained unit (model layer 7) underlies layer 6. The thickness of this layer was set at 25 feet, an estimate based on available data. Below these layers there was so much uncertainty about the make up of the materials present that they were simulated by one layer (model layer 8) having a variable thickness. The thickness of this layer was determined by subtracting the thickness of all overlying layers (1 to 7) from the total thickness of the unconsolidated sediments shown on figure 5. Thickness of this unit ranged from 0 to 2,000 feet. The thickest part of this layer lies in the northern part of the study area and it generally thins southward.

Visual MODFLOW requires that all layers must be present in all active nodes in the model. In order to accurately simulate missing layers, a 1-foot thickness was assigned where a unit was not present and the hydraulic properties were altered to represent a large vertical hydraulic conductivity (1,000 feet per day) and a small horizontal hydraulic conductivity (0.00001 feet per day). This results in the simulated flow passing vertically through the "missing" layer essentially as if it weren't present.

Boundaries

The boundaries of the model coincide as much as possible with natural hydrologic boundaries. For example, most of the southern and western boundaries are located where the unconsolidated sediments lap onto a rising bedrock (Tb) surface (see fig. 4). It is assumed that the Tb unit is impermeable when compared to the unconsolidated units overlying it; therefore, the contact between the two was simulated as a "no-flow boundary," which allows no ground-water flow into or out of the model across this boundary. The bottom of the model is the top of the Tb unit and is also a no-flow boundary.

The northern boundary occurs either where the unconsolidated sediments terminate at steep bluffs above sea level, resulting in springs and seepage faces (generally model layers 1 to 4), or where the unconsolidated sediments extend below sea level and are truncated by the sloping bottom of Puget Sound, resulting in submarine seeps (generally model layers 5 to 8). Along this boundary, each layer was terminated laterally with a head-dependent flux boundary (drain cells).

The eastern boundary coincides with the Nisqually River. Beneath the Nisqually River it is assumed that ground water flows upward into the river. Water-level maps (figs. 18 and 19) show ground-water flow in Thurston County in both the Qva and Qc units (model layers 3 and 5) to be toward the Nisqually River. Previous work reported by Walters and Kimmel (1968) and Griffin and others (1962) show a similar pattern of ground-water flow toward the river in the Vashon Drift (equivalent to model layers 1 to 3) in Pierce County. A seepage-study on the Nisqually River (see section on Discharge) indicates that the river gains about 92 ft^3/s downstream of McKenna. Based on the water-level and discharge evidence, there is assumed to be no ground-water flow out of the model under the river. Therefore, the boundary below the Nisqually River is simulated as a no-flow boundary. At depths below layer 3, the validity of this assumption is presently unknown.

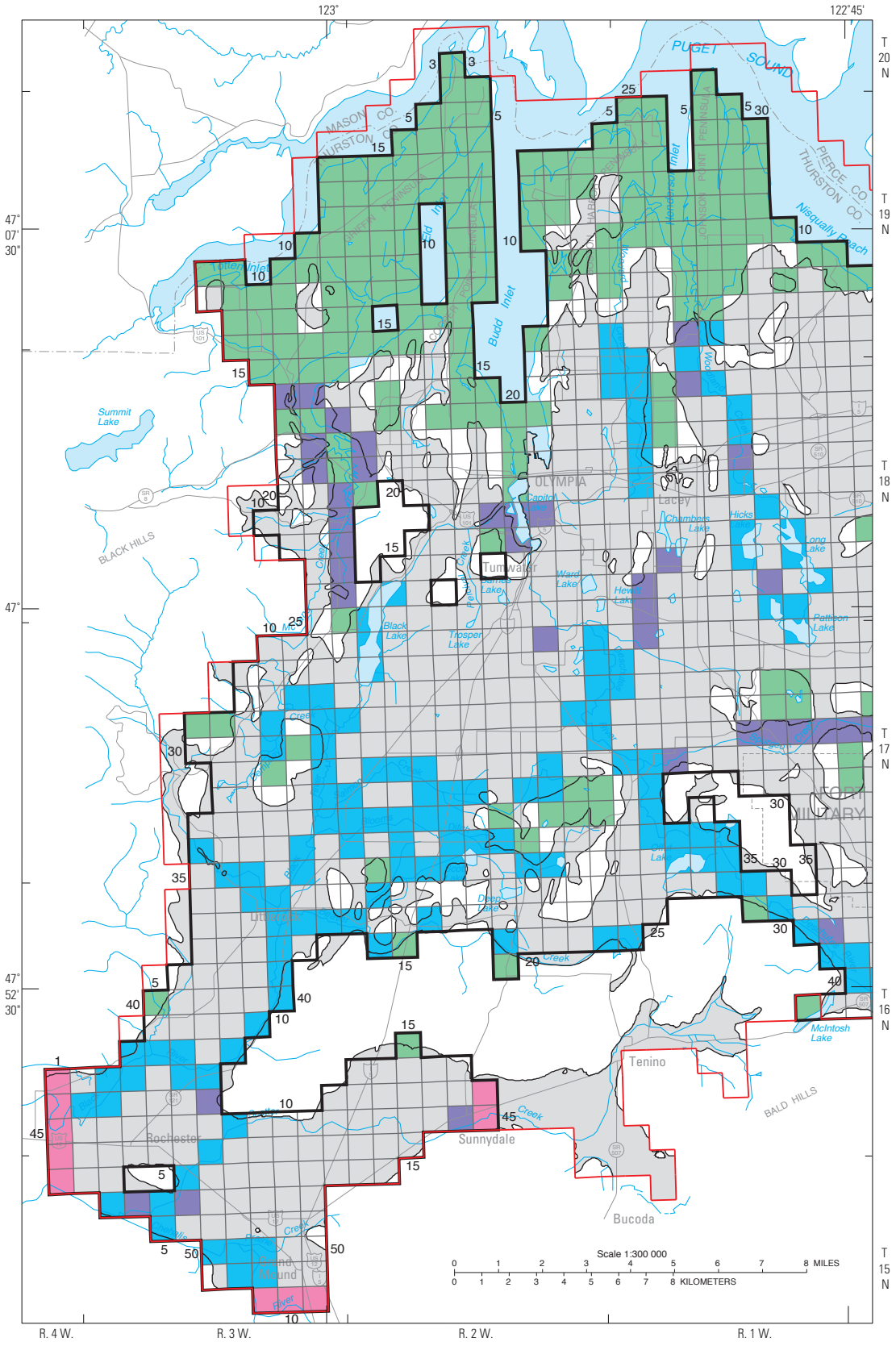


Figure 23a. Model grid and boundaries, and locations of specified-head, drain, and river cells for Layer 1-Qvr.

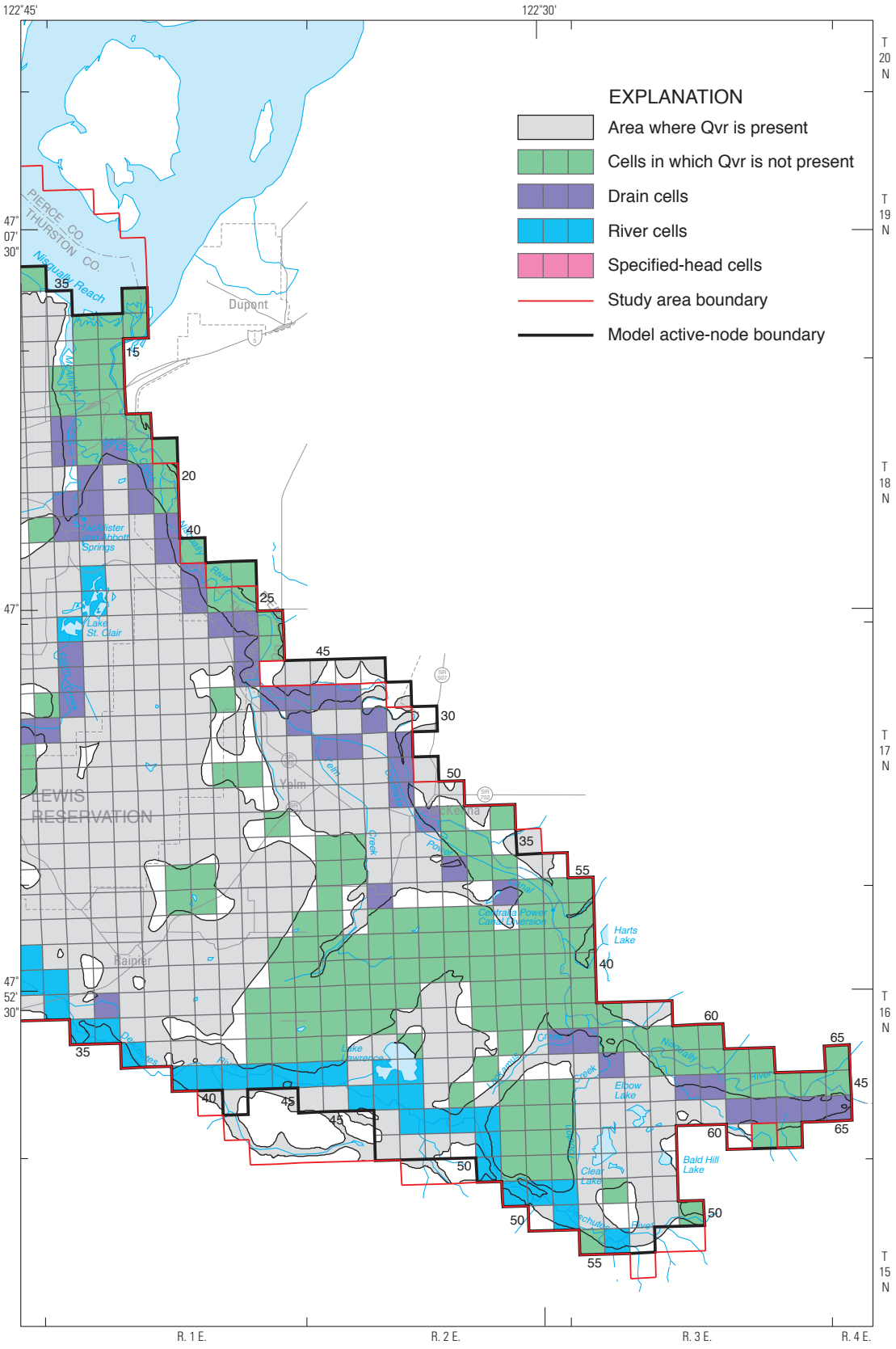


Figure 23a. continued.

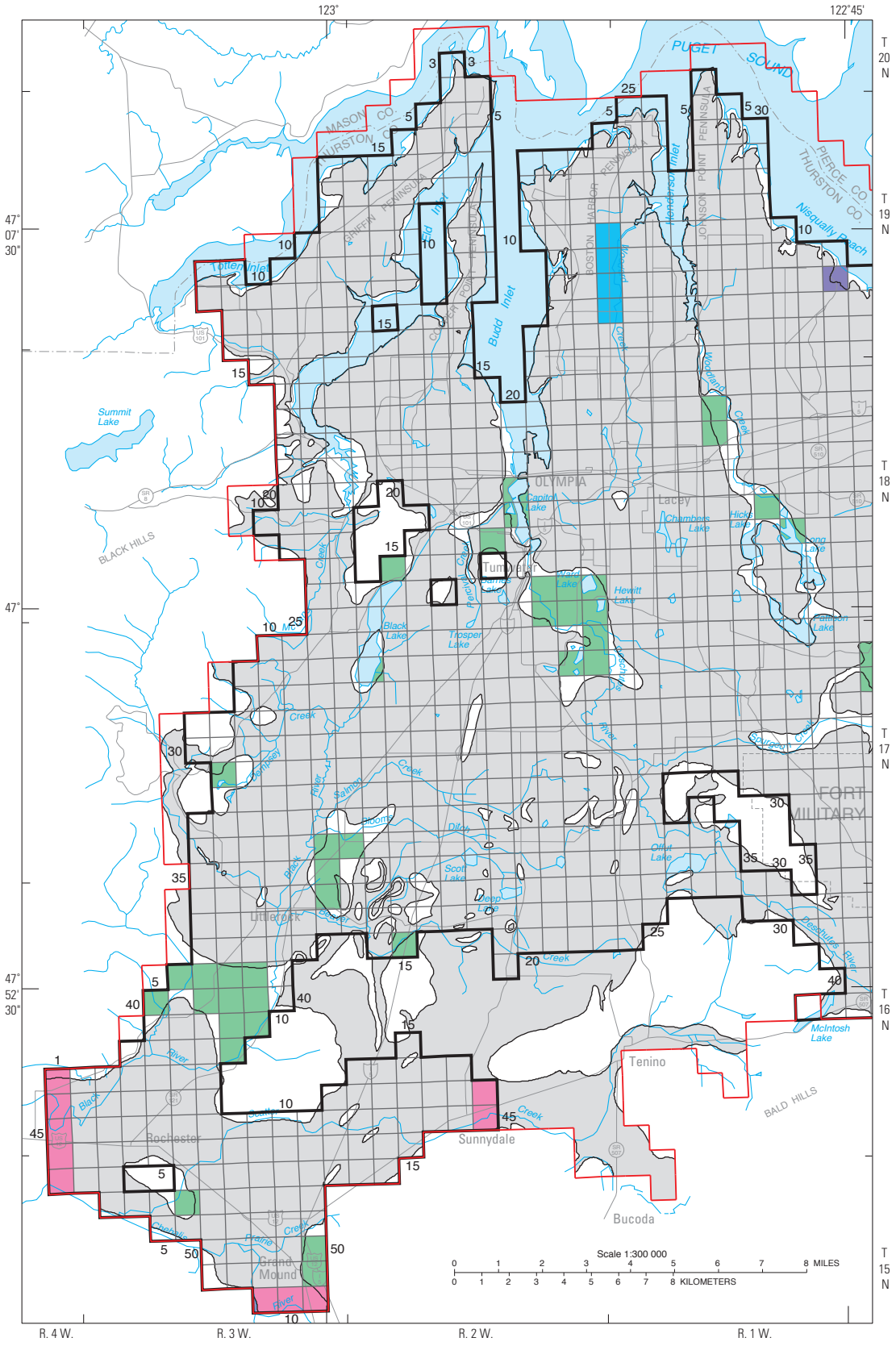


Figure 23b. Model grid and boundaries, and locations of specified-head, drain, and river cells for Layer 2-Qvt.

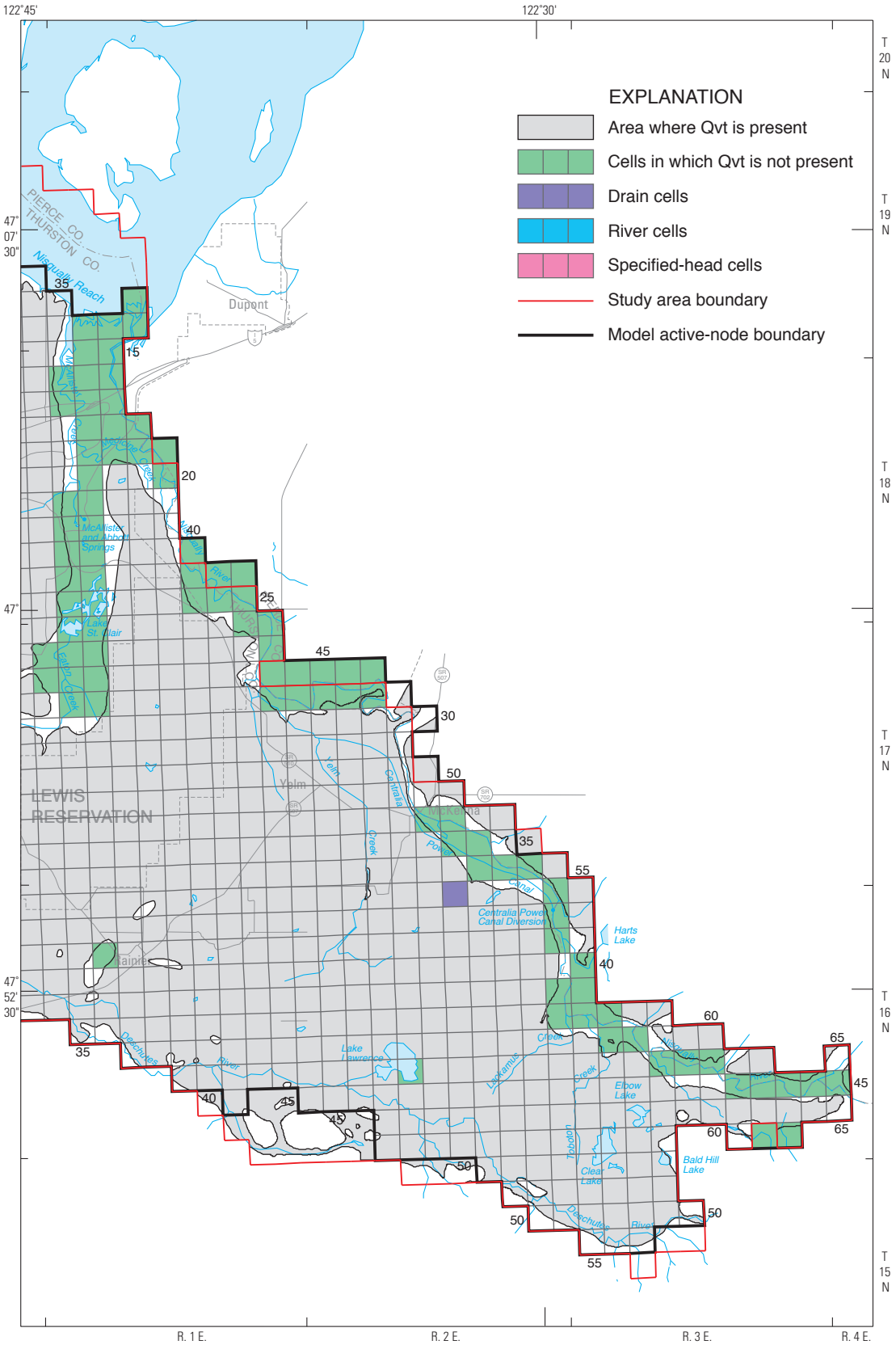


Figure 23b. continued.

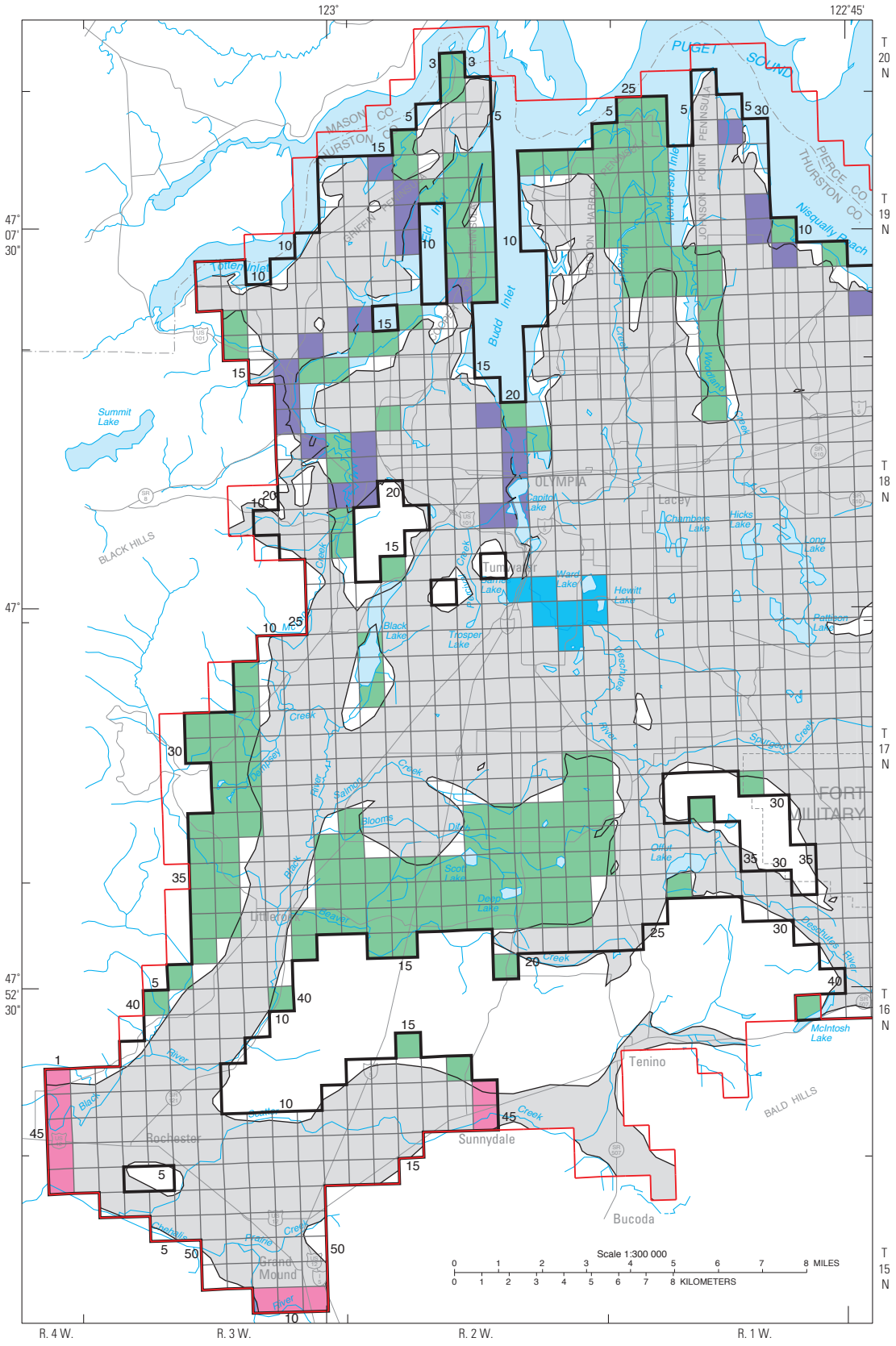


Figure 23c. Model grid and boundaries, and locations of specified-head, drain, and river cells for Layer 3-Qva.

