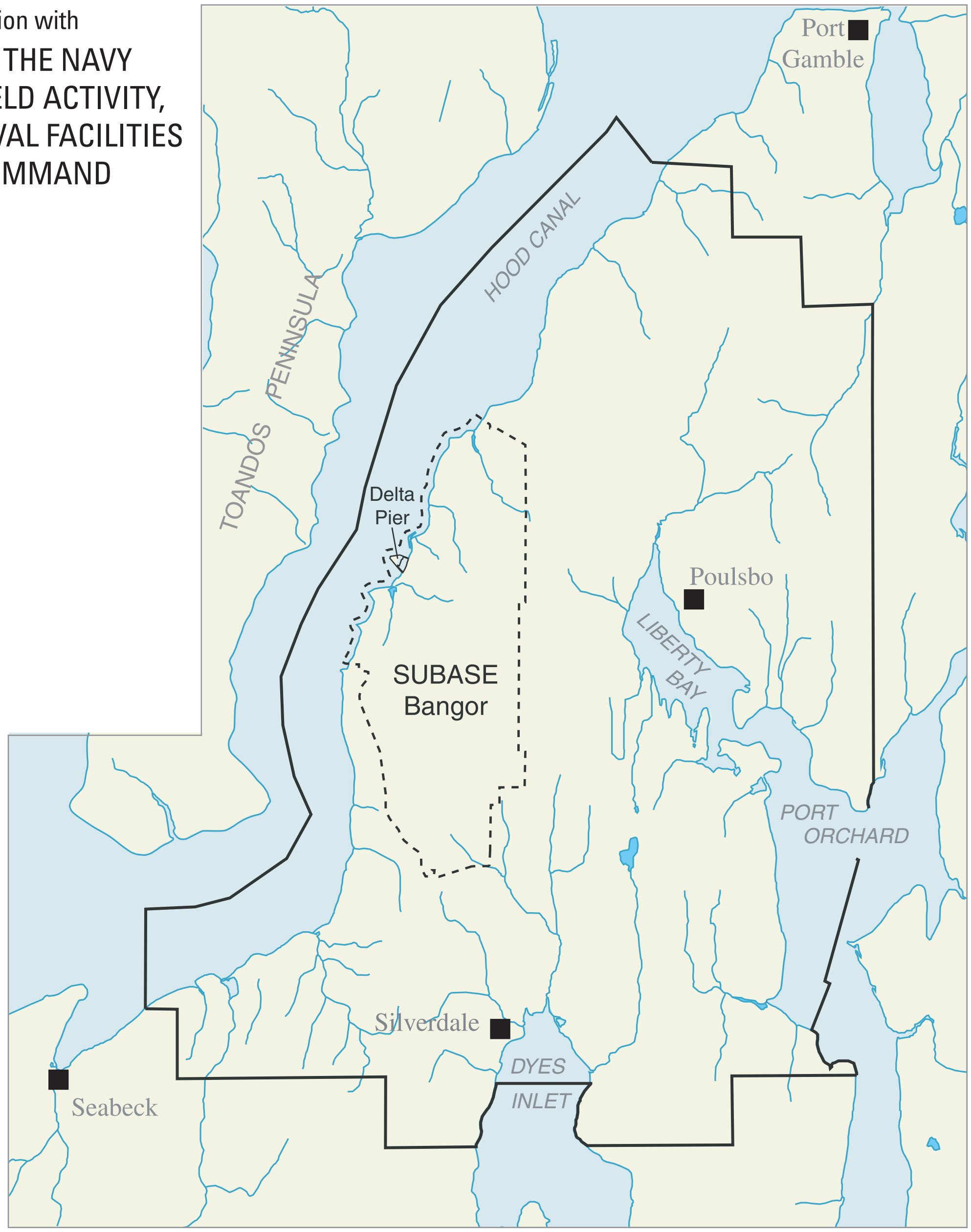
Simulation of the Ground-Water Flow System at Naval Submarine Base Bangor and Vicinity, Kitsap County, Washington