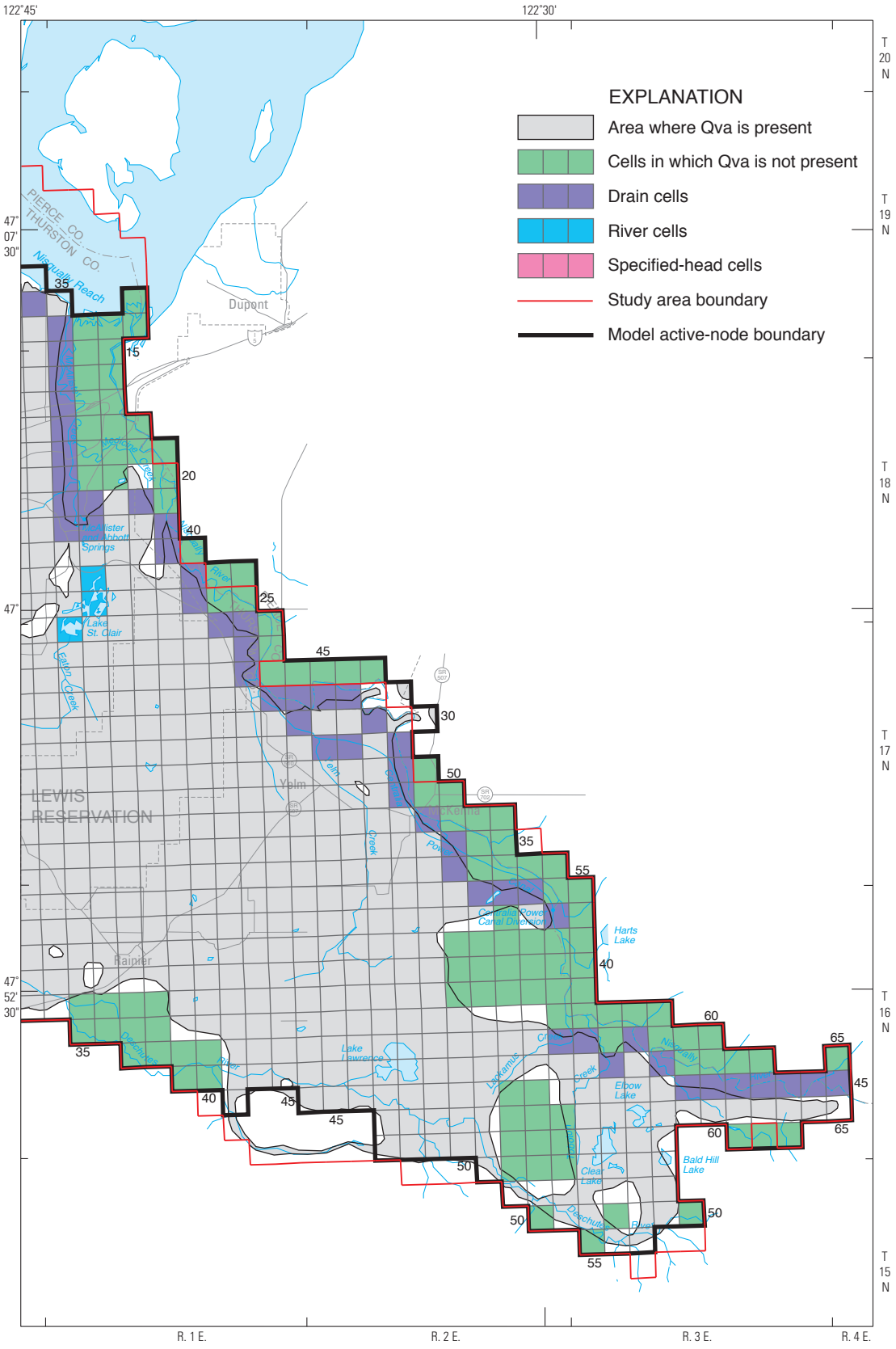


Figure 23c. continued.

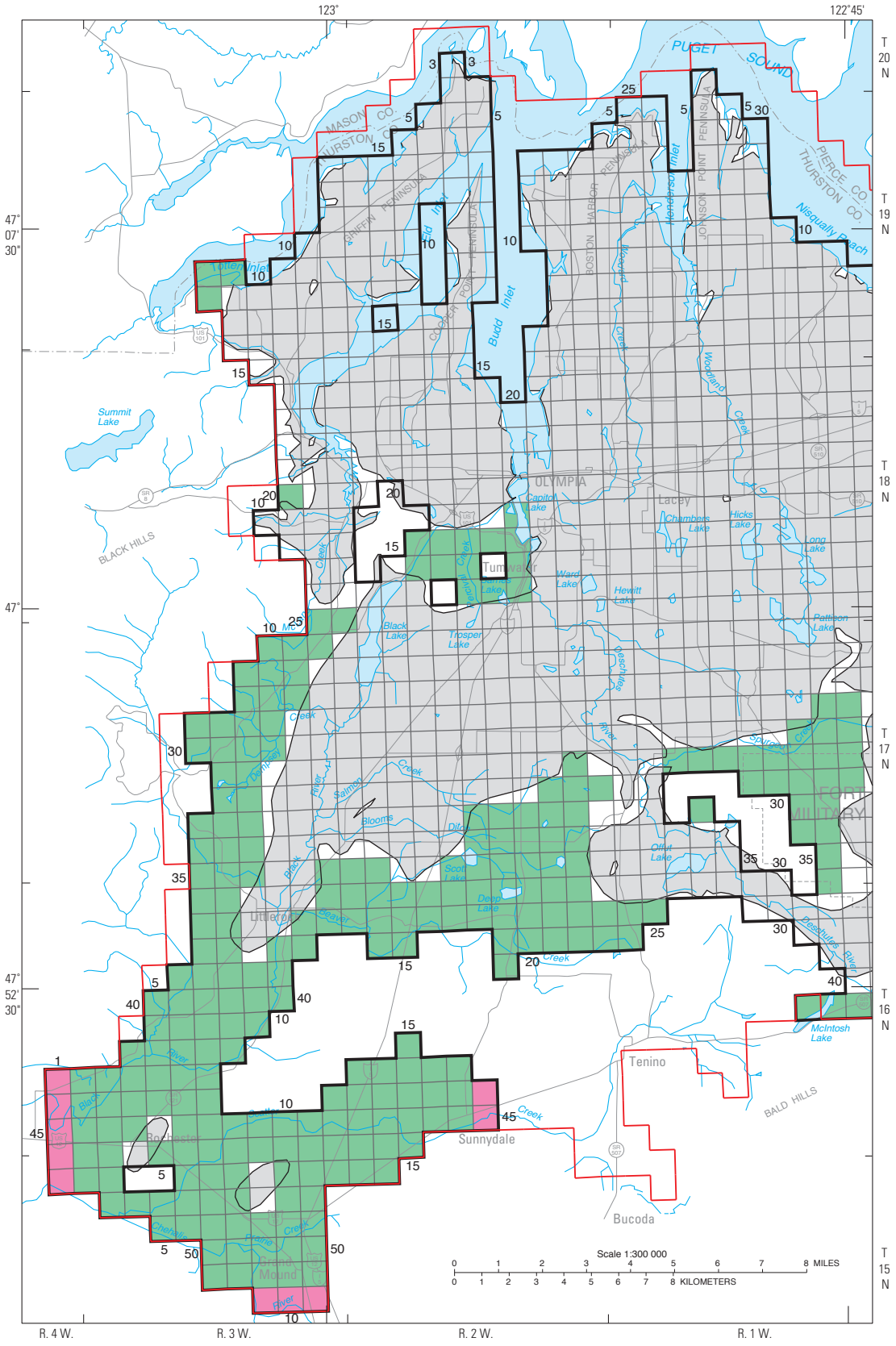


Figure 23d. Model grid and boundaries, and locations of specified-head, drain, and river cells for Layer 4-Qf.

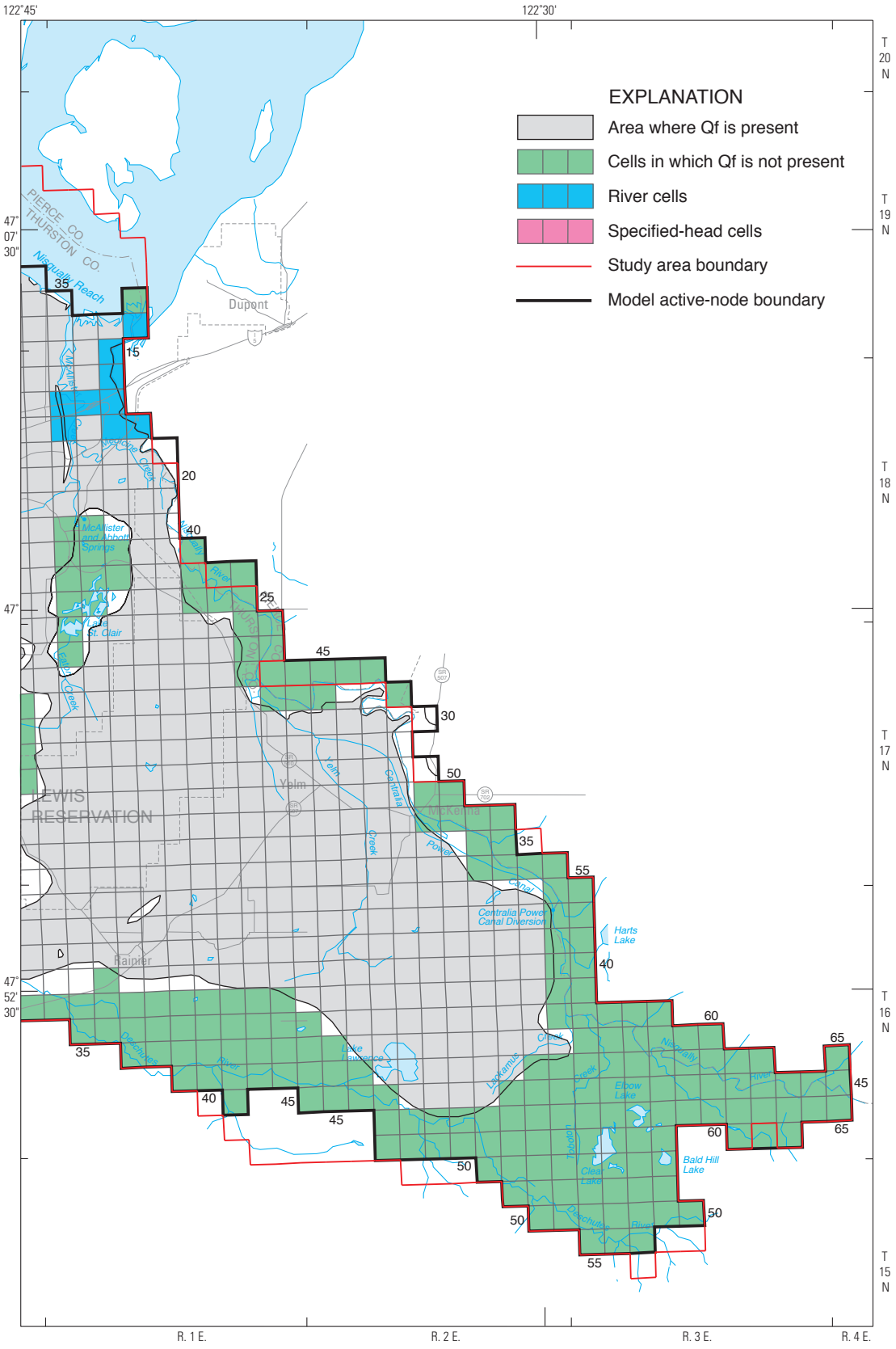


Figure 23d. continued.

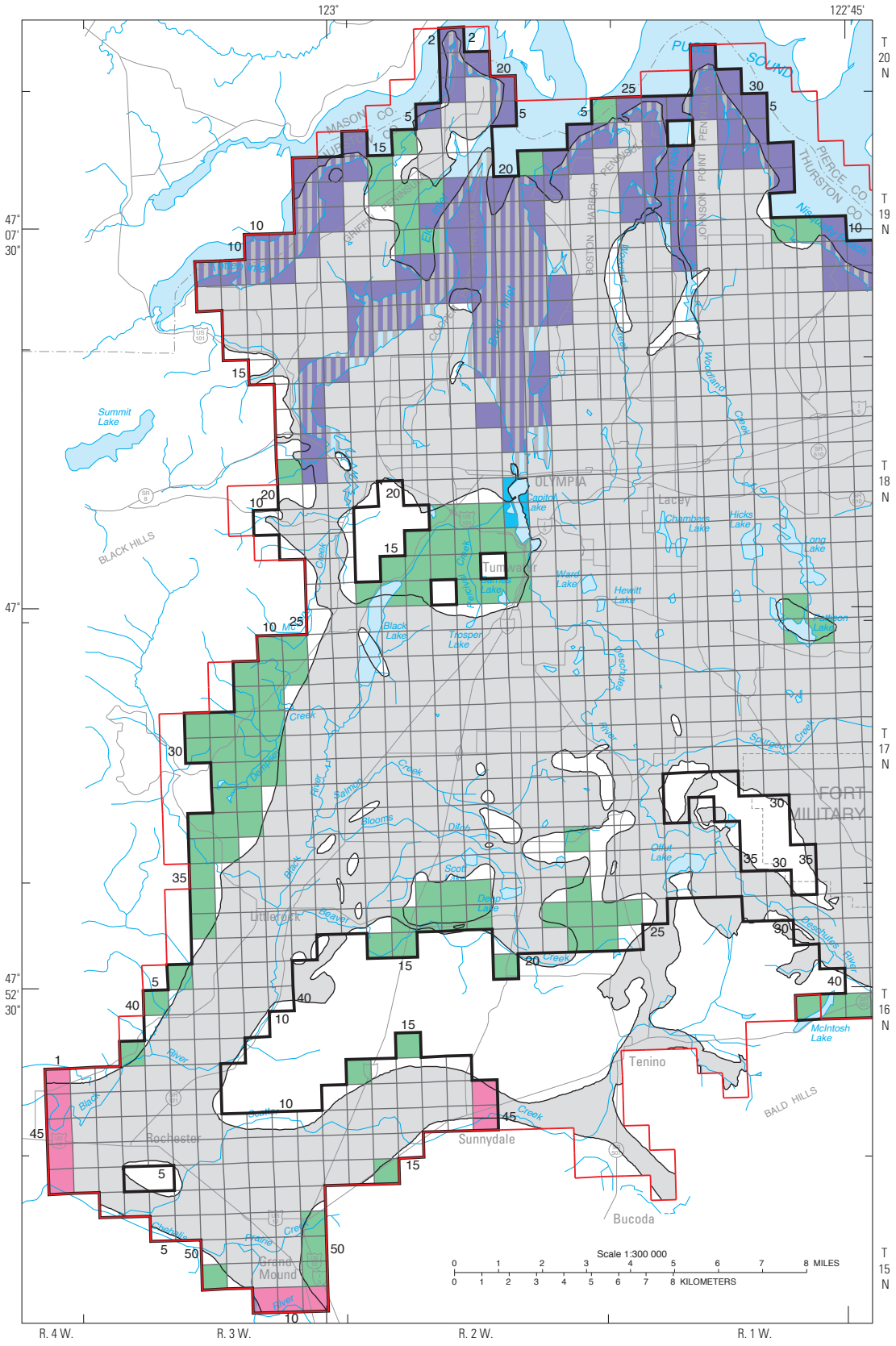


Figure 23e. Model grid and boundaries, and locations of specified-head, drain, and river cells for Layer 5-Qc.

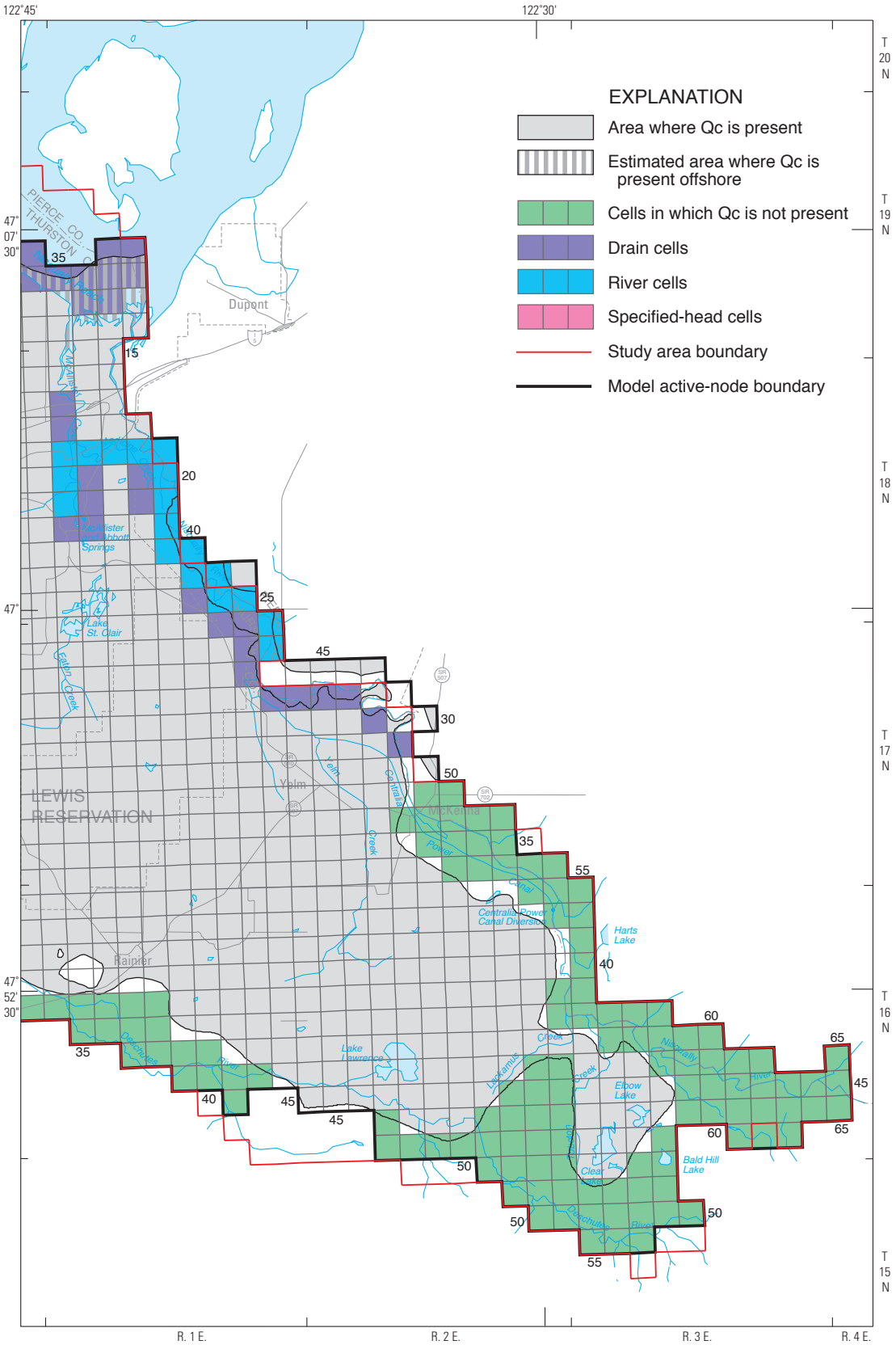


Figure 23e. continued.

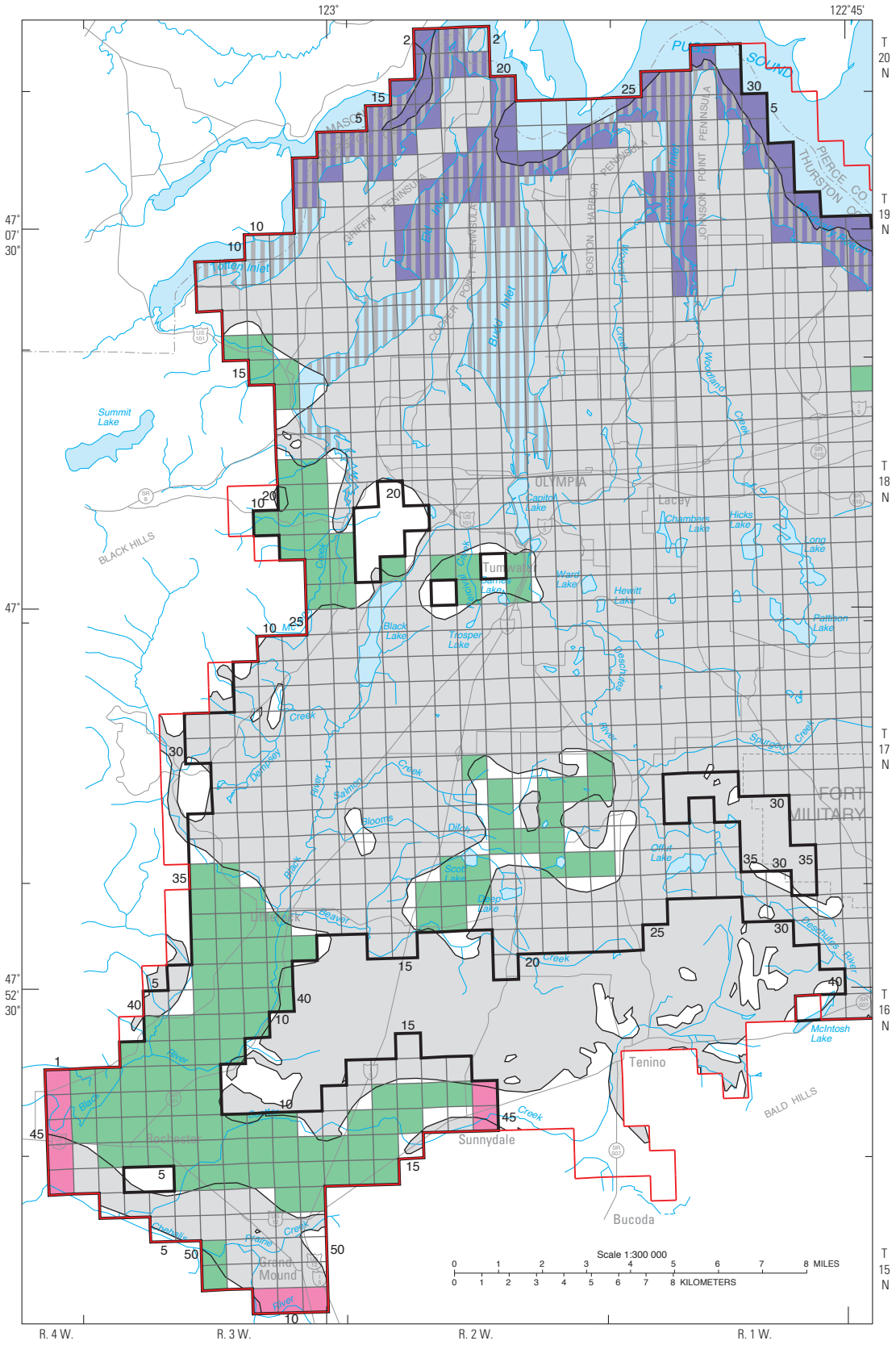


Figure 23f. Model grid and boundaries, and locations of specified-head, drain, and river cells for Layer 6-TQu upper confining bed.

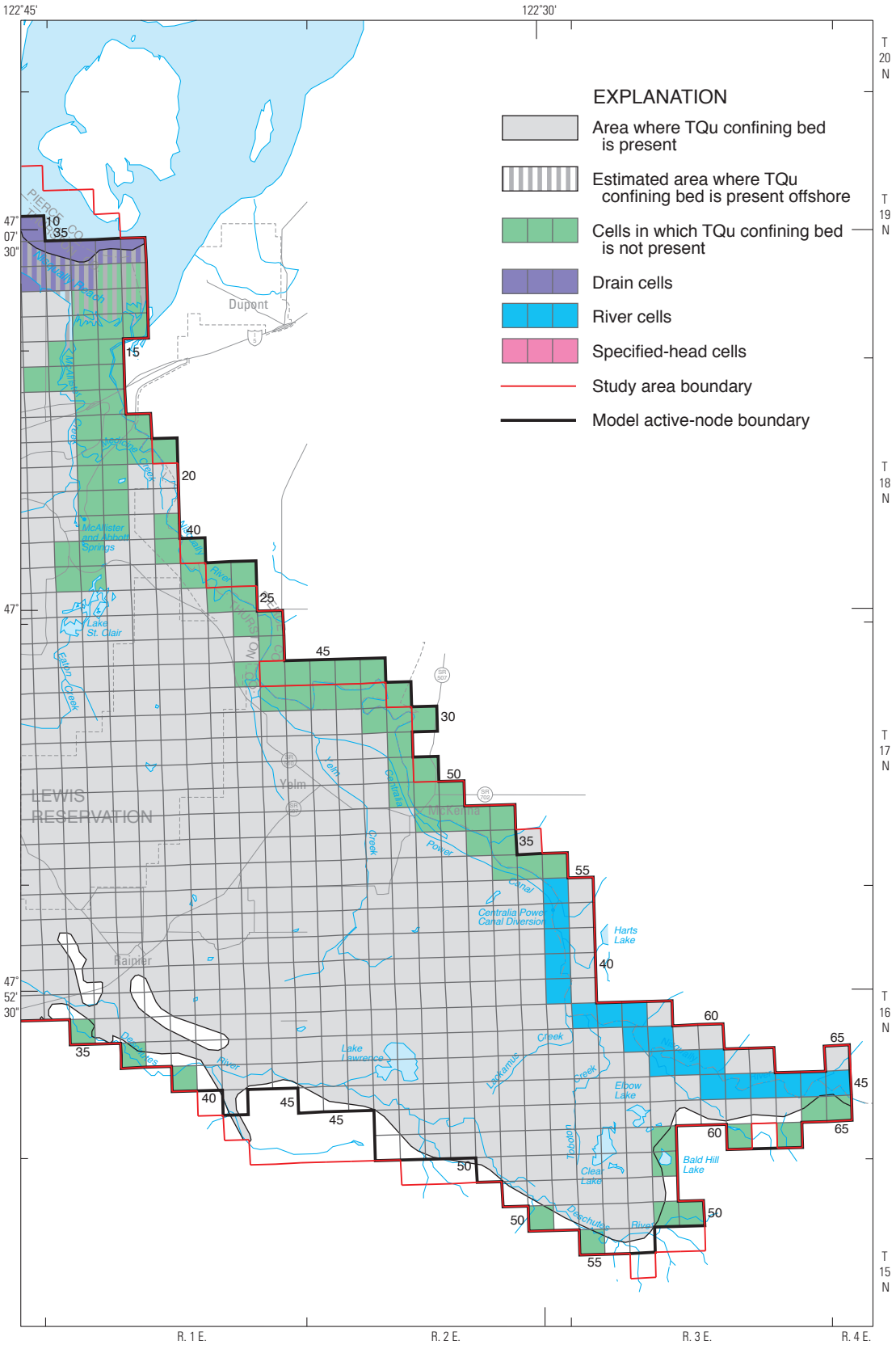


Figure 23f. continued.

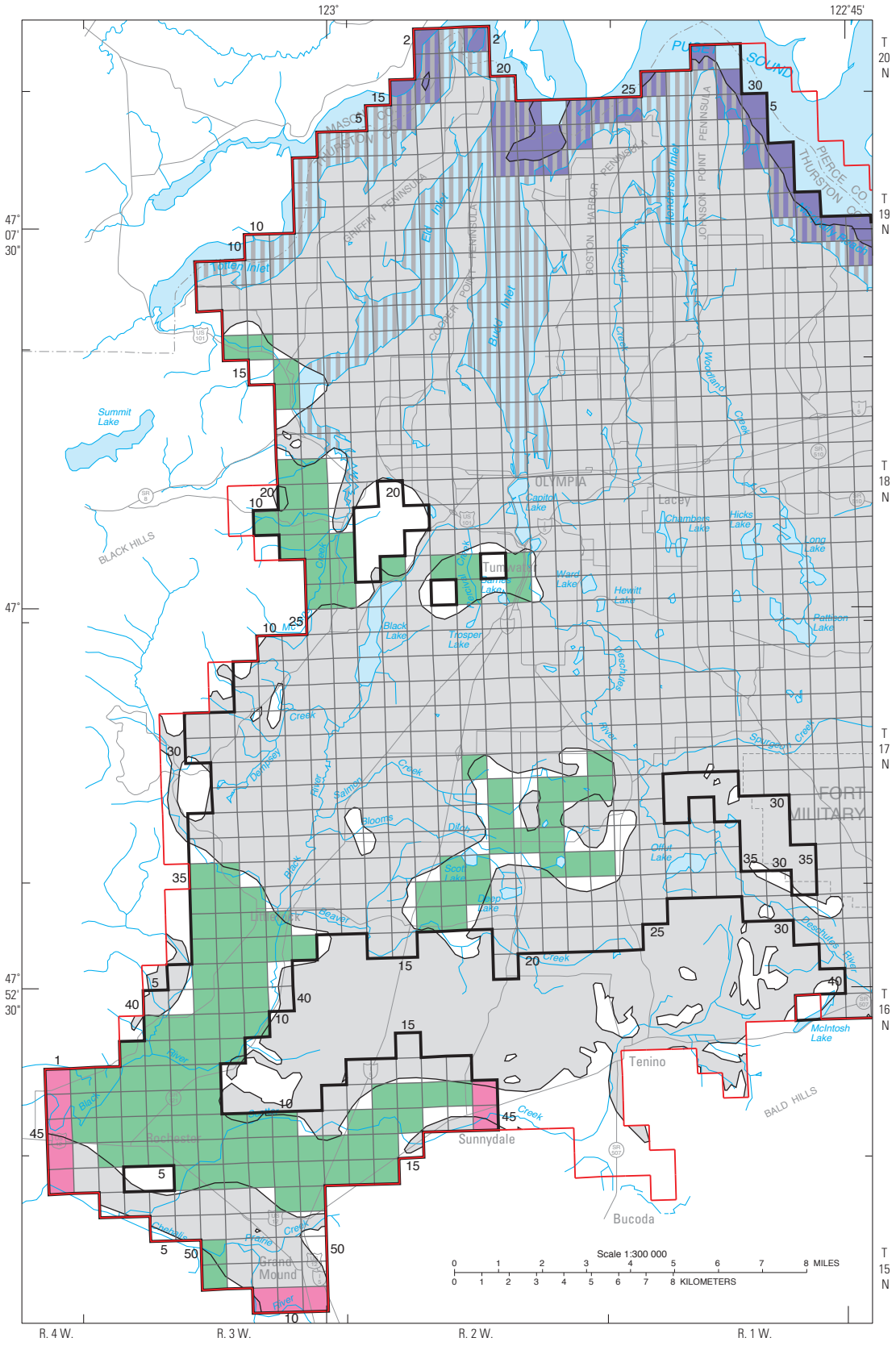


Figure 23g. Model grid and boundaries, and locations of specified-head, drain, and river cells for Layer 7-TQu upper aquifer.

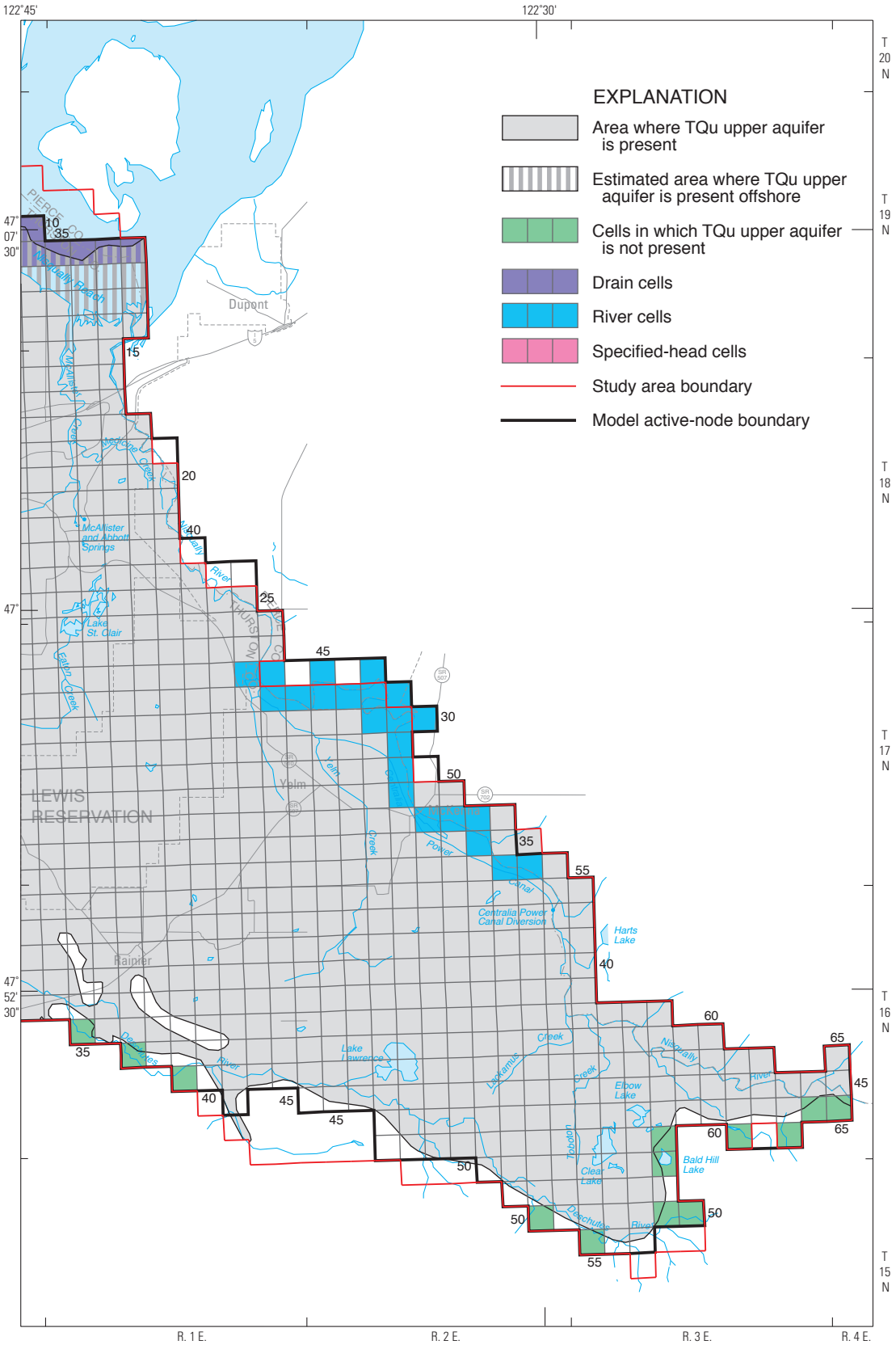


Figure 23g. continued.

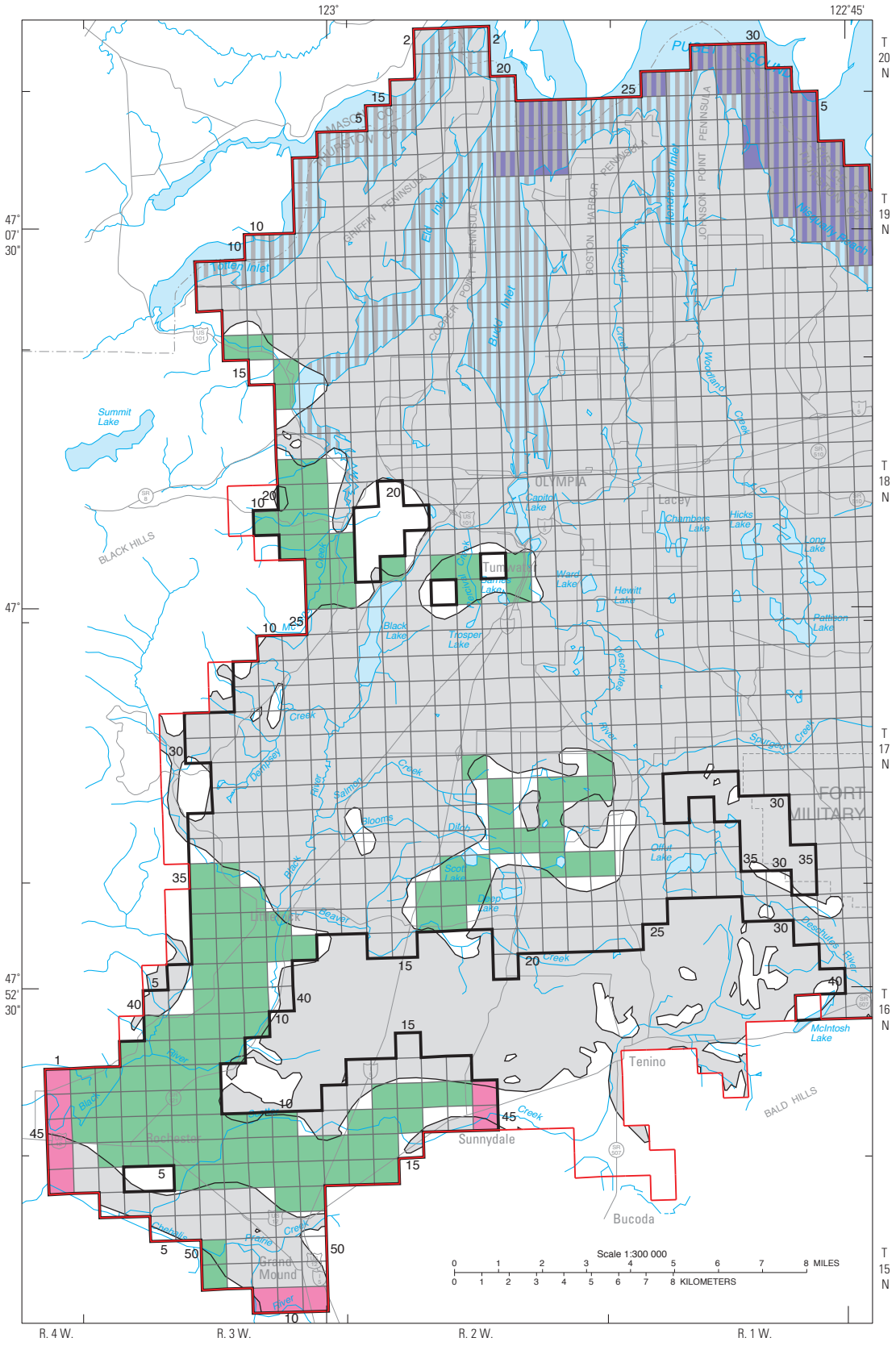


Figure 23h. Model grid and boundaries, and locations of specified-head, drain, and river cells for Layer 8-TQu below upper aquifer.

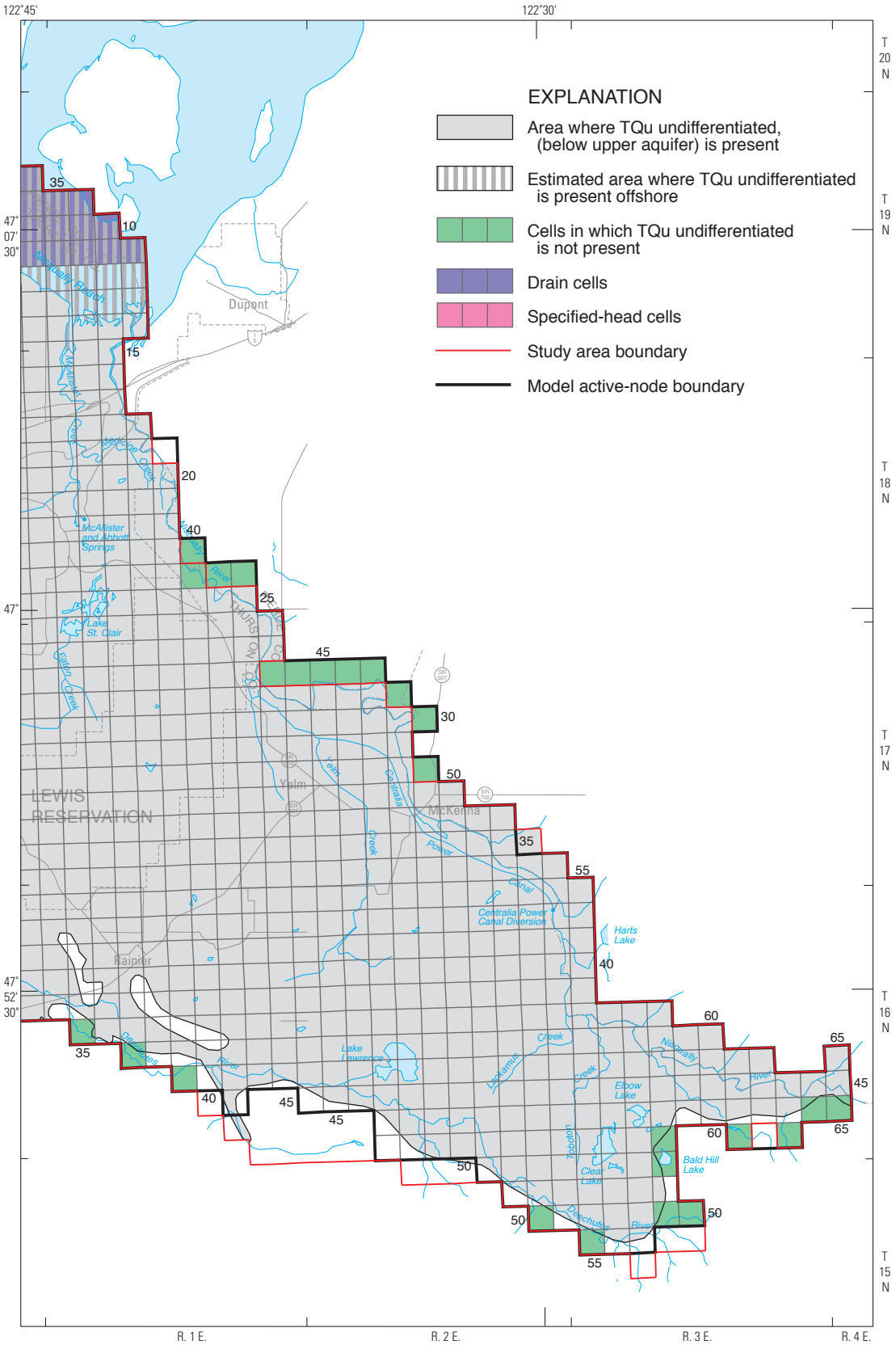


Figure 23h. continued.

Where the Chehalis River valley enters (columns 9 to 11, row 52) and exits the southwest corner of the model area (column 1, rows 43 to 47), ground-water conditions are not well known. Based on water-level maps by Sinclair and Hirschey (1992) and Schlax (1947), ground water is probably exiting to the west along the downstream extent of the Chehalis River valley and may be entering or exiting along the upstream extent (water-table contours drawn by Schlax are perpendicular to the upstream boundary). A specified-head boundary was used where the Chehalis River valley enters and exits the model and where Scatter Creek enters, to allow for ground-water flow into or out of the model. Specified-head locations are shown on figures 23 a-h and listed in table C1of Appendix C.