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 02-4261

Prepared in cooperation with
DEPARTMENT OF THE NAVY
ENGINEERING FIELD ACTIVITY,
NORTHWEST NAVAL FACILITIES
ENGINEERING COMMAND



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By Marijke van Heeswijk *and* Daniel T. Smith

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Tacoma, Washington
2002

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CONVERSION FACTORS

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
per foot (ft^{-1})	3.281	per meter
foot per day (ft/d)	0.3048	meter per day
foot squared per day (ft^2/d)	0.09290	meter squared per day
gallon per minute (gal/min)	0.06309	liter per second
inch (in.)	25.4	millimeter
mile (mi)	1.609	kilometer
million gallons (Mgal)	3,785	cubic meter
inch per year (in/yr)	25.4	millimeter per year
gallon per day (gal/d)	0.003785	cubic meter per day
pound per square inch per foot [(lb/in^2)/ft]	22.62	kilopascal per meter
square inch per pound (in^2/lb)	0.145	per kilopascal
pound per cubic foot (lb/ft^3)	16.02	kilogram per cubic meter
square mile (mi^2)	2.590	square kilometer

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

°C=(°F-32)/1.8.

Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Concentrations of chemical constituents in water are given in micrograms per liter (µg/L). One thousand micrograms per liter is equivalent to one milligram per liter. Micrograms per liter is equivalent to "parts per billion."

VERTICAL DATUM

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.

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

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ABSTRACT

An evaluation of the interaction between ground-water flow on Naval Submarine Base Bangor and the regional-flow system shows that for selected alternatives of future ground-water pumping on and near the base, the risk is low that significant concentrations of on-base ground-water contamination will reach off-base public-supply wells and hypothetical wells southwest of the base. The risk is low even if worst-case conditions are considered — no containment and remediation of on-base contamination. The evaluation also shows that future saltwater encroachment of aquifers below sea level may be possible, but this determination has considerable uncertainty associated with it. The potential effects on the ground-water flow system resulting from four hypothetical ground-water pumping alternatives were considered, including no change in 1995 pumping rates, doubling the rates, and 2020 rates estimated from population projections with two different pumping distributions.

All but a continuation of 1995 pumping rates demonstrate the possibility of future saltwater encroachment in the Sea-level aquifer on Naval Submarine Base Bangor. The amount of time it would take for encroachment to occur is unknown. For all pumping alternatives, future saltwater encroachment in the Sea-level aquifer also may be possible along Puget Sound east and southeast of the base. Future saltwater encroachment in the Deep aquifer also may be possible throughout large parts of the study area. Projections of saltwater encroachment are least certain outside the boundaries of Naval Submarine Base Bangor.

The potential effects of the ground-water pumping alternatives were evaluated by simulating the ground-water flow system with a three-dimensional uniform-density ground-water flow model. The model was calibrated by trial-and-error by minimizing differences between simulated and measured or estimated variables. These included water levels from prior to January 17, 1977 (termed "predevelopment"), water-level drawdowns since predevelopment until April 15, 1995, ground-water discharge to streams in water year 1995, and residence times of ground water in different parts of the flow system that were estimated in a separate but related study. Large amounts of ground water were pumped from 1977 through 1980 from the Sea-level aquifer on Naval Submarine Base Bangor to enable the construction of an off-shore drydock. Records of the flow-system responses to the applied stresses were used to help calibrate the model. Errors in the calibrated model were significant. The poor agreement between simulated and measured values could be improved by making many local changes to hydraulic parameters but these changes were not supported by other data. Model errors may have resulted in errors in the simulated effects of ground-water pumping alternatives.