Streams and lakes may act as recharge or discharge areas for the ground-water-flow system. In the model they were simulated as head-dependent flux boundaries (river cells). Given the regional nature of the model, there is uncertainty regarding what size stream or lake could (or should) be simulated by the model. Initially, all large streams and large lakes, as well as selected smaller streams and lakes, were simulated. During calibration, some smaller streams and lakes were added as needed to attain a good calibration.

Along the river valleys and hillsides some layers (generally model layers 1 to 4) are cut by the sloping land surface, resulting in springs and seepage faces. These were represented as head-dependent flux boundaries (drain cells).

Model Hydraulic Conductivity

Horizontal hydraulic conductivities used for the aquifers in the model were those determined from specific-capacity data (see section on Hydraulic Conductivity). For aquifers Qva and Qc, in which zones of different median conductivity values were identified (figs. 14 and 15), these zones were input to the model. The boundaries of the zones shown in the figures reflect some changes made during model calibration. For aquifer Qvr, the median value of 150 ft/day (table 2) was used. The upper aquifer in TQu (layer 7) was assigned the same value. Where the saturated thickness of Qvr was known to be much less than the total thickness as represented by the model, the conductivity was reduced accordingly in order to produce transmissivity values that more correctly represented the unit. During calibration, a high-conductivity zone was added to Qvr (see section on Model Calibration).

The confining beds were assumed to have horizontal conductivities of 1 ft/day. The lower part of TQu (layer 8) represents a composite of aquifers and confining beds and was assigned an intermediate value of 74 ft/day.

Vertical hydraulic conductivities were initially estimated as ratios of the horizontal values. Aquifer ratios were estimated to be 1:10 and confining bed ratios were estimated to be 1:100. During calibration, the confining bed ratios were changed to 1:500.

Drain Conductances and Altitudes

In the model, a drain cell is used to simulate water leaving the ground-water system at specific points, like springs, or over large areas, like seepage faces. Locations of the 462 drain cells in the model are shown on figures 23a-h and their altitudes and conductances are listed in Appendix C (table C2). The simulated quantity of water leaving the ground-water system at a drain cell is equal to the product of a user-specified conductance and the difference between the simulated water level in the cell and a user-specified reference altitude (McDonald and Harbaugh, 1988, p. 9-3, eq. 69).

The conductance of a drain cell is a function of the horizontal and(or) vertical hydraulic conductivity of the geologic material represented by the cell and the cell geometry. For springs and seepage faces, hydraulic conductivities were assumed to be equal to the horizontal hydraulic conductivity of the unit represented by the drain cell. Surface areas were assumed for seepage faces and "minor" springs (less than 1 ft^3/s) to be 200 ft^2, and for "major" springs (1 ft^3/s or more) to be 2,000 ft^2. Actual land-surface altitudes were assigned to springs, and seepage face altitudes were estimated to be 5 feet above the bottom of the unit. Because flow from the ground-water system to Puget Sound can be horizontal or vertical (depending on the geometry of the seafloor), conductances for submarine seeps (offshore drain cells) were calculated in two ways: vertical hydraulic conductivity times surface area of the unit divided by one-half the unit thickness, and, horizontal hydraulic conductivity times cell width times unit thickness divided by one-half the cell length. The larger of the two values was used as the initial conductance for submarine seeps. The drain altitudes for submarine seeps were set equal to fresh-water equivalent heads at the seafloor. Freshwater equivalent heads were set equal to 0.022 times the depth of saltwater at the cell (Collias and others, 1974).

River Conductances and River Stages

Locations of the 250 river cells used in the model to simulate water moving between the ground-water system and streams and lakes are shown on figures 23a-h and their altitudes and conductances are listed in Appendix C (table C3). The simulated quantity of water moving between a stream or lake and the ground-water system is equal to the product of a user-specified conductance and the difference in water level between the stream or lake and the simulated water level in the cell (McDonald and Harbaugh, 1988, p. 6-5, eq. 63a). In the model, streams and lakes are treated similarly.

The conductance of a river cell is a function of the vertical hydraulic conductivity of the aquifer and stream or lake bed materials and the area of the stream or lake bed. Because the nature of the stream and lake beds was unknown, initial hydraulic conductivities were assumed to equal the vertical hydraulic conductivity of the unit represented by the river cell. The water levels (or stages) assigned to the streams or lakes were determined from topographic maps. Initial conductances were computed as the product of the conductivity and surface area of the stream or lake within the river cell, divided by an assumed bed thickness of 2 feet. Thereafter, the conductance was treated as a lumped parameter and adjusted during calibration.

Model Recharge

Recharge from precipitation for entering into the model was determined by placing the model grid over the recharge map (fig. 17); in each of the grid cells, the predominant recharge rate (that is, the rate with the largest area) was assigned to the cell. This resulted in overestimation or underestimation of precipitation recharge in some cells. However, precipitation recharge calculated by this method (560,000 acre-ft/yr) for the model area was within 3 percent of the GIS-derived rate determined independent of the model grid. This initial estimate of precipitation recharge was reduced by 10 percent during model calibration.

Where secondary recharge occurs (see section on Recharge and Appendix B, table B2), it was added to the precipitation recharge. In most instances, secondary recharge was assigned to the model cell from which the water was withdrawn. In the case of large public-supply systems, secondary recharge was distributed on the basis of population density. Total secondary recharge to the model was 63,000 acre-ft/yr.

Ground-Water Withdrawals

Ground-water withdrawals (see section on Discharge and Appendix B, table B3) were assigned on a well-by-well basis. The model used 619 pumping wells to represent the 1988 ground-water withdrawals. About 60 of these wells represent withdrawals by that portion of the population not served by public systems. Each of these 60 wells represented the non-public domestic supply, within a quarter of a township, that is actually pumped from numerous individual domestic wells. Locations and rates of withdrawals are shown on figure 24. Total ground-water withdrawals in the model area were 62,000 acre-ft/yr. These data represent withdrawals for calendar year 1988 and are average rates for the year. They range from very accurate gaged values to values estimated from minimal information (see Appendix B, table B3 for details of calculation and estimation methods).

Model Calibration

Model calibration was accomplished using a trial-and-error process of adjusting selected input parameters with the goal of getting simulated ground-water levels and discharges to agree with observed values. After initial estimates were made of the hydraulic characteristics of geohydrologic units, of streambed and drain conductances and altitudes, and of recharge from precipitation, the process of model calibration began. The primary data used for comparisons during calibration were the water levels in wells, the flow of McAllister Springs, and ground-water discharge to the Deschutes and Nisqually Rivers. Secondary emphasis for calibration was placed on ground-water flows to or from Lakes St. Clair, Pattison, and Long, and ground-water discharges to Woodland, Eaton, Woodard, and Scatter Creeks and the Black and Chehalis Rivers. Simulated rates of water flow to other points of discharge, such as unmeasured rivers, springs, and streams, were evaluated for their reasonableness.

Acceptable ranges were established for each of the primary and secondary calibration targets. For simulated water levels to be acceptable, the distribution of water levels and the patterns of flow in units Qva and Qc had to match the general water-level distributions and flow patterns shown on figures 18 and 19.

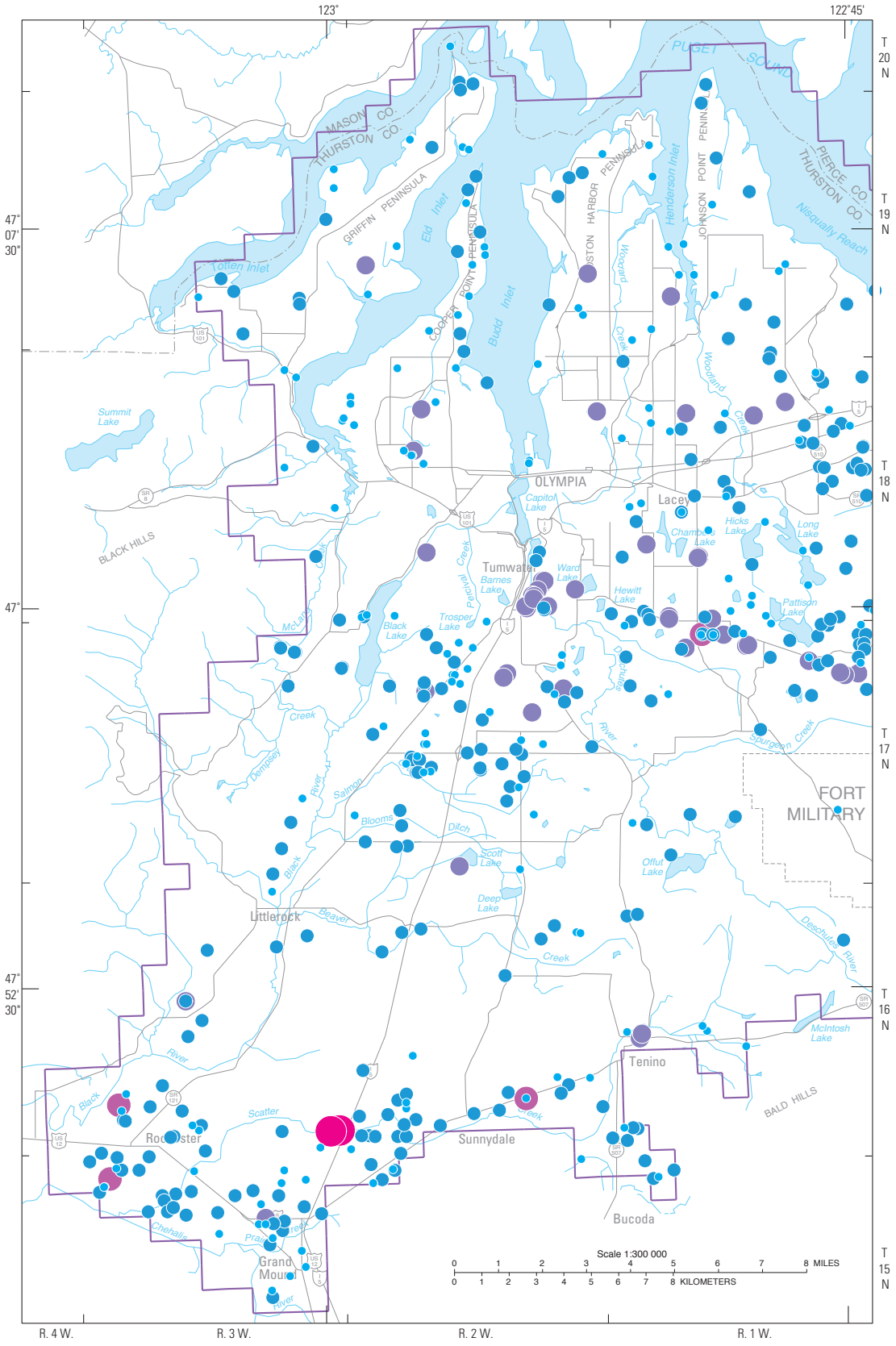


Figure 24. Locations and magnitudes of ground-water withdrawals during 1988 in the study area.

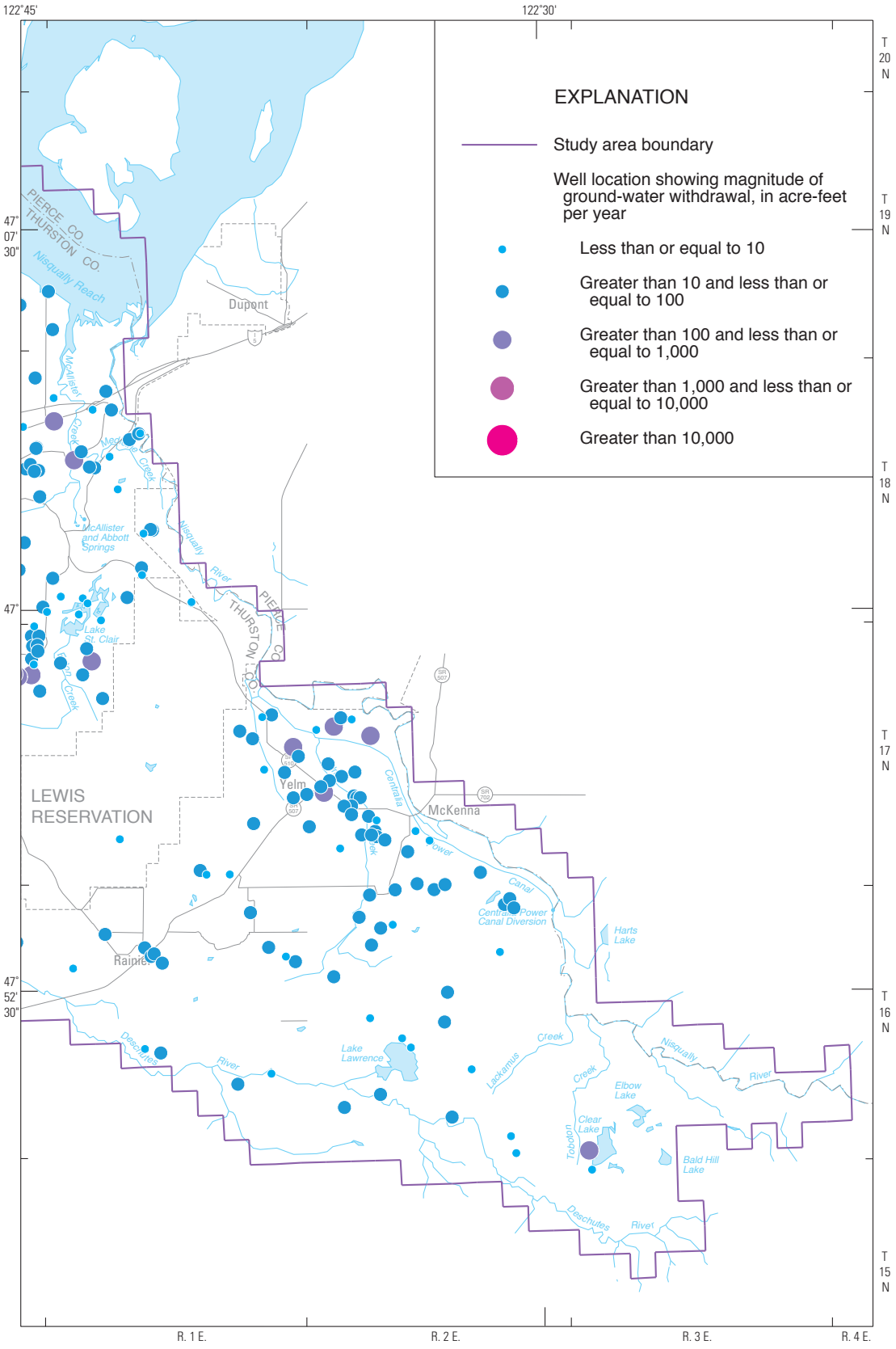


Figure 24. continued.

Also, the root-mean-square (RMS) error of the difference between simulated and measured water levels in the 308 observation wells, divided by the total difference in water levels in the ground-water system (Anderson and Woessner, 1992, p. 241), had to be less than 10 percent to be acceptable. The observation wells occur in all units, but are concentrated in unit Qva (125 wells) and unit Qc (100 wells). For discharges, a range of acceptable simulated values was established for each calibration target based on the accuracy of the measured discharge and the significance of the feature to ground-water flow in the GWMA (table 7).

Table 7. Calibration targets and acceptable ranges of simulated values

[ft^3/s, cubic feet per second]

Calibration target	Measured discharge[1] (ft^3/s)	Acceptable deviation (percent)	Acceptable range of simulated discharge (ft^3/s)	Simulated discharge (ft^3/s)
McAllister Springs[2]	+23.6	10	+21.2 to +26.0	+25.6
Deschutes River	+54	25	+40 to +68	+68
Nisqually River	+206	50	+103 to +309	+132
Lake St. Clair[3]	-4.8	30	-3.4 to -6.2	-4.3
Woodland Creek	+12	30	+8.4 to +16	+15
Woodard Creek[4]	+3.5	50	+1.8 to +5.2	+4.3
Pattison and Long Lakes[5]	-2.5 to +7.4	50	-3.8 to +11	-0.9
Eaton Creek	+3.2	40	+1.9 to +4.5	+3.4
Black River	+21 to +25	40	+13 to +35	+33
Scatter Creek	+3	50	+1.5 to +4.5	+3.5
Chehalis River	+16	50	+8 to +24	+12

[1]Discharges represent ground-water flows to (+) or from (-) the listed surface-water feature (see table 3 and Appendix B, table B2).

[2]See table 4.

[3]See Appendix B.

[4]Estimated base flow from 1988–89 hydrographs (Berris, 1995).

[5]Discharge range is combination of U.S. Geological Survey seepage study and Entranco Engineers, Inc. (1987) measurements and ground-water-flow model.

If simulated water levels or ground-water discharges in part or all of an aquifer were not within acceptable ranges, then selected input variables were altered slightly and the model simulation was repeated. The largest changes were made to the variables about which least was known; the range over which more-well-known variables were altered was less. The lesser-known and the better-known hydrologic data are listed below.

Lesser-known hydrologic data:

- Vertical hydraulic conductivity;
- Distribution of horizontal hydraulic conductivity in geohydrologic units other than Qva and Qc.
- Thickness, extent, and hydraulic character of materials in geohydrologic unit TQu (model layers 6, 7, and 8); and
- Drain and river conductances.

Better-known hydrologic data:

- Thickness and extent of geohydrologic units above unit TQu (model layers 1 to 5);
- Ground-water pumping rates;
- Distribution of horizontal hydraulic conductivity in aquifers Qva and Qc; and
- Recharge rates.

The model was constructed to simulate steady-state 1988 ground-water levels and discharges. Water levels calculated by the model were compared with water levels observed during June through August 1988. Water levels during the June through August period approximate the annual average (fig. 21). The assumption was made that there were no long-term changes in storage taking place in the ground-water system; that is, the system was in equilibrium in 1988. This assumption appears to be reasonable, based on observed long-term water levels and lake stages (fig. 21). However, the data are not sufficient to prove equilibrium conditions.

Five categories of model input were adjusted during the calibration process: model extent, hydraulic conductivities, riverbed conductances, drain conductances, and recharge. The model extent was adjusted by removing the upper Scatter Creek valley (from near Sunnydale and continuing upvalley; see fig. 23 a-h). This area is a narrow valley surrounded by high-elevation bedrock that proved unsuitable for representation by a coarse-grid regional model. The area is of no significance to the simulation of conditions in the GWMA, which is the focus of this study.

The horizontal hydraulic conductivity zones in units Qva and Qc were adjusted during calibration, but only within reasonable limits imposed by the conceptual model of the geohydrologic units. All zone values were calculated as the median of all values within each zone. A high-conductivity zone was added to unit Qvr in the vicinity of McAllister Springs. This zone was drawn to match the areal extent of the high- conductivity zone (640 ft/day) in unit Qc, and was assigned a value (500 ft/d) equal to the average value of the Qva and Qc zones in the vicinity of McAllister Springs. The conceptual model assumes a high conductivity in unit Qvr in the vicinity of McAllister Springs, but the data are insufficient to delineate zones in the unit with any degree of certainty.

The vertical hydraulic conductivity of the confining beds (units Qvt, Qf, and TQu [layer 6]) were lowered during calibration from an initial estimated value of 0.01 to 0.002 ft/d. This final value fits well within the range observed by Vaccaro and others (1998) for similar deposits: 0.0001 to 0.01 ft/d.

River-cell conductances were adjusted to produce simulated discharges to or from the ground-water system that were within acceptable limits (table 7):

River-cell conductances decreased by less than or equal to one order of magnitude:

- Black River
- Salmon Creek
- Blooms Ditch
- Beaver Creek
- Hewitt Lake
- Scott Lake
- Nisqually River (only those nodes in unit Qf)

River-cell conductances decreased by more than one but less than two orders of magnitude:

- Woodard Creek
- Scatter Creek
- Woodland Creek
- Deschutes River
- Ward Lake

River-cell conductances decreased by more than two but less than three orders of magnitude:

- Pattison Lake
- Long Lake
- Hicks Lake

River-cell conductances increased by one order of magnitude:

- Medicine Creek
- McAllister Creek

River-cell conductance increased by more than one to less than two orders of magnitude

- Lake St. Clair, at northern end (starting values were from core samples, which may only represent lake bottom conditions, while much of the flow may be lateral flow along the edges of this very deep kettle.

Drain-cell conductances were adjusted to produce simulated discharges from the ground-water system that were within acceptable limits (table 7):

Drain-cell conductances unchanged during calibration:

- Submarine seeps

Drain-cell conductances decreased by less than one order of magnitude:

- Eaton Creek
- Abbott Springs
- unnamed springs and seeps near McAllister and Abbott Springs

Drain-cell conductances decreased by one order of magnitude:

- All drains not listed above or below

Drain-cell conductances decreased by more than one and less than two orders of magnitude:

- Woodland Creek springs (Beatty and St. Martins)
- McAllister Springs

Eaton Creek was represented with drain cells rather than river cells because all of the creek flow included in the calibration target is assumed to be ground-water discharge. Precipitation recharge was decreased by 10 percent as the final calibration adjustment. This adjustment resulted in the best combination of simulated ground-water discharges and water levels.

A comparison of the final calibrated model discharges to the calibration targets is shown in table 7. Values within the established acceptable ranges were attained for all calibration targets.

Simulated water levels met the calibration target of less than 10 percent (RMS error divided by total difference in water levels in the ground-water system) with a value of 7.0 percent. Each observed water level was compared to the simulated water level at the center of the cell containing the observation well. A significantly lower percentage of error would be calculated if the cell-centered simulated water levels were interpolated to each observation well location, particularly in areas with steep gradient. A comparison of simulated and observed water levels is shown in the graph on figure 25.

Deciding if the patterns of simulated water levels matched the actual patterns within units Qva and Qc proved to be difficult (figs. 26 and 27). The difficulty resulted both from limitations of the model and from uncertainties in the observed patterns inferred from the existing data. In a number of locations, the observed water levels indicate the presence of very steep gradients (exceeding 125 feet over the length of one model cell). Because the model only produces one simulated water level for each cell, the detail in the areas with steep gradient is not observable in the simulation. This is most apparent in the peninsulas where the observed water levels indicate local mounds, but the model only simulates a few water levels (the peninsulas are only a few cells wide) across each peninsula.

There are significant uncertainties in the patterns of observed water-level distribution (see section on Ground-Water Flow). Some of the differences between the simulated and observed patterns of flow may reflect inaccuracies in the interpretation of the observed water levels used to generate the contours. In particular, the apparent ground-water divide in unit Qc that runs north from near Spurgeon Creek, between Olympia and Lacey, and onto the Boston Harbor Peninsula, may not be an accurate representation of the ground-water system. The same applies to the apparent ground-water mound in unit Qva east of Lacey.

Sensitivity Analysis

A sensitivity analysis is a procedure to determine how sensitive the model-simulated variables are to changes in input variables, such as hydraulic conductivity, recharge, and river and drain conductances. As is usually the case with numerical models, not all the variables of the initial model were known completely. Because some uncertainty is found in each input variable, there is some uncertainty in model results. This uncertainty is reflected in simulated hydraulic heads and inflow and outflow rates that differ somewhat from measured heads and flows. A sensitivity analysis determines which input variables exert the most control over the model simulations and, therefore, may generate the largest differences in simulated hydraulic heads and flows.

For the analysis, selected input variables of the ground-water model were altered from the calibrated values. The amount of the alteration was determined by estimating the likely range of realistic values for each variable. To simplify the analysis, variables for an entire hydrogeologic category, such as layer hydraulic conductivity, were altered together. Those variables associated with the most change in the model solution were identified as the most sensitive.

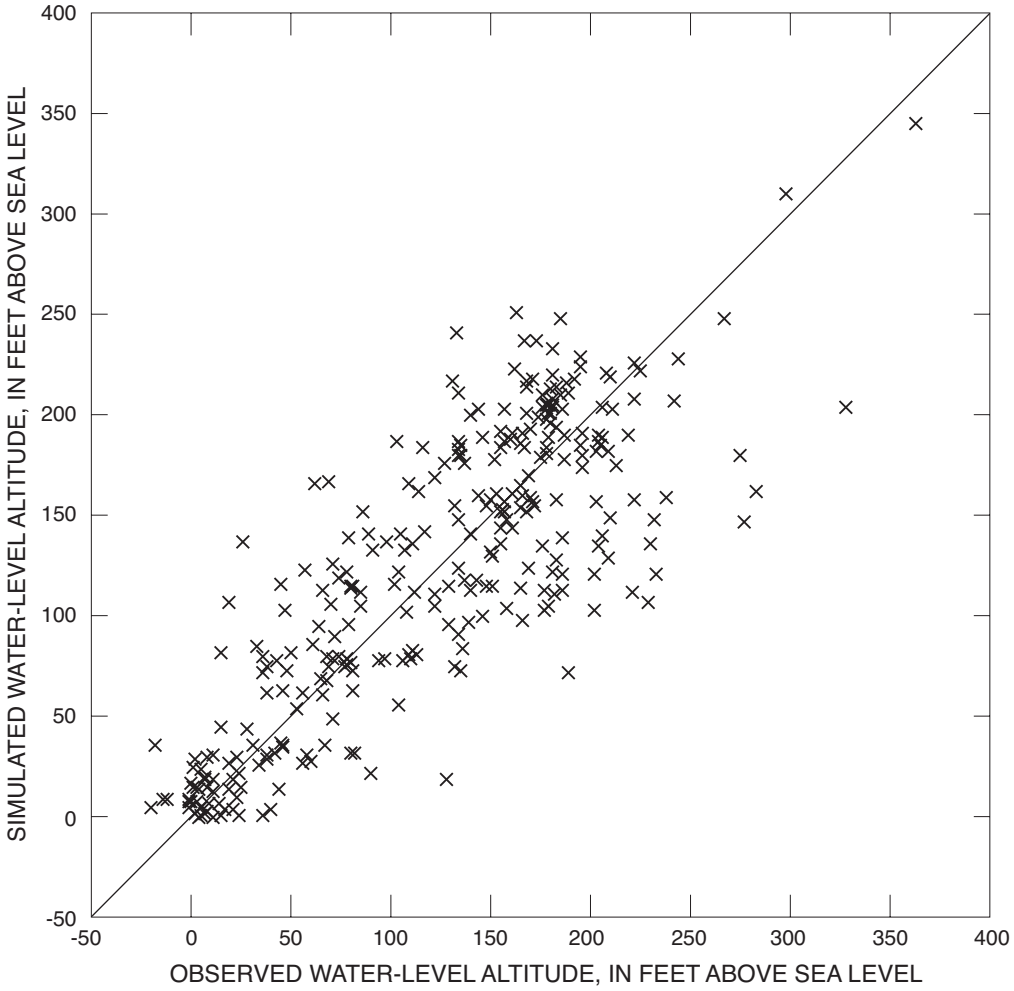


Figure 25. Simulated versus observed water-level altitudes for calibrated model.

Although useful, this method of testing sensitivity is subject to a potentially significant flaw. Because each variable in the model is tested separately, the additive effects of changes in more than one variable are not considered. For example, the simultaneous overestimation of both recharge and transmissivity in the model would tend to be self-correcting. However, overestimating recharge and underestimating transmissivity would produce considerably different results. If neither recharge nor transmissivity were by itself a sensitive part of the model, the conclusions from a routine sensitivity analysis would be that additional refinement of estimates for these items is unnecessary. Nevertheless, the additive effects of errors in recharge and pumpage might produce significantly erroneous results in some simulations of the ground-water system. An important way to prevent this type of miscalculation is through a more subjective analysis of sensitivity observed during calibration of the ground-water model. For this reason, observations from the calibration process are also included in the following discussion of the sensitivity of each variable (discussion after Danskin, 1988).

There is uncertainty associated with the areal extent of layers and their thicknesses and hydraulic conductivities. The sensitivity of the model to layer extent is best evaluated by altering the extent, recalibrating the model, and observing the differences. However, given the current understanding of the geohydrologic framework, there is no logical way to systematically adjust layer extents or thicknesses that would result in a meaningful test of sensitivity.

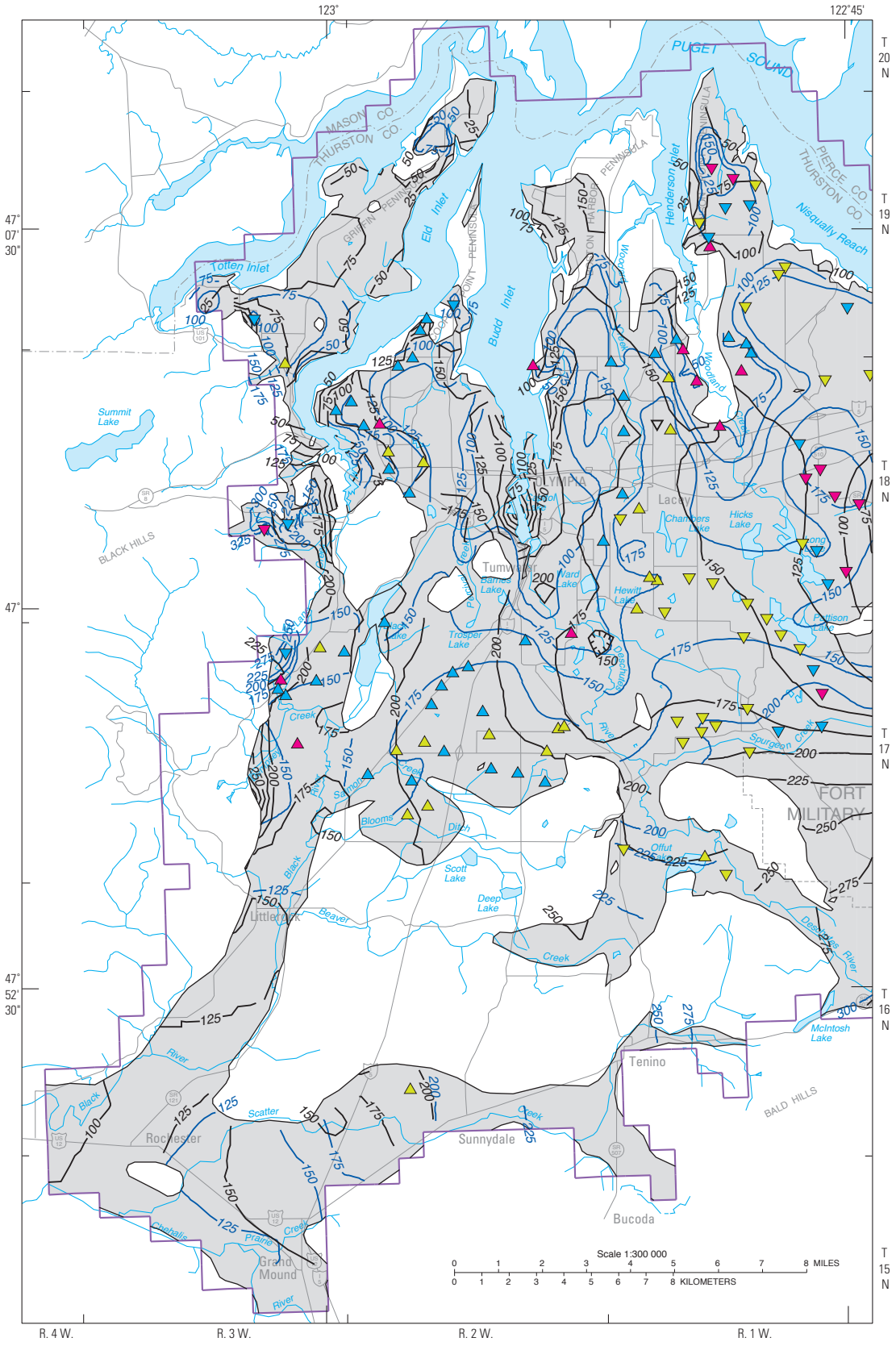


Figure 26. Simulated and observed water levels in unit Qva for calibrated model (1988 conditions).

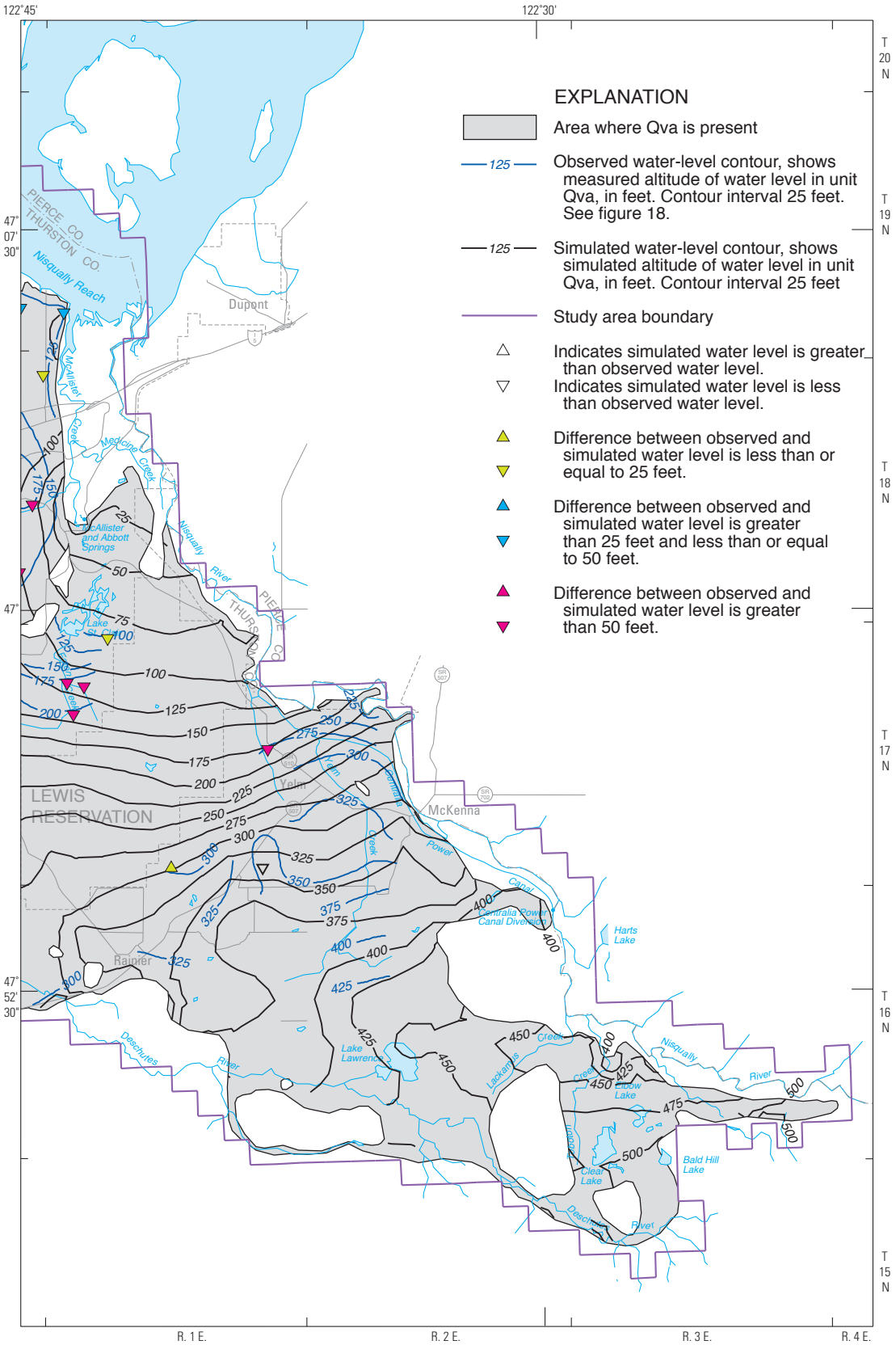


Figure 26. continued.

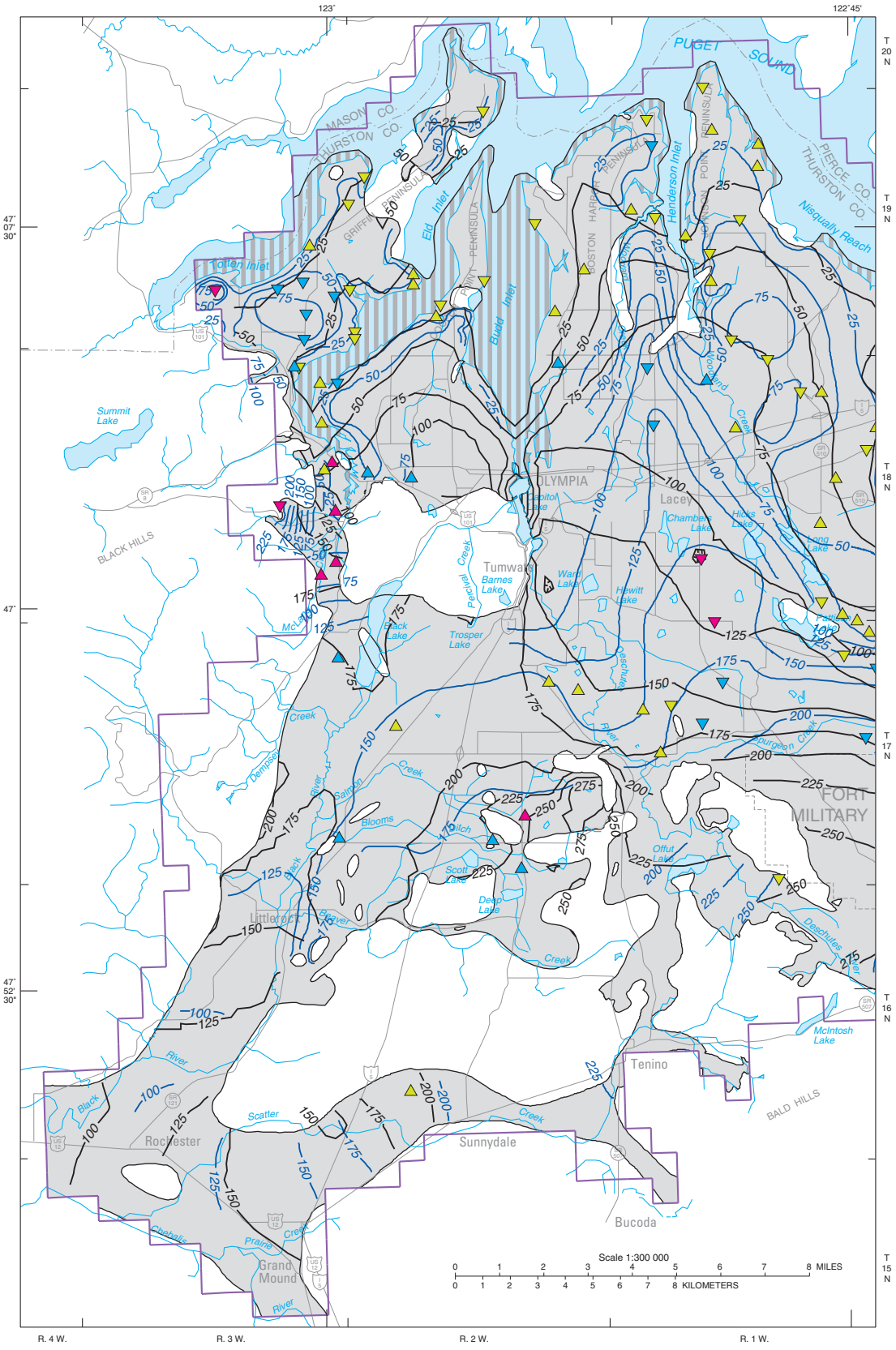


Figure 27. Simulated and observed water levels in unit Qc for calibrated model (1988 conditions).

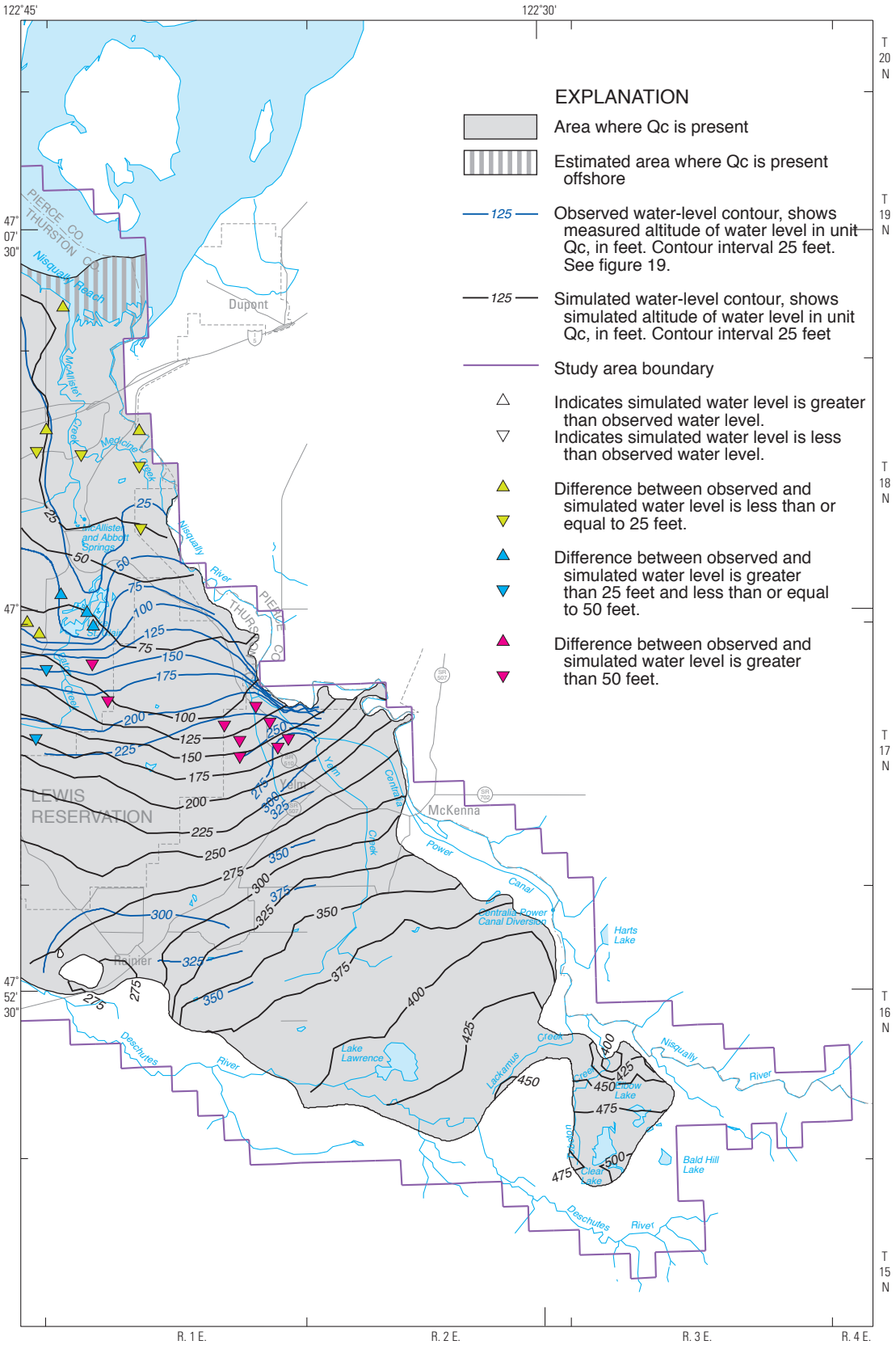


Figure 27. continued.