INTRODUCTION

Naval Submarine Base Bangor (SUBASE Bangor) is a U.S. Navy installation of about 11 mi^2 that has been in operation since 1944. SUBASE Bangor is located along Hood Canal in Kitsap County, Washington (fig. 1). As a result of past activities on SUBASE Bangor, about 10 percent of the base contains sites with contaminated soil and shallow ground water. Contaminants include ordnance chemicals, metals, chlorinated hydrocarbons, petroleum hydrocarbons, pesticides, and polychlorinated biphenyls (PCBs). All sites were in remediation by 2000 and remaining ground-water contamination consisted of three well-characterized plumes (fig. 2). At the inception of this investigation, contaminated ground-water sites had been studied as individual units, rather than on a larger, regional scale.

The U.S. Navy recognizes that an understanding of the regional ground-water flow system of SUBASE Bangor and surrounding areas is required to understand how contaminated water could flow from shallow to deep aquifers, and how changes in rates of pumping of deep ground water could affect contaminant pathways and possibly cause saltwater encroachment in nearshore areas. The U.S. Navy also recognizes the need for a thorough understanding of the ambient quality of ground water in the area. As a result, the U.S. Geological Survey (USGS), at the request of SUBASE Bangor, began an investigation of the hydrology and water quality of SUBASE Bangor and vicinity in 1993, in cooperation with the Department of the Navy, Engineering Field Activity, Northwest (EFANW), Naval Facilities Engineering Command. This report describes the numerically simulated characteristics of the ground-water flow system of the study area for predevelopment conditions, development of the resource until April 15, 1995 and possible future conditions. It represents one of five studies undertaken as part of the entire investigation. Topics of the other studies are the: (1) ambient quality of ground water (Greene, 1997), (2) hydrogeology (Kahle, 1998); (3) recharge to ground water from precipitation (Bidlake and Payne, 2001); and (4) estimated ground-water residence times (Stephen E. Cox, U.S. Geological Survey, written commun., 2002).

Purpose and Scope

The purpose of this report is to evaluate how ground-water flow on SUBASE Bangor interacts with the regional ground-water flow system and how four hypothetical alternatives of future ground-water pumping potentially affect the ground-water flow system. The study examines the effects of projected ground-water pumping on (1) locations of zones of recharge of hypothetical pumping wells southwest of the base and public-supply wells on-base and off-base, (2) traveltimes of advectively transported, imaginary particles from a ground-water contaminant plume on-base to hypothetical pumping wells, (3) traveltimes from zones of recharge on-base to specific public-supply wells off-base, and (4) potential saltwater encroachment. Four hypothetical alternatives of projected ground-water pumping rates were considered. Pumping rates for 1995 were assumed to continue in the future for the first alternative; 1995 rates were doubled for the second alternative; and pumping rates were estimated for the projected population growth through 2020 with different areal distributions of pumping for the third and fourth alternatives.

The evaluation of the ground-water flow system was based on a numerical three-dimensional model for simulating steady or transient flow of ground water with uniform density. The model was calibrated to historical water levels from prior to 1977 until April 15, 1995, ground-water discharge to streams in water year 1995, and residence times of ground water in different parts of the flow system (Stephen E. Cox, U.S. Geological Survey, written commun., 2002). The conceptual model of the three-dimensional hydrogeology was based on interpretations by Kahle (1998) and simulated ground-water recharge from precipitation was based on estimates by Bidlake and Payne (2001).