Therefore, this was not a part of this investigation and sensitivity analysis regarding the geohydrologic framework was limited to varying the values of transmissivity. This was accomplished by changing horizontal hydraulic conductivities for all aquifer layers while maintaining constant layer thicknesses and extents. The results of the analysis indicate that changes in aquifer transmissivity values have a considerable effect on water levels in the principal aquifers and on the distribution of flows (table 8). Simulated water levels were very sensitive to aquifer transmissivity changes, resulting in mean errors (table 8) of -15.7 and +24.0 feet. The mean error for the calibrated model was +1.2 feet. Doubling or halving aquifer transmissivity values resulted in simulated flows at McAllister Springs and ground-water discharges to the Deschutes River and offshore that ranged from 19 to 39 percent more or less than the calibrated flows.

Table 8. Results of sensitivity analysis of the model

Model-input parameter	Difference between simulated and observed water levels[1]		Changes in simulated flows (acre-feet per year)			
	Mean error (feet)	RMSe/ domain (percent)	Off-shore drains	McAllister Springs	Deschutes River[2]	Nisqually River[2]
Aquifer transmissivity						
Increase by factor of 2	-15.7	7.4	+34,000	+4,500	-13,000	+3,700
Decrease by factor of 2	+24.0	8.9	-19,000	-3,800	+9,200	-7,700
Vertical conductivity of confining beds						
Increase by factor of 10	-18.1	7.5	+36,000	-940	-18,000	+19,000
Decrease by factor of 10	+9.2	12.9	-40,000	-1,300	+22,000	-24,000
Recharge (precipitation and secondary)						
25-percent increase	+13.6	8.1	+13,000	+2,000	+20,000	+21,000
25-percent decrease	-11.6	6.9	-14,000	-1,700	-20,000	-20,000
Well pumpage						
Increase by factor of 2	-2.9	7.0	-4,100	-430	-5,100	-2,900
Zero pumpage[3]	+2.2	7.0	+1,100	-800	+650	-3,700
River conductance						
Increase by factor of 10	-5.8	6.4	-4,600	+870	+2,500	+3,000
Decrease by factor of 10	+15.4	9.0	+6,400	+1,200	-2,600	+3,000
Drain conductance[4]						
Increase by factor of 10	-6.7	7.0	-17,000	+7,200	-290	-7,500
Decrease by factor of 10	+15.2	8.6	+20,000	-1,200	+510	+1,100
Offshore drain conductance						
Increase by factor of 10	+1.0	7.0	+1,300	-36	-43	+360
Decrease by factor of 10	+2.1	7.1	-5,200	+140	+220	+1,400

[1]Calibrated model; mean error = +1.2 feet, RMSe/domain (root mean squared error divided by total difference in water levels in the ground-water system) = 7.0 percent.

[2]Includes river and drain cells contributing to river flow.

[3]This scenario also included the removal of all secondary recharge. It effectively represents "pre-development" conditions.

[4]Does not include offshore drains.

Because no measurements of vertical hydraulic conductivity were available, values were initially estimated using reasonable ratios of vertical to horizontal hydraulic conductivity and then adjusted during model calibration. The effects of increasing or decreasing the vertical conductivity of the confining beds by an order of magnitude are shown in table 8. An order of magnitude change resulted in ground-water discharges to the Deschutes River and offshore that ranged from 37 to 45 percent more or less than the calibrated flows. Changes in vertical conductivity resulted in significant changes in simulated water levels (table 8).

Recharge was calculated from precipitation using data for Olympia, which is considered to be reasonably accurate. However, precipitation for the rest of the modeled area is estimated. Secondary recharge was estimated from water-use estimates and reported secondary-recharge percentages, each of which has potentially significant errors. For the sensitivity analysis, a potential error of 25 percent was assumed for estimated recharge. The most significant effect of varying recharge was change in ground-water discharge to the Deschutes River (41 percent decrease). Simulated water levels varied nearly as much as they did with changes in horizontal and vertical hydraulic conductivities.

Other model input parameters have a lesser influence on model results (table 8). Ground-water pumpage was varied over a large range (100 percent increase and decrease). The model was relatively insensitive to changes in pumpage. The method of simulating the interaction of the ground-water system with streams, lakes, springs, and seepage faces was varied by changing river- and drain-cell conductances by an order of magnitude. The model was relatively insensitive to these changes. The only change in flow that exceeded 25 percent occurred at McAllister Springs (38 percent) when drain conductances were increased by a factor of ten. Varying offshore drain conductances had very little effect on the model results.

Some interesting observations about the ground-water system, as represented by the calibrated model, can be made from the sensitivity analysis. The "zero pumpage" (table 8) simulation is an approximation of pre-development conditions. It is important to note that the ground-water discharge at McAllister Springs and to the Nisqually River are less in the pre-development scenario than in the developed (calibrated) scenario. This is because in the developed scenario, much of the naturally occurring discharge at McAllister Springs becomes secondary recharge, in effect cycling through the ground-water system a second time, and discharging to the springs or the Nisqually River. Although this indicates that there is more ground water available for use in the developed scenario than in the pre-developed scenario, the quality of the ground water must also be considered. Much of the secondary recharge has undergone some changes in water quality (having been discharged to septic systems, applied as irrigation water, etc.).

The ground-water discharges to the Deschutes and Nisqually Rivers had opposite reactions in many of the sensitivity scenarios. Increases in aquifer transmissivity or confining bed conductance resulted in decreases in simulated ground-water discharge to the Deschutes River and increases to the Nisqually River, whereas decreases in these variables had the opposite effect. Decreased pumpage resulted in increased simulated flow to the Deschutes and decreased simulated flow to the Nisqually. Increased river conductance and decreased offshore drain conductance resulted in decreased simulated flow to the Deschutes and increased simulated flow to the Nisqually. These opposite reactions of the two rivers are due to the different nature of ground-water discharges to the rivers. The Deschutes receives ground-water flow primarily from river cells in the surface unit (Qvr), whereas the Nisqually receives flow primarily from river and drain cells in deeper units (Qc and TQu). The two rivers also are affected to different degrees by secondary recharge.

The following table shows the most and least sensitive variables in regard to water levels and the most significant calibration flow targets (McAllister Springs, the Deschutes River, and the Nisqually River).

Target	Variables that target is:	
	Most sensitive to	Least sensitive to
Water levels	Decreased aquifer transmissivity and vertical conductivity of confining beds	Increased offshore drain-cell conductance and pumpage
McAllister Springs	Increased drain conductance and aquifer transmissivity	Increased or decreased offshore drain-cell conductance
Deschutes River	Decreased vertical conductivity of confining beds and increased recharge	Increased or decreased offshore drain-cell conductance
Nisqually River	Decreased vertical conductivity of confining beds and increased recharge	Increased offshore drain-cell conductance and decreased drain-cell conductance

Model Limitations

Any attempt to simulate a ground-water flow system is subject to limitations inherent in the technique used. A constructed numerical model is essentially a set of equations that describes a conceptual system having properties similar to the real ground-water system. If the model adequately represents a real ground-water system, then the response of the model to imposed stresses, such as ground-water pumpage, will be an adequate simulation of response of the real system if it were to undergo the same stress. The accuracy with which a model can simulate a natural system is limited by characteristics of both the model used and the system being described. Examples of three types of limitations in most models are as follows:

1. The inability of a model to handle all the complexities of a natural system. The simplifying assumptions and generalizations that are incorporated into a model affect the output. If a model is designed to perform a specific task, the simplifying assumptions can be made so that their effects on the results are minimal. If the model is used for simulations other than those for which it was designed, the generalizations and assumptions used could significantly affect the results.
2. The inadequacy of existing data to describe the system. Data on unit types and thicknesses, water levels, and hydraulic properties in the vicinity of the GWMA were taken directly from Drost and others (1998) and represent approximations of the actual values. Outside the GWMA, in rural Thurston County, information is generally more sparse and estimated aquifer thicknesses, hydraulic properties, and water levels had a higher degree of uncertainty. A major deficiency is the lack of a water-table map for the study area. Because all units are simulated as confined, there are inaccuracies in simulations in which the saturated thickness of a unit should change due to changing water levels (that is, confined simulations result in constant transmissivities, which may not be the case in the ground-water system). With sufficient water-table information, the upper unit(s) could be simulated as a water-table unit, which could result in a better overall simulation. This might also require a smaller model-grid cell size. Another deficiency that falls in this category is generalization of the areal and vertical distribution of ground-water pumpage over the area, which in some instances was estimated from very little information. Because most of the available data needed to construct the model are restricted to a short time interval (1988 to 1990), there was no opportunity to check the calibration against a second data set. These inadequacies in data, errors in estimates, and necessary generalizations may significantly affect the accuracy of the results of the model. The severity of these adverse effects varies with the intended uses of the model. For some purposes, the probable errors associated

with data deficiencies in areas remote from existing development may have little effect on the results. For other purposes, it may be necessary to collect additional data before the model can be adequately reconstructed.

3. The problem of non-unique solutions. Most models are calibrated by adjusting model parameters, within limits, until a reasonable agreement is obtained between simulated and observed water levels and ground-water discharges. However, in most cases it is possible to obtain a similar degree of agreement with different combinations of parameters. Consequently, calibrated models are not always unique and a match between simulated and observed conditions does not guarantee that the model parameters and the parameters of the real system are identical. If the parameters used are generally compatible with known information, errors caused by non-uniqueness would probably be small.

These examples illustrate several factors that can limit the accuracy of model results. Generally, if the intended uses of a model are carefully considered prior to its formulation, the model can be constructed so that the adverse effects of these and other factors will be minimal (discussion after Harrill, 1986). The model described in this report was constructed to act as a tool to increase the understanding of the regional-scale ground-water-flow system. Consequently, simulations of regional-scale questions are the only ones described in this report.

MODEL APPLICATIONS

Model-Derived Ground-Water Budget

An approximate ground-water budget for a typical year in the model area is expressed in the following equation,

$$GW_{in} + R = GW_{out} + D + \Delta S , \qquad (2)$$

where

GW_{in} is ground-water inflow to the model area,
GW_{out} is ground-water outflow from the model area,
R is recharge,
D is discharge, and
ΔS is change in ground-water storage.

Recharge to the ground-water system occurs primarily as recharge from precipitation and seepage from streams and lakes, and secondarily as (1) seepage from septic systems, (2) leakage from water and sewer lines, and (3) deep percolation of irrigation water. Discharge from the system occurs as seepage to streams, lakes, springs, and seepage faces, as evaporation from soils and transpiration by plants, as submarine seepage to Puget Sound, as ground-water outflow, and as withdrawals from wells. A more detailed representation of the ground-water budget of the model area is

$$GW_{in} + R_{pp} + R_{sw} + R_{sed} = GW_{out} + D_{sw} + D_{spr} + D_{er} + D_{ss} + D_{ppg} + \Delta S , \qquad (3)$$

where

R_{ppt} is recharge from precipitation,
R_{sw} is recharge from streams and lakes,
R_{sec} is secondary recharge,
D_{sw} is discharge to streams and lakes,
D_{spr} is discharge to springs and seepage faces,
D_{et} is discharge by evapotranspiration,
D_{ss} is discharge as submarine seepage, and
D_{ppg} is pumping from wells.

All of the water-budget components can be quantified based on the calibrated model except discharge by evapotranspiration and change in ground-water storage. Evapotranspiration from the ground water (D_{et}) is not known, but is assumed to be relatively insignificant to the total budget (assume $D_{et} = 0$) and was therefore not explicitly represented in the model. It was assumed that the ground-water system is in a state of dynamic equilibrium; that is, inflow to the system is equal to outflow from the system and there is little or no change in the amount of water stored within the system ($\Delta S = 0$). Therefore, changes in storage were not simulated in the model.

Substituting the calibrated-model values and above assumptions into equation 3 yields the following (all values in thousands of acre-ft/yr).

$$GW_{in} + R_{ppr} + R_{aq} + R_{sed} = GW_{in}D_{sw} + D_{spr} + D_{et} + D_{ss} + D_{ppg} + \Delta S$$

(Substituting)

$$5.8 + 560 + 38 + 63 = 12 + 310 + 190 + 0 + 88 + 62 + 0$$

$$660 = 660$$

The calibrated-model ground-water budget can be used to make some general observations of the ground-water system in 1988. Total flow through the ground-water system of the model area was in excess of 660,000 acre-ft/yr. The principal form of ground-water recharge was from precipitation. However, secondary recharge equalled one-ninth of precipitation recharge and, as development continues, may increase significantly. Principal forms of ground-water discharge were to streams, lakes, springs, and seepage faces and as submarine seepage to marine waters. Total ground-water withdrawals in 1988 were about 9 percent of the total flow, and net withdrawals (total withdrawals minus secondary recharge) were essentially zero, due to large amounts of naturally occurring springflow which became secondary recharge.

There is often a tendency to assume that the quantity of water that discharges naturally is available for further ground-water development; this is not necessarily so. As pointed out by Theis (1940) and Bredehoeft and others (1982), any new discharge (withdrawals) superimposed on a previously stable system must be balanced by an increase in recharge, a decrease in the original discharge, a loss of storage within the aquifer, or by a combination of these factors. Considering the ground-water system in the unconsolidated sediments in Thurston County in particular, the possibility of increased precipitation recharge on a long-term basis appears remote. In fact, the trend of increased residential development and central storm sewers may result in decreased precipitation recharge, which will be mitigated to some extent by the accompanying increase in secondary recharge. Additional withdrawals, therefore, would result in a loss of storage (with an attendant decline in water levels) and a decrease in natural discharge. An important factor regarding secondary recharge is a probable decline in ground-water quality associated with increasing volumes of secondary recharge. As discussed previously, not all natural discharge in the model area is to Puget Sound; a large quantity of ground water discharges to streams, lakes, springs, and seepage faces. In those places, it is used both directly and indirectly for streamflow maintenance, fish propagation, waste dilution, recreation, and public supply. The magnitude of potential ground-water development, therefore, depends on the hydrologic effects on discharge that can be tolerated. Because it may take many years for a new equilibrium to become established, the effects of additional ground-water development will most likely not be immediately apparent.

Simulation of Increased Ground-Water Withdrawals

Washington State law allows for the reservation of the legal right to withdraw ground water in the future for public water supply (Revised Code of Washington 90.54.050(1)). The reservation of additional ground-water withdrawals of up to 23,000 acre-ft/yr was requested and granted to Thurston County in 1988 (Chapter 173-591,WAC, Washington Administrative Code). The WAC assigns these withdrawals to eight subareas, mostly within the GWMA boundaries.

The calibrated steady-state model was used to simulate the effects of adding 23,000 acre-ft/yr of ground-water withdrawals to the 1988 withdrawals. The wells and rates of withdrawal used for this simulation are shown in table 9. No change was made in the amount of secondary recharge input to the model. Assuming that some of the additional ground-water withdrawn would become secondary recharge, this simulation represents a situation where the maximum probably effects of ground-water withdrawal would occur.

Calculated water-level drawdown in units Qva and Qc due to the simulated increased withdrawals are shown on figures 28 and 29. Approximately 80 percent of the increased pumping was assigned to these two units. As shown on figures 28 and 29, large portions of units Qva and Qc would experience drawdowns of 1 foot or more, and smaller, though significant areas would experience 10 feet or more of drawdown. Drawdown in specific cells where pumping was greatest was as much as 35ft in unit Qva west of Tumwater (cell 22, 16) and up to 35 ft in unit Qc south of Lacey (cells 22, 16 and 23, 27). Because these are averages over a cell, drawdown in the pumping wells would be much greater. The increased pumping rates assigned to some of the wells may exceed their actual maximum production rates; however, for the purposes of the simulation, representing the withdrawal in any one model cell as being from a single well or a group of wells has little effect on the results.

There is some error in the simulated drawdowns because unit Qvr is simulated as confined although it is a water-table aquifer. In most of the model area, simulated drawdowns are a small fraction of the saturated thickness of unit Qvr. However, two of the simulated pumping wells in the Lacey area tap unit Qvr and the resulting drawdown in the model cell containing these wells is nearly one-half of the saturated thickness of the unit. Because the model represents Qvr as confined, the transmissivity remains constant instead of gradually decreasing as drawdowns increase. Actual drawdown in unit Qvr would be greater than that simulated.

As previously mentioned, general hydrologic principles state that when steady-state conditions have been achieved in a ground-water system after a new stress has been applied (such as increased withdrawals), the source of the water for these increased withdrawals is from reduced discharge from the system or from increased recharge to the system. The source of the additional water can be estimated from the results of the ground-water-flow model.

The simulation with increased pumping indicates that most of the increase in the rate of ground-water withdrawal would come from decreased ground-water discharge to springs, seepage faces, and submarine seeps (51 percent) and to streams (46 percent). About 3 percent of the increase would come from increased river leakage to the ground-water system. The largest effects would be decreased ground-water flow to the Deschutes and Nisqually Rivers (4,600 and 1,400 acre-ft/yr, respectively), decreased springflows at McAllister and Abbott Springs (1,200 acre-ft/yr), and decreased flow to submarine seeps (3,600 acre-ft/yr). Ground-water flow to Woodland Creek and Black Lake would also decrease (870 acre-ft/yr and 720 acre-ft/yr, respectively). Leakage from Pattison and Long Lakes, as well as Lake St. Clair, would increase by a total of 1,600 acre-ft/yr and Woodard and Eaton Creeks would each experience a reduction in ground-water flow of 140 acre-ft/yr. Numerous other small streams and springs would also experience reduced flow from ground water.

Simulation of Ground-Water-Flow Pathlines

Local interest in three areas--McAllister and Abbott Springs, a pumping center southeast of Lacey, and a pumping center along the lower reaches of the Deschutes River--led the authors to estimate (and describe below) the recharge areas contributing the water withdrawn from the ground-water system in those areas.

The contributing areas were delineated using the post-processing particle-tracking computer code, MODPATH (Pollock, 1989), to backtrack simulated ground-water flow paths from the areas of discharge to the points of recharge.

Procedure

The computer code MODPATH uses a semi-analytical particle-tracking scheme. The method is based on the assumption that each directional velocity component (calculated from MODFLOW output) varies linearly within each model cell. This assumption allows an analytical expression describing the flow path within each cell to be obtained using the simulated flows through the faces of the cell. Given the initial position of a particle, the position of the particle at any future time can be calculated. A series of calculations for successive locations of a particle provide a picture of its path through the cell and into adjacent cells if appropriate. The reader is referred to Pollock (1989) for a detailed discussion of the procedure.

MODPATH requires initial locations of the particles to be tracked. In each of the two pumping center locations, a similar method of particle placement was employed. A slightly different approach was used for the cells containing McAllister and Abbott Springs. The pumping center southeast of Lacey contained five wells, tapping units Qvr, Qva, and Qc. The pumping center along the lower reaches of the Deschutes River was composed of 16 wells located in all four aquifer units and unit Qf. Due to the close spacing of the wells in the Deschutes case, only five cells actually contained pumping wells. Particles were placed closely around each well using a combination of a horizontal ring and four vertical lines. The rings contained 100 particles and were placed at the altitude of the center of the cell. Each vertical line contained 100 particles spanning the entire thickness of the cell. McAllister and Abbott Springs are represented in the calibrated model by adjoining drain cells. A similar system of particle placement was employed, with the lines placed at cell faces and the rings inside the cells but with radii equal to the cell width. In all cases, a minimum of 500 particles was placed in each cell.

Table 9. Pumping rates from wells used in simulation of increased ground-water withdrawals

Subarea[2]	Well identifier[3]	Pumping rate (acre-feet per year)[1] 1988	Pumping rate (acre-feet per year)[1] Full development[4]	Aquifer[5]
Airport	17N/02W-10B01	320	1,046	Qva
	17N/02W-10B02	320	1,046	Qva
	17N/02W-12N02	15	49	TQu(A1)
Allison Springs	18N/02W-18L02	0	1,888	Qc
Black Lake	17N/02W-04M	16	186	Qc
	17N/02W-08E01	12	139	TQu(A1)
	17N/02W-09C02	6.5	75.5	Qva
	17N/02W-17J01	9.2	107.2	Qva
	17N/02W-17R03	9.2	107.2	Qva
	17N/02W-17R04	9.2	107.2	Qva
	17N/02W-20B05	16	186	Qva
	17N/02W-20B06	16	186	Qva
	17N/02W-20G01	16	186	Qva
	17N/02W-20G05	16	186	Qva
	17N/02W-20G06	16	186	Qva
	17N/02W-20H01	10	116	Qva
	17N/02W-20H02	16	186	Qva
	17N/02W-20H03	10	116	Qva
Deschutes Valley	18N/02W-35M01	140	307	Qva
	18N/02W-35M02	140	307	Qva
	18N/02W-35M03	140	307	Qva
	18N/02W-35M04	140	307	Qva
	18N/02W-35M05	140	307	Qva
	18N/02W-35M06	140	307	Qva
	18N/02W-35M08	140	307	Qva
Hawks Prairie	18N/01W-01H02	12	302	Qc
	18N/01W-12F01	26	655	TQu(UN)
	19N/01W-25P01	74	1,865	Qva
	19N/01W-25P02	23	580	Qva
	19N/01W-27N02	11	277	Qva
	19N/01W-31K04	3.9	97.9	Qvt
	19N/01W-33K03	11	277	Qva
	19N/01W-33K04	11	277	Qc
McAllister Springs	18N/01E-19R01	0	1,878	Qc
Mottman Industrial Park	18N/02W-28J02	0	1,888	Qva

Table 9. Pumping rates from wells used in simulation of increased ground-water withdrawals—Continued

Subarea[2]	Well identifier[3]	Pumping rate (acre-feet per year)[1] 1988	Pumping rate (acre-feet per year)[1] Full development[4]	Aquifer[5]
Southeast	17N/01W-02A03	12	34	TQu(UN)
	17N/01W-04E01	15	43	Qvr
	17N/01W-04E02	1,590	4,517	Qva
	17N/01W-04F01	15	43	Qvr
	18N/01W-21B04	56	159	Qva
	18N/01W-21P02	2.2	6.2	Qc
	18N/01W-21P02	2.2	6.2	TQu(UN)
	18N/01W-28E01	200	568	Qc
	18N/01W-28M01	480	1,364	Qc
	18N/01W-28M02	188	534	Qc
	18N/01W-30A01	186	529	TQu(UN)
	18N/01W-31R02	66	187	Qc
	18N/01W-32P01	480	1,364	Qvr
	18N/01W-32P04	340	966	Qvr
	18N/01W-33N01	16	45	TQu(A1)
	18N/01W-33N01	49	90	TQu(UN)
	18N/01W-33P01	960	2,727	Qc
Total		6,642.4	29,527.4	

[1]As assigned in ground-water model.