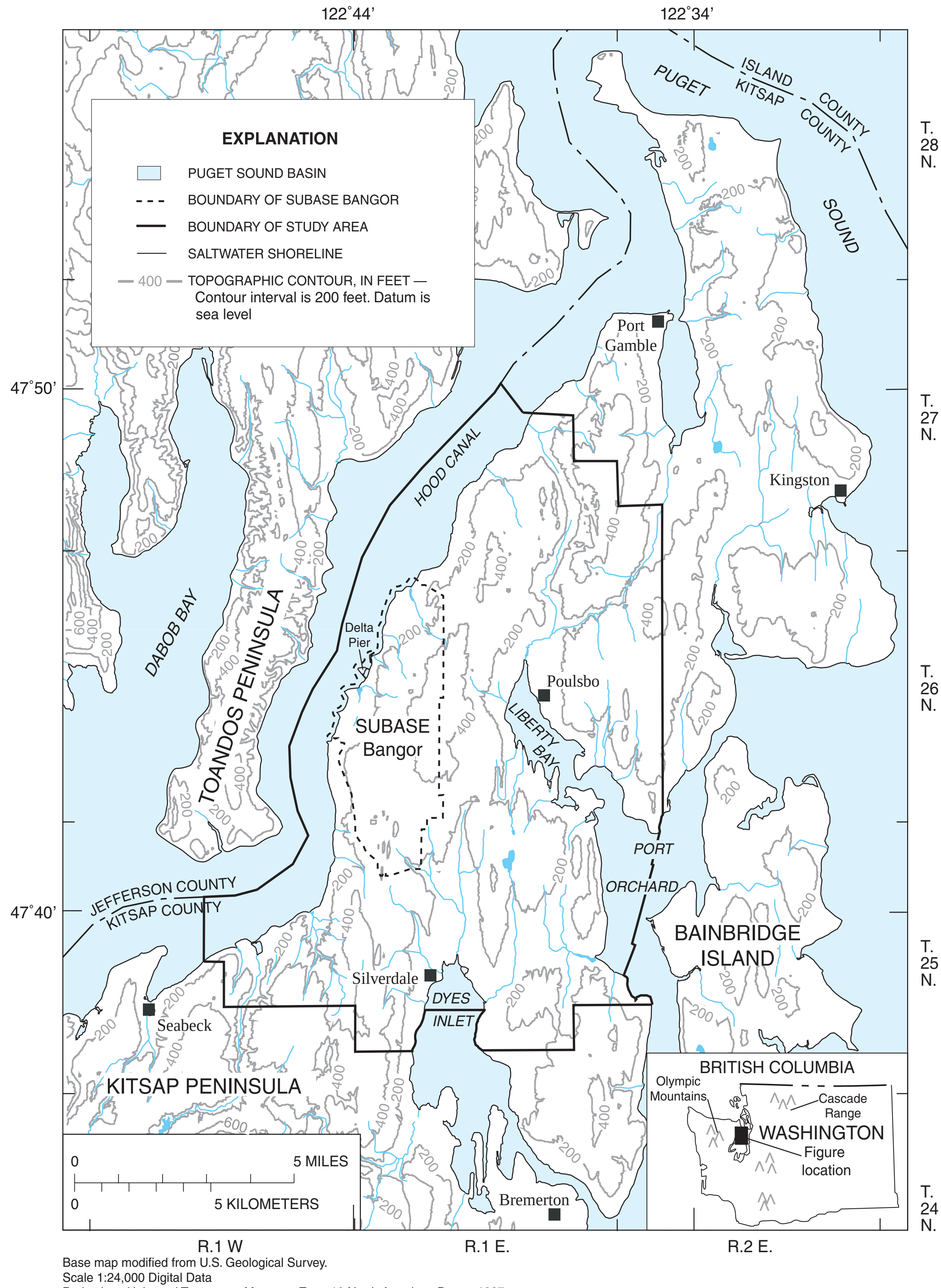


Figure 1. Location of SUBASE Bangor and vicinity, Kitsap County, Washington.

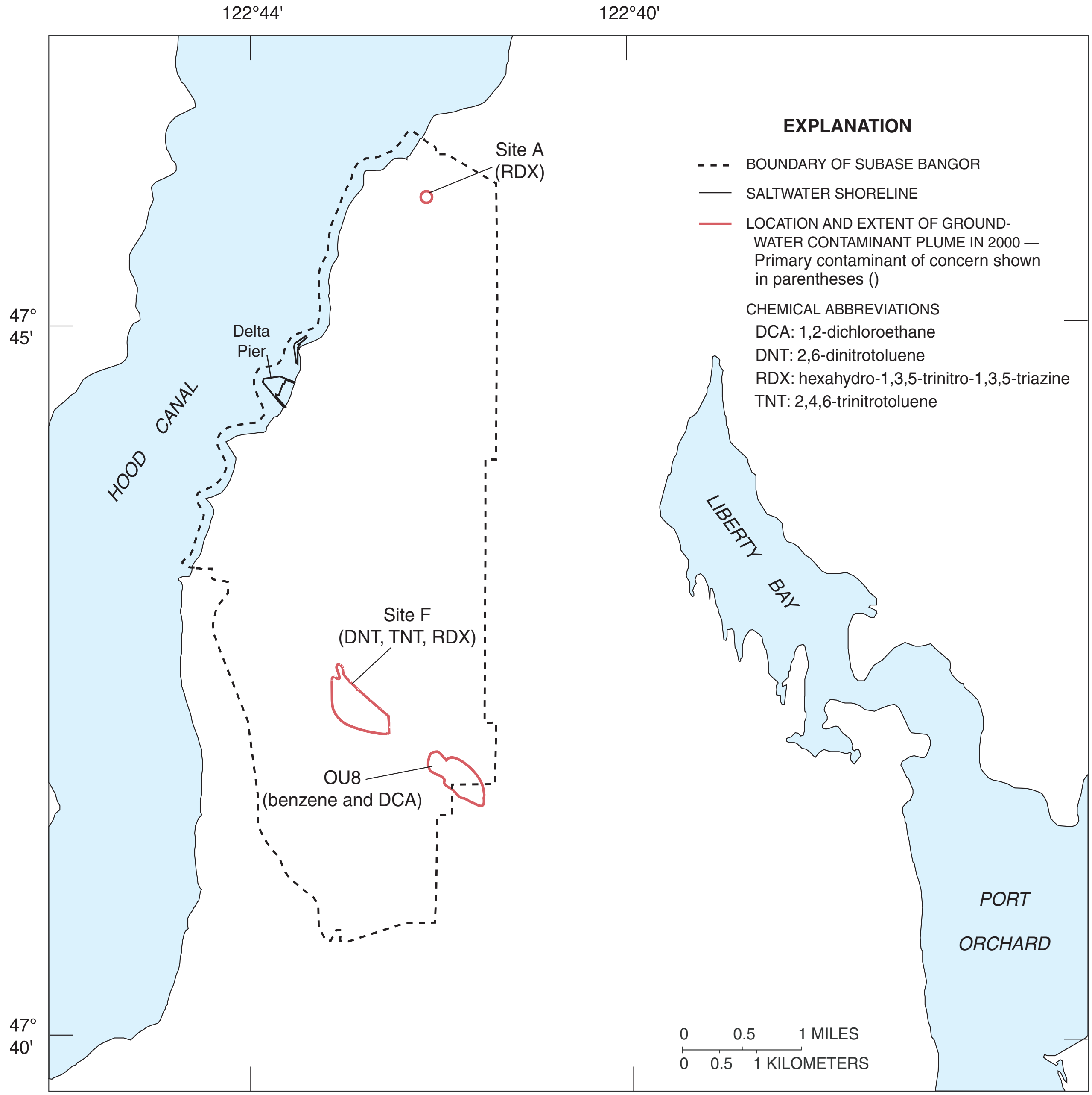


Figure 2. Locations of ground-water contamination sites on SUBASE Bangor, Kitsap County, Washington.