[2]Subarea as named in WAC, 173-591-130, Illustration 2.

[3]"Full development" pumping assigned to primary 1988 municipal, industrial, or irrigation wells in each subarea. Exceptions:

1. "Allison Springs" and "McAllister Springs" subareas had no significant withdrawals in 1988. An unused City of Olympia well and a City of Olympia test well were used for each subarea, respectively, for the "Full development" scenario.
2. "Mottman Industrial Park" subarea had no significant withdrawals in 1988. A representative private domestic well was used for the "Full development" scenario.

[4]Reserved water rights (WAC, 173-591) added to 1989 pumping rates.

[5]See table 1; unit TQu subdivided into TQu(A1), uppermost aquifer in TQu; TQu(UN), below uppermost aquifer in TQu.

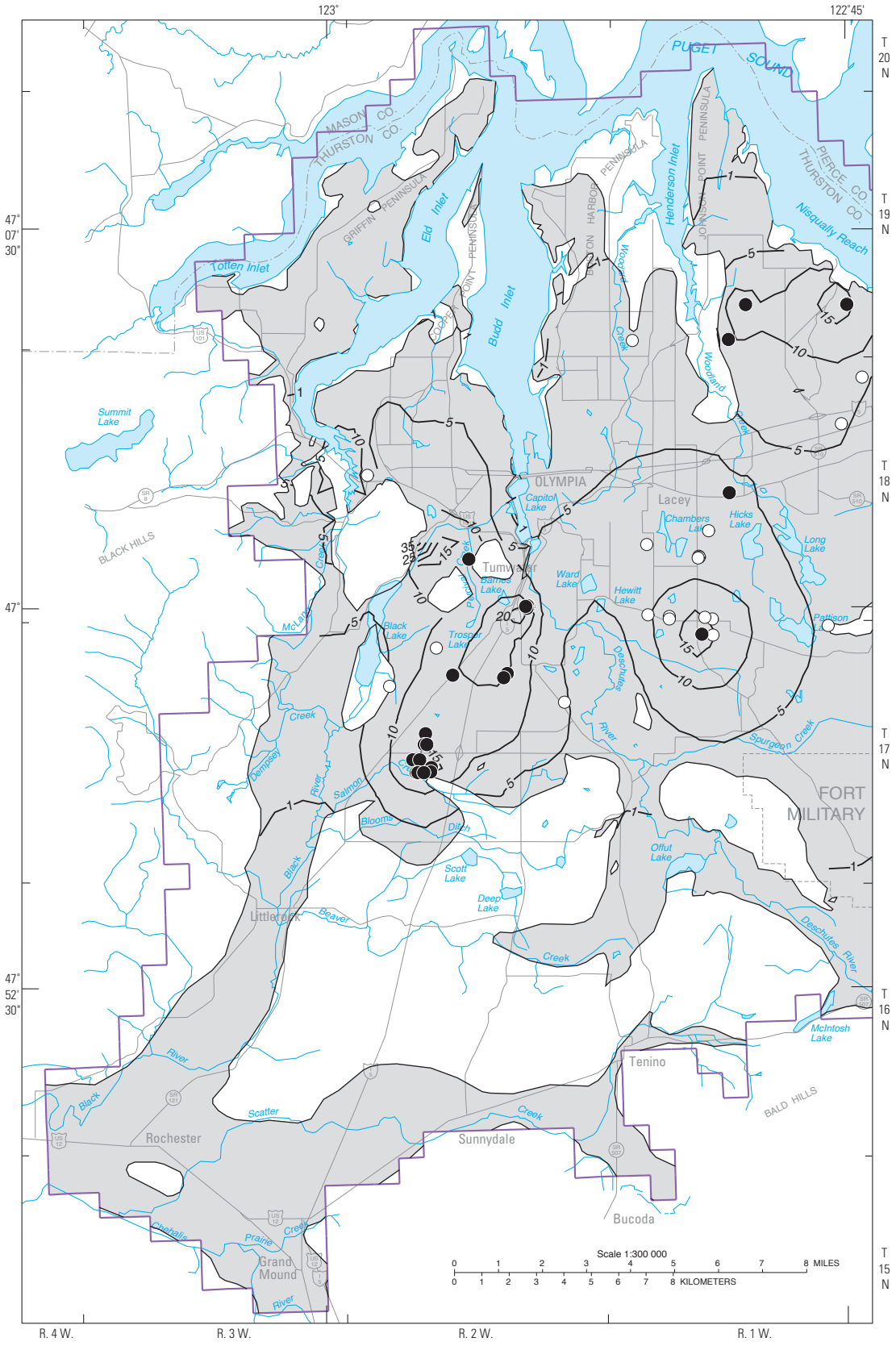


Figure 28. Simulated drawdown in unit Qva due to increased pumping.

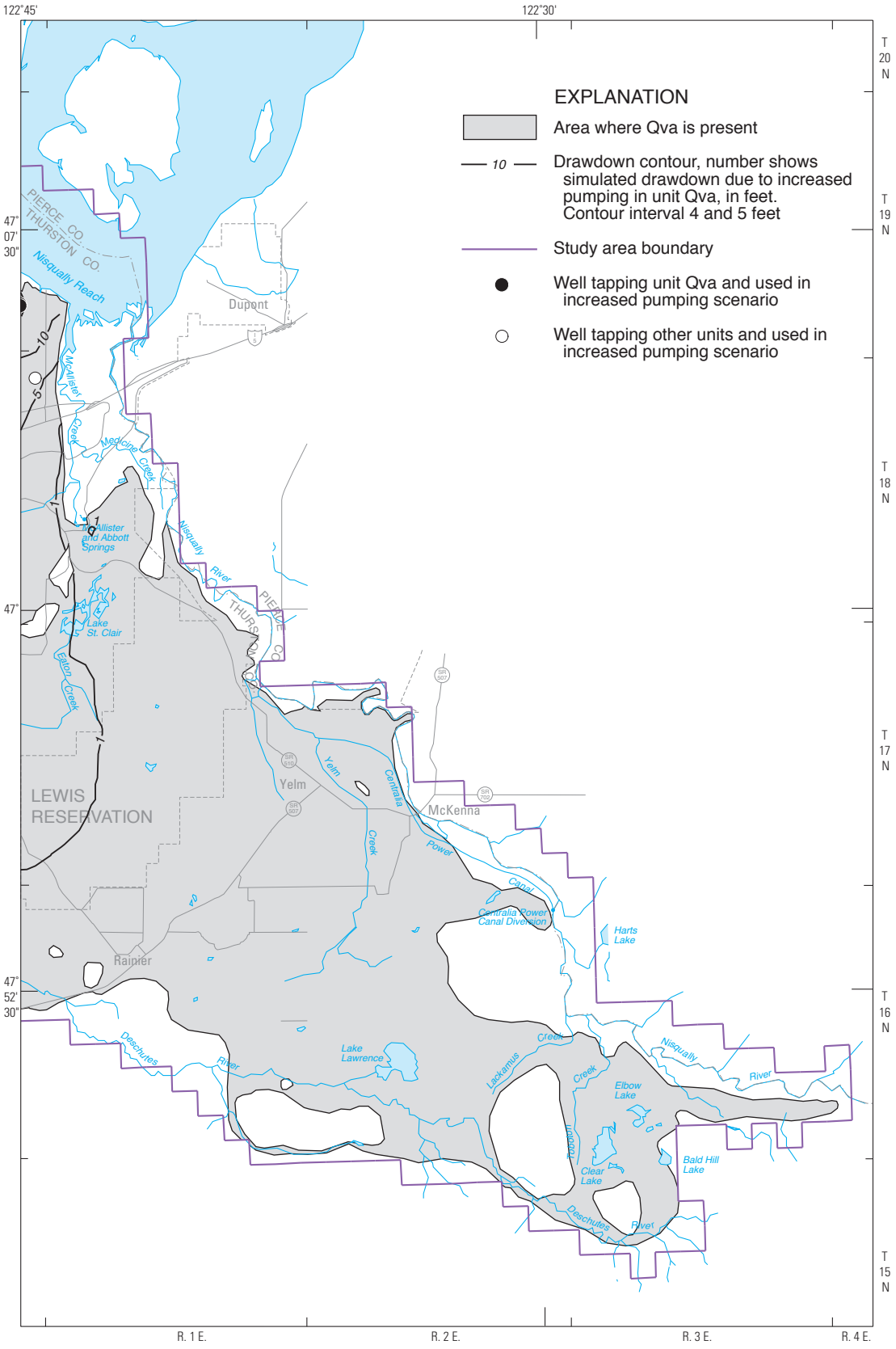


Figure 28. continued.

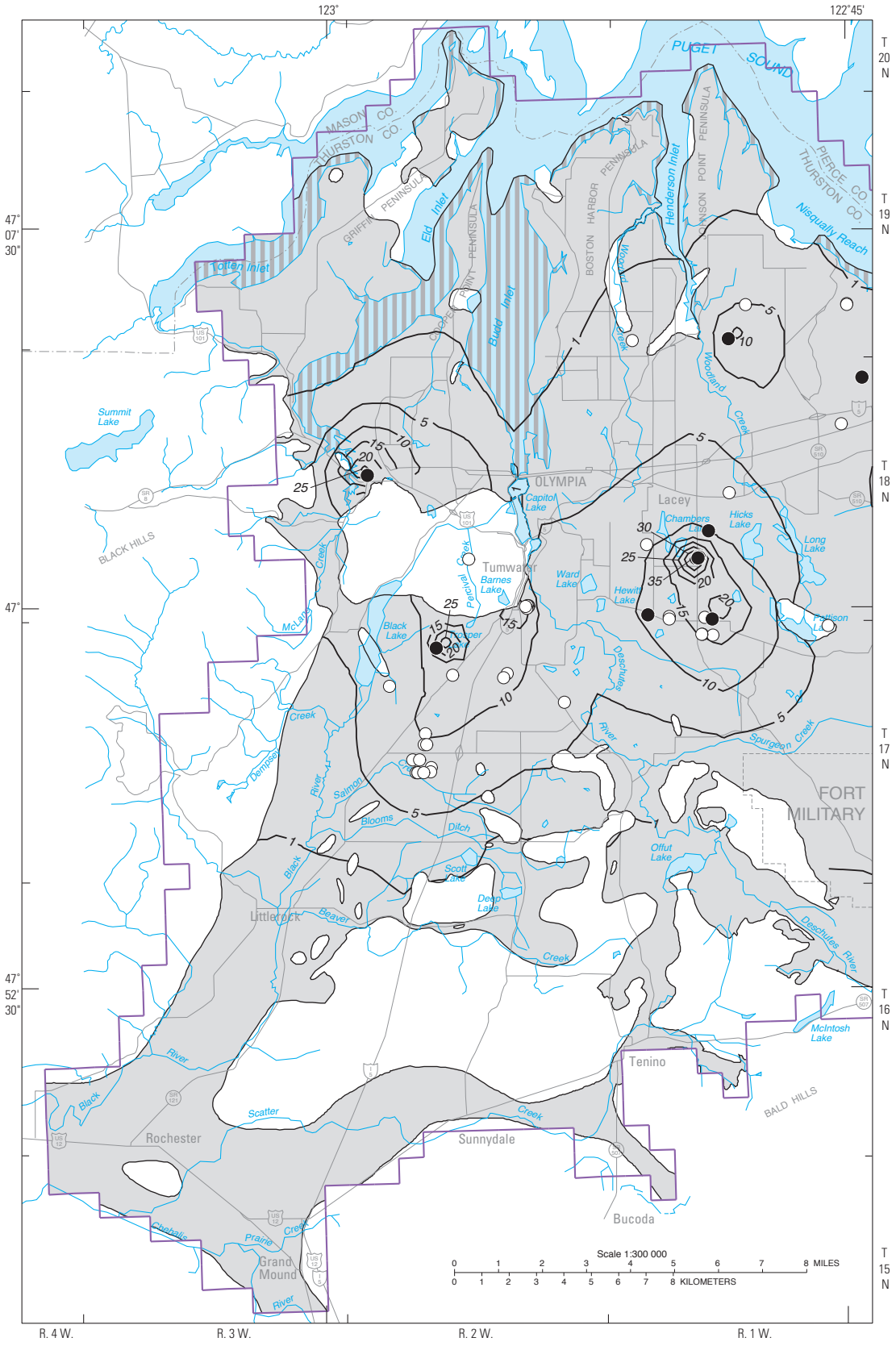


Figure 29. Simulated drawdown in unit Qc due to increased pumping.

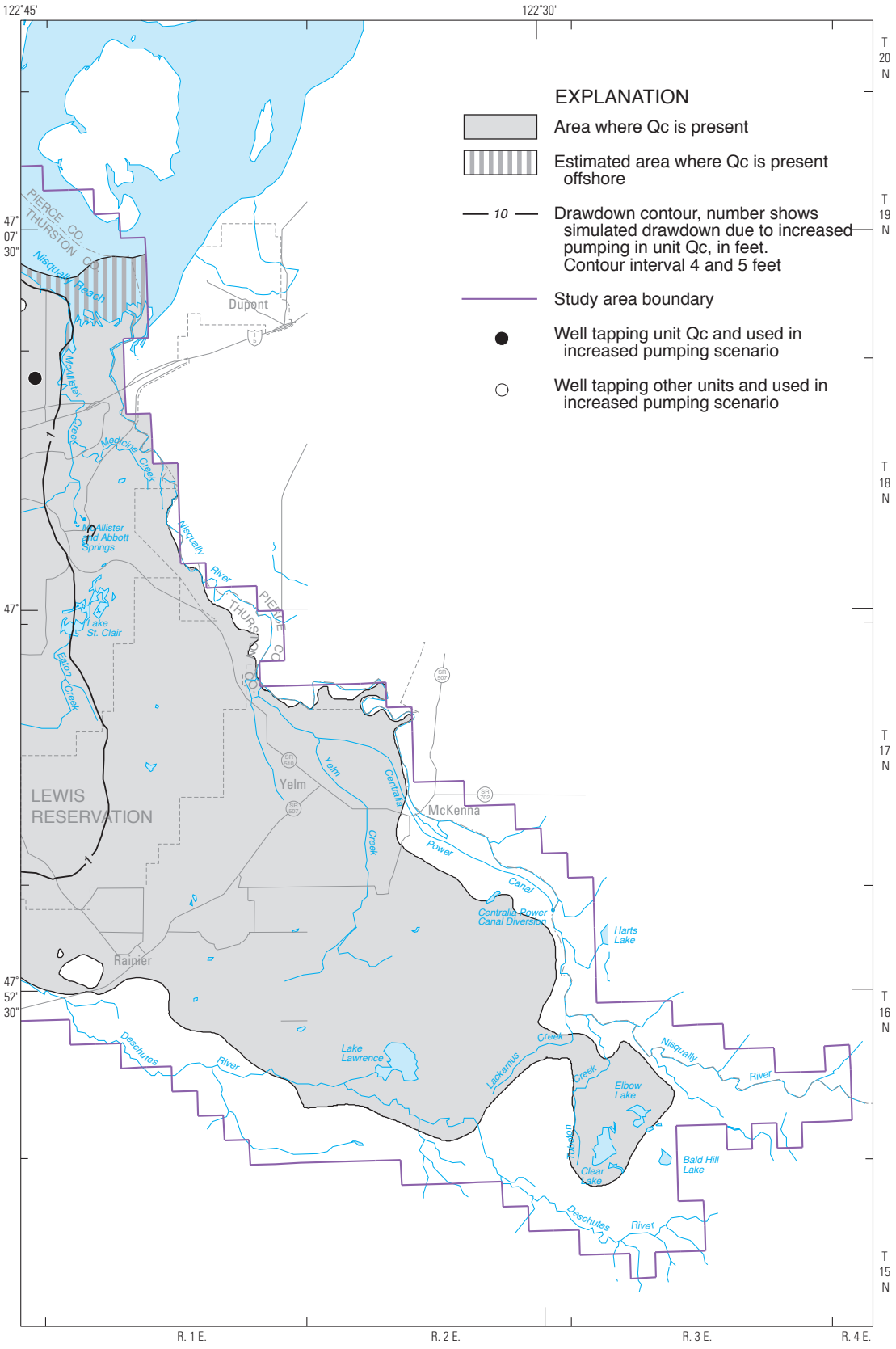


Figure 29. continued.

Results of Pathline Simulations

Three particle-tracking analyses are discussed. In each case, they analyze the area contributing ground water to a point or area of discharge from the ground-water-flow system. The reader is cautioned that the uncertainty associated with inaccuracies in the flow-system simulation are carried forward to these analyses and new uncertainties are introduced. The reader is referred to the discussion of uncertainty in the flow model preceding this part of the report and the discussion concerning MODPATH that follows these descriptions of the results of the particle tracking.

Contributing Area for Water Discharging from McAllister Springs and Abbott Springs

Results of the MODPATH simulation identify the contributing area for water discharging from the springs. Water recharging the ground-water system at the water table over about a 20-mi^2 area immediately adjacent to and extending to the south and west of the springs may discharge at the springs (fig. 30). In addition, several areas farther south also contribute some of the spring discharge. In these more distant areas, some of the recharge that moves deeply into the ground-water system (to unit Qc) eventually discharges at McAllister and Abbott Springs. The water that discharges at the springs enters the ground-water system as precipitation recharge, secondary recharge, and as leakage from Lakes: Long, Pattison, Hicks, and St. Claire, and possibly from Eaton Creek.

Contributing Area for Water Pumped Southeast of Lacey

During 1988, the Cities of Lacey and Olympia withdrew about 3,800 acre-feet of ground water from five municipal wells southeast of Lacey (fig. 30). The ground water withdrawn by these wells came from precipitation recharge and secondary recharge over six discontinuous areas totaling about 1.1 mi^2, and possibly leakage from several marshes and an unnamed creek flowing out of Chambers Lake (fig. 30).

Contributing Area for Water Pumped Along the lower Deschutes River

During 1988, 15 wells withdrew about 3,900 acre-feet of ground water for municipal and private industrial use along the lower Deschutes River. The ground water withdrawn by these wells came from precipitation recharge and secondary recharge over two discontinuous areas totalling about 1.3 mi^2, and probably leakage from surface water features, including the Deschutes River, Trosper and Barnes Lakes, several marshes, and possibly Percival Creek (fig. 30).

Sensitivity of Pathline Simulations

MODPATH uses the ground-water-flow field calculated by MODFLOW, therefore it incorporates the sensitivity of the underlying MODFLOW simulation. As previously discussed, the MODFLOW simulation is most sensitive to uncertainty in aquifer transmissivity, vertical hydraulic conductivity of confining beds, and rates of recharge, and least sensitive to river and drain conductances, and pumpage. Any errors in the flow field calculated by MODFLOW would result in errors in flow pathlines and the identified contributing areas.

The sensitivity of the simulated locations and sizes of the contributing areas was investigated by repeating the MODPATH simulations with different values of the input parameters to which the MODFLOW model was most sensitive: aquifer transmissivity, vertical hydraulic conductivity of the confining beds, and recharge. As expected, each MODPATH sensitivity simulation produced contributing areas for McAllister and Abbott Springs and the Lacey and lower Deschutes pumping centers that differed from those produced for the calibrated model. The most significant differences occurred using twice the calibrated aquifer transmissivity and an order of magnitude increase in the vertical hydraulic conductivity of the confining beds. For McAllister Springs and Abbott Springs, increasing aquifer transmissivity resulted in an increase in the contributing area immediately west and northwest of the area designated by the calibrated model and a complete disappearance of the remote contributing area to the south (fig. 31). The contributing area for the lower Deschutes pumping center also was very sensitive to increased aquifer transmissivity and increased hydraulic conductivity of the confining beds. Increased aquifer transmissivity resulted in the appearance of remote contributing areas to the west. Increased vertical hydraulic conductivity of the confining beds resulted in a contributing area more concentrated around the pumping center. Each of the MODPATH sensitivity simulations produced significant changes in the contributing areas for the Lacey pumping center, but without any obvious pattern.

Limitations of Pathline Simulations

MODPATH has a number of limitations that must be recognized if it is to be used effectively and results from it are to be understood. The limitations are related to (1) the underlying assumptions of the particle-tracking scheme, (2) discretization (cell-size) effects, and (3) uncertainty carried forward from the MODFLOW simulation.

The limitations associated with the particle-tracking scheme include:

- MODPATH was used to calculate flow pathlines for the steady-state calibrated model. If the flow system is changing due to changes in pumping stress, then the results of the particle tracking may be invalid. It is assumed the flow system in Thurston County is not changing significantly. This is suggested by the synoptic measurement of water levels (1988 and 1990) in wells done for this study and by the few long-term well and lake hydrographs (see Water-Level Fluctuations and Trends section). However, the existing data neither conclusively prove nor disprove the assumption of steady-state conditions.

The limitations associated with discretization include:

- It is assumed that the geohydrologic units can be accurately represented by hydraulically homogeneous cells that are 3,000 feet by 3,000 feet and up to several hundreds of feet thick. Variations in hydraulic properties within cells could cause inaccuracies in MODPATH results.
- If the boundaries are not well known or not well represented by the model cell size, then inaccuracies in discretization of boundaries can also affect particle pathline simulations.
- Inaccuracies in simulating features, such as rivers or drains, that are much smaller than the 3,000-foot by 3,000-foot model cells limit the accuracy of the MODPATH simulations.

The reader is referred to the section of this report on the assumptions and limitations for the ground-water-flow model for a discussion of uncertainty in the flow model. Those uncertainties are carried forward to this set of calculations for particle pathlines.

The summation of these limitations and uncertainties may result in uncertainty in the level of confidence to place in the results of the MODPATH calculations. Although the simulated contributing areas shown in this report are thought to be of reasonable accuracy, they must be used with caution. In cases where an accurate knowledge of contributing areas is needed, simulated results should be supported by detailed hydrogeologic mapping and other evidence of the system behavior such as water-level maps. An excellent illustrated discussion of the uncertainty present in estimating contributing areas is contained in U.S. Geological Survey Circular 1174 (Franke and others, 1998).

SUMMARY AND CONCLUSIONS

The demand for water in Thurston County has increased steadily in recent years because of a rapid growth in population. Surface-water resources in the county have been fully appropriated for many years and Thurston County now relies entirely on ground water for new supplies of water. Previous cooperative studies by the U.S. Geological Survey and the Thurston County Health Department have characterized the geohydrology of the unconsolidated sediments over much of Thurston County. This report summarizes a study that extended this characterization to the entire county and used this information to construct a numerical model of the ground-water flow in the unconsolidated sediments. This model was used to gain a greater understanding of the ground-water-flow system and to quantify unmeasured components of the ground-water budget such as recharge, leakage between streams and lakes and the ground-water system, and discharge to Puget Sound. The model was also used to simulate increased-pumping and to estimate contributing areas to two pumping centers and to McAllister and Abbott Springs.

Thurston County is underlain by unconsolidated sediments that are of both glacial and non-glacial origin. Beneath these unconsolidated sediments, which are as much a.s 2,000 feet thick under Thurston County, are consolidated rocks of Tertiary age. Six geohydrologic units have been identified within the unconsolidated sediments. These unconsolidated sediments are generally moderately to very permeable.

Water levels in wells in Thurston County vary seasonally and over longer time frames due to temporal changes in recharge and discharge of the ground-water-flow system. Water levels in 607 wells were measured for this study in 1988 and again in 1990. Median water levels rose 0.6 to 1.9 feet in all geohydrologic units except bedrock, where they decline 1.4 feet.

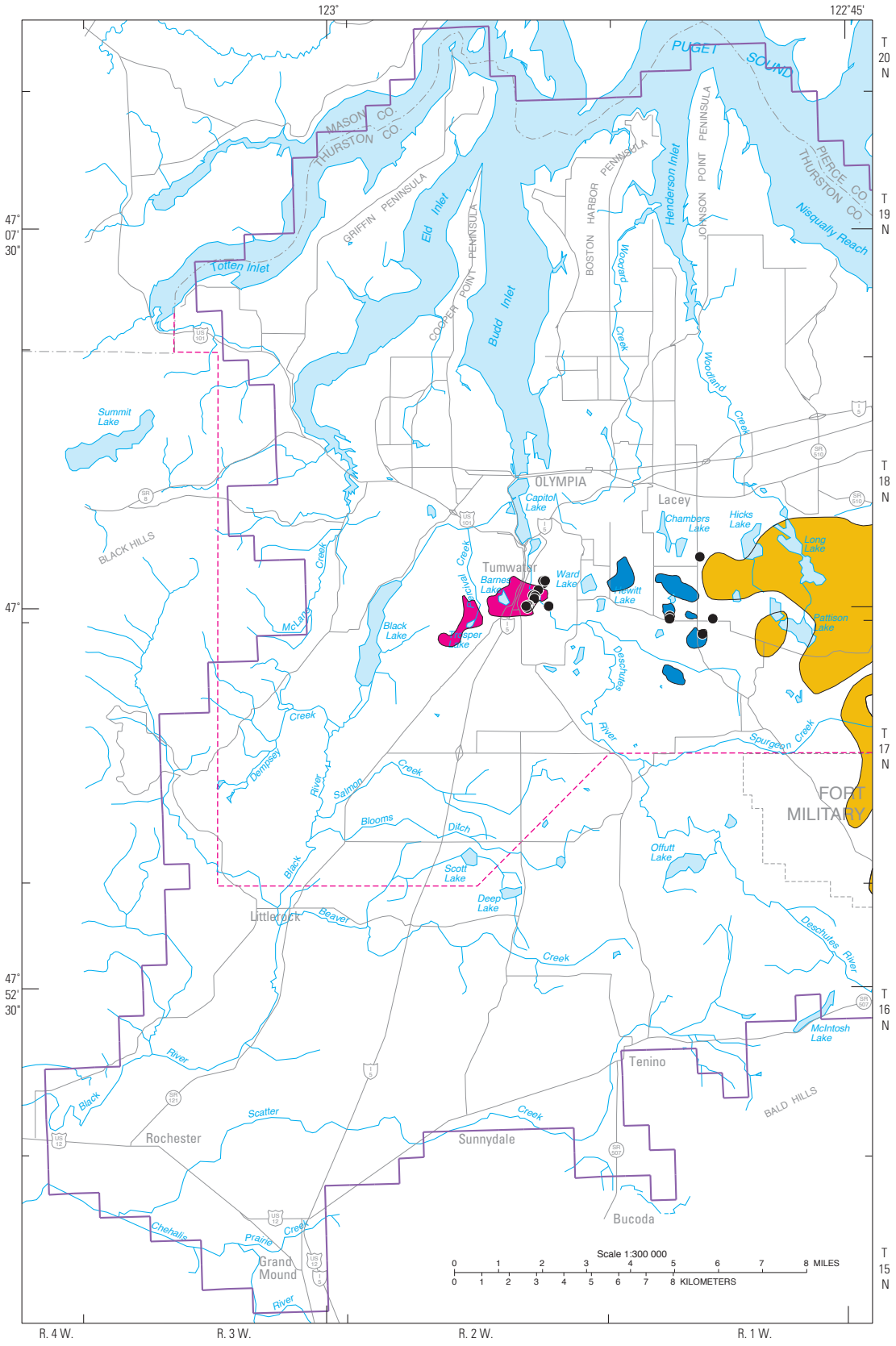


Figure 30. Simulated contributing areas for water discharging at McAllister and Abbott Springs, and water pumped southeast of Lacey and along the lower Deschutes River, for calibrated model (1988 conditions).

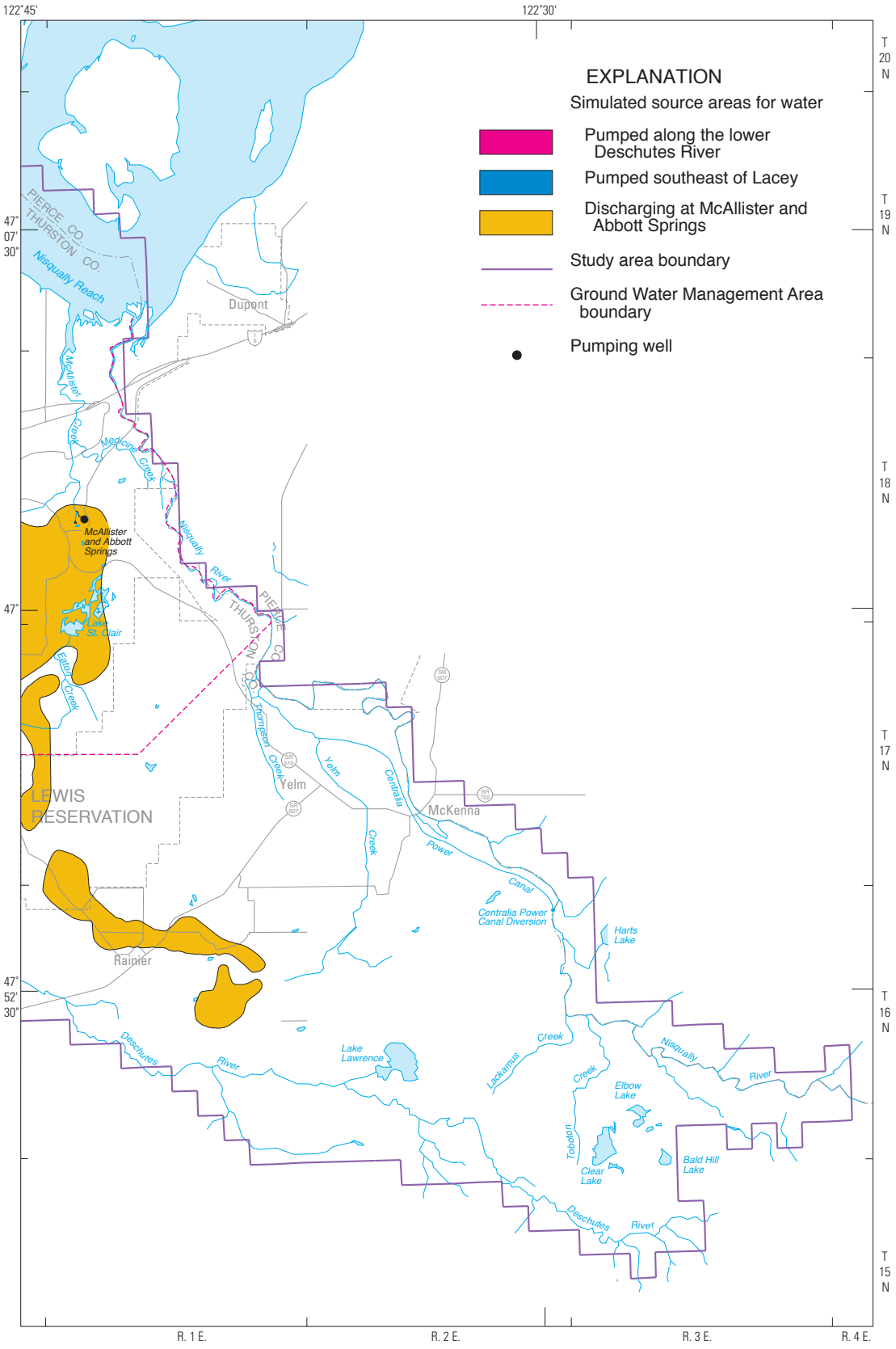


Figure 30. continued.

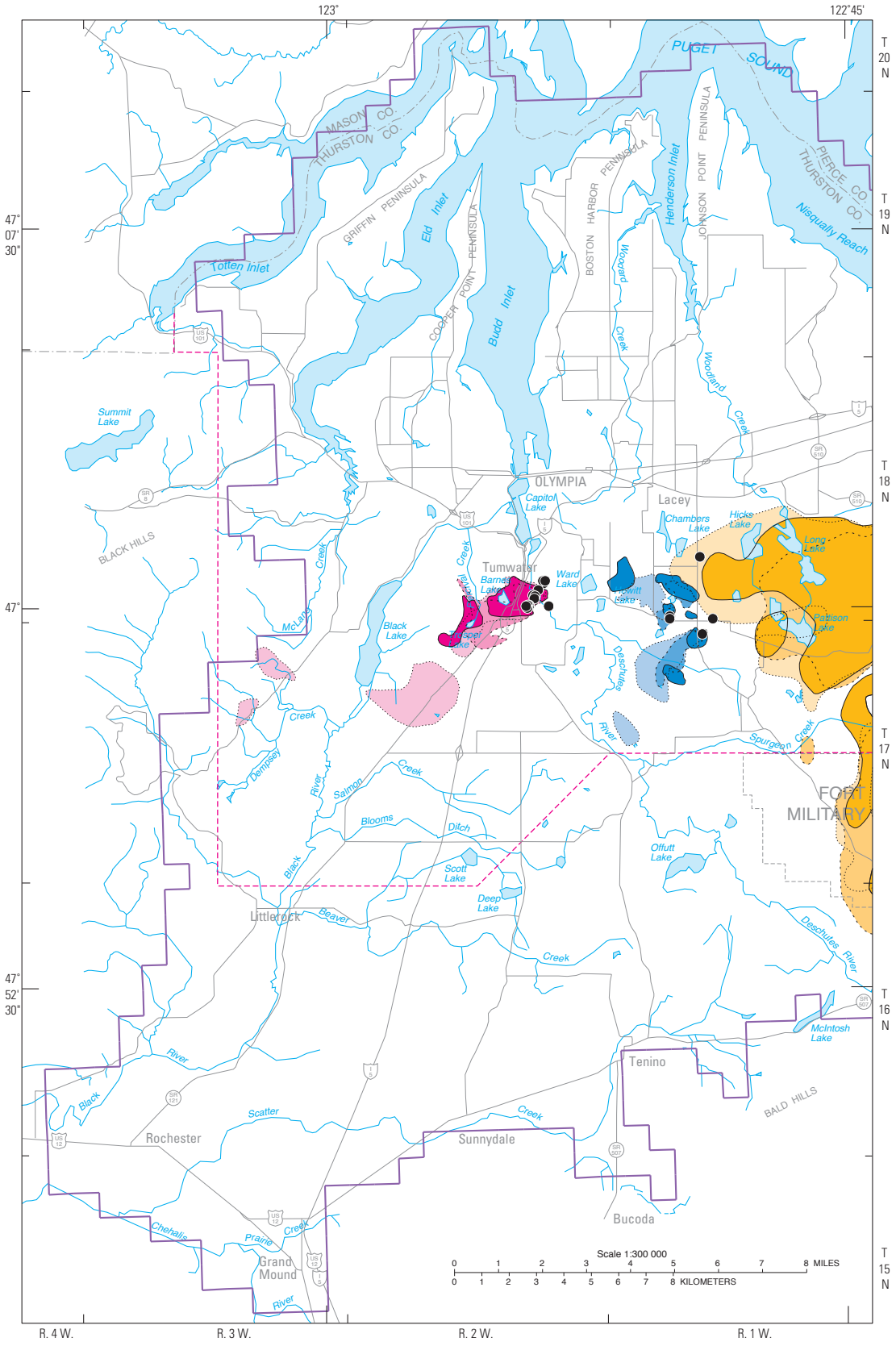


Figure 31. Simulated contributing areas produced by MODPATH sensitivity tests.

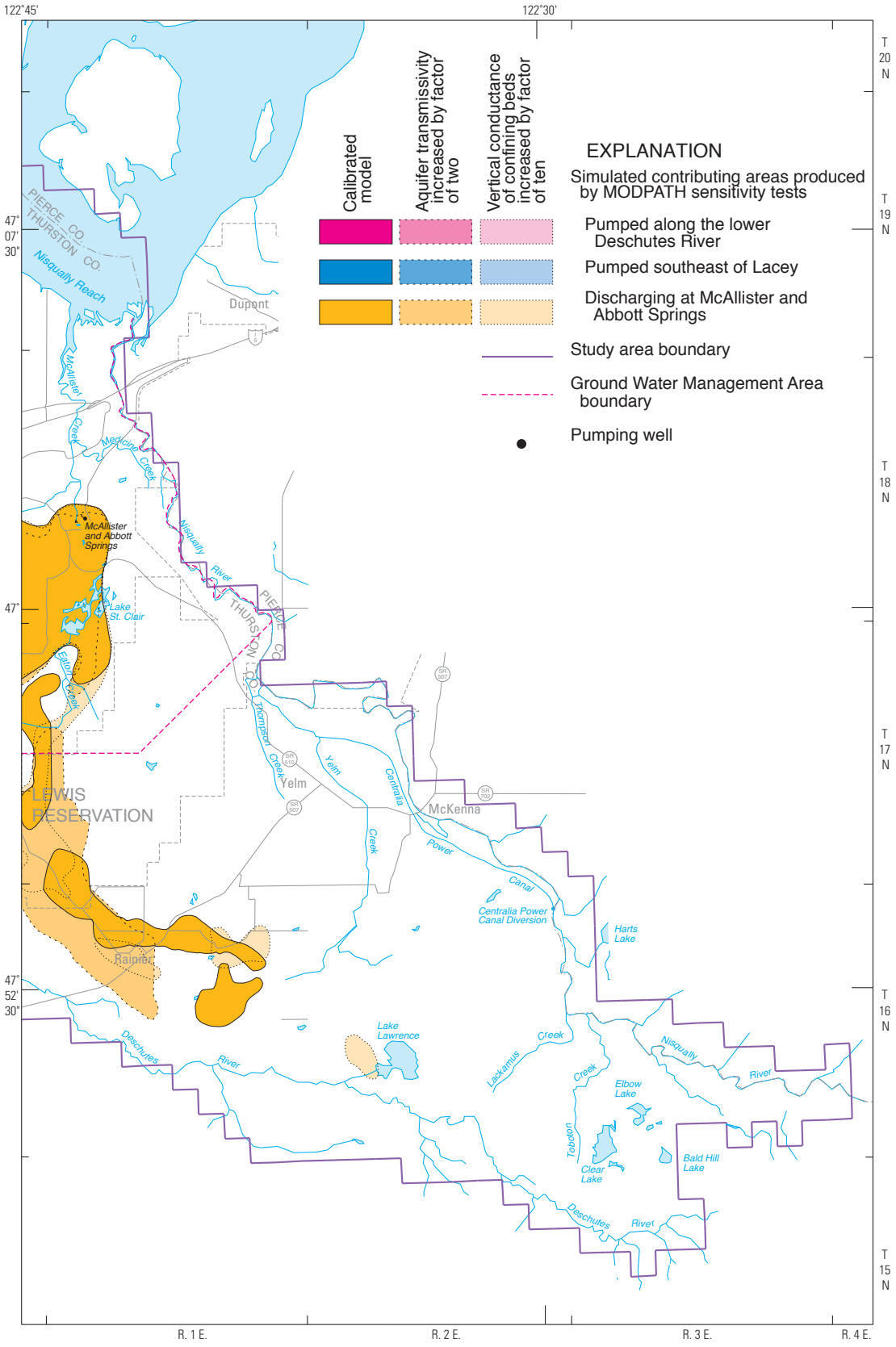


Figure 31. continued.

Ground-water flow in the unconsolidated sediments underlying Thurston County was simulated with a computerized numerical model (MODFLOW). Eight model layers were used to simulate the saturated unconsolidated sediments that overlie the Tertiary bedrock in the study area. Total thickness of the eight layers ranged from 0 to about 2,000 feet. Generally, the total thickness of the modeled sediments is greatest in the northern part of the county and thins toward the south. The model was calibrated in steady-state mode against observed and estimated 1988 ground-water levels and discharges.

Horizontal hydraulic conductivity values in the calibrated model ranged from 920 feet per day to 14 feet per day in the aquifer layers. The best estimate of the vertical hydraulic conductivity of the confining beds was determined to be 0.002 ft/d

Simulated inflow to the model area from precipitation and secondary recharge was 620,000 acre-ft/yr (93 percent), leakage from streams and lakes was 38,000 acre-ft/yr (6 percent) and ground water entering the model along the Chehalis River valley was 5,800 acre-ft/yr (1 percent). Simulated outflow from the model was primarily leakage to streams, lakes, springs, and seepage faces(500,000 acre-ft/yr or 75 percent of the total outflow). Submarine seepage to Puget Sound was simulated to be 88,000 acre-ft/yr (13 percent). Simulated ground-water discharge along the Chehalis River valley was 12,000 acre-ft/yr (2 percent). Simulated withdrawals by wells for all purposes was 62,000 acre-ft/yr (9 percent).

Thurston County has reserved water rights for an additional 23,000 acre-ft/yr for public water supply. The numerical model was used to simulate the possible effects of increasing ground-water withdrawals by 23,000 acre-ft/yr above the 1988 rate of withdrawal. The model indicated that the increased withdrawals would come from reduced discharge to springs, seepage faces, and offshore (51 percent) and decreased flow to rivers (46 percent). About 3 percent would come from increased leakage from rivers. Water levels would decline more than 1 foot over most of the model area, more than 10 feet over some areas, and would be at a maximum of about 35 feet in unit Qva west of Tumwater, and in unit Qc south of Lacy.

Contributing areas for water discharging to McAllister and Abbott Springs and to pumping centers near Tumwater and Lacey were estimated using a particle-tracking post-processing computer code (MODPATH). The MODFLOW model, calibrated to steady-state conditions (1988), was used for the MODPATH simulation. Water discharging at McAllister and Abbot Springs was determined to come from water entering the ground-water system at the water table in an area of about 20 square miles south of the springs. This water was estimated to come from recharge (both precipitation and secondary) and from leakage from Lake St. Clair and several other surface-water bodies. The source of 3,800 acre-ft of ground water pumped from five municipal wells southeast of Lacey during 1988 was estimated to be an area of about 1.1 mi^2. The water was estimated to come from recharge (both precipitation and secondary) and leakage from surface-water bodies. The source of 3,900 acre-ft/yr of ground water pumped during 1988 from 15 wells along the lower Deschutes River was estimated to be an area of about 1.3 mi^2. Within the calculated contributing area, the pumped ground water came from recharge (both precipitation and secondary) and leakage from the Deschutes River and several other surface-water bodies.

The model constructed for this project can be a useful tool for water-resources managers to qualitatively assess the regional effects of changes in stresses on the ground-water system. The model could also provide the larger context for detailed models covering smaller areas within the large model (primarily by supplying ground-water flow rates at the boundaries of the smaller models).

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