Description of Study Area

The study area is located on the Kitsap Peninsula of the Puget Sound Lowland in northwest Kitsap County (fig. 1). The study area includes SUBASE Bangor (11 mi^2) and surrounding land that cover a total area of about 85 mi^2. The study area was selected with hydrologic boundaries that could be used as boundaries of a numerical model for simulation of the ground-water flow system. The peninsula is surrounded by saltwater on the west, north, and east, and has a hydrologic setting similar to that of an island. Many coastal areas are steep, with altitudes ranging from sea level to 500 ft or more above sea level. Inland, slopes are moderate, and many areas are nearly flat. Glacial and interglacial deposits make up much of the subsurface of the study area and are exposed in cliffs along many shorelines. The deposits consist primarily of alternating layers of glacial till, sand and gravel, and silt and clay and were deposited on top of bedrock. The total thickness of unconsolidated sediments in the study area ranges from less than 600 ft to more than 1,500 ft. The deposits fill the western part of a regional basin that deepens to the east (Jones, 1996).

The study area is incised by mostly short streams that flow from the interior of the peninsula to Puget Sound (Hood Canal, Dyes Inlet, Liberty Bay, and Port Orchard). Most streams flow year-round and are fed by springs, distributed ground-water discharge, and surface runoff after storms. Where cliffs are present along the coastline, springs and seeps discharge water directly onto the beach and into Puget Sound. The maximum depth of Puget Sound in the study area ranges from more than 18, 30, and 60 ft to more than 360 ft in Dyes Inlet, Liberty Bay, Port Orchard, and Hood Canal, respectively. The magnitude of the tidal range in Hood Canal near SUBASE Bangor is about 13 ft.

The study area has a temperate maritime climate. Mean annual precipitation ranges from about 30 in/yr in the northeastern part of the study area to about 60 in/yr in the southwestern part (Kitsap County Ground Water Advisory Committee and others, 1991). Precipitation amounts are in large part controlled by the Olympic Mountains to the west and the Cascade Range to the east that impede the flow of humid air masses that are generated over the Pacific Ocean. Precipitation generally reaches a minimum during midsummer and a maximum during the late autumn and early winter. Mean monthly temperature in the study area ranges from about 39 °F in January to 64 °F in July and August (Owenby and Ezell, 1992). Winter temperatures at times are sufficiently low for a few inches of snow to accumulate; however, snow accumulation usually is insignificant.

About 47 percent of the study area is covered by coniferous and deciduous forests and about 13 percent by urban and military development. The remaining 40 percent of the study area is covered by non-forest vegetation, which includes agricultural and natural vegetative cover.

The population of the study area is concentrated in the towns of Silverdale and Poulsbo (fig. 1), with 1990 populations of 7,660 and 4,848 (U.S. Bureau of the Census, 1992). The countryside outside of these towns is rural and semi-rural, and many homes obtain potable water from individual wells instead of public-supply systems. The population in the study area increased by about 150 percent from 1970 to 1990. The increase in population is expected to continue with growth from about 39,000 inhabitants in 1990 to about 76,000 in 2020 (Puget Sound Council of Governments, 1988; U.S. Bureau of the Census, 1992). The resident population of SUBASE Bangor was 2,830 in 1993. This population has been projected to increase to 6,372 in 2012 as additional residential housing is constructed on-base (Parametrix, Inc., 1994).

Previous and Concurrent Investigations

The hydrogeology and ground-water resources of Kitsap County were first described by Sceva (1957) and Garling and others (1965). Later studies provided updated information about ground-water availability and quality in the part of Kitsap County covered by this investigation (Hansen and Molenaar, 1976; Lum, 1979; Hansen and Bolke, 1980; Dion and Sumioka, 1984). The most recent comprehensive update of the water resources of Kitsap County was prepared by the Kitsap County Ground Water Advisory Committee and others (1991) as part of the Kitsap County ground-water management plan.

The hydrogeology of SUBASE Bangor was first studied in detail during the 1970s in preparation for the construction of an off-shore drydock called Delta Pier (for example, Shannon and Wilson, Inc. and others, 1975). This study included the development of a ground-water flow model that was used to design the pressure reduction that was needed in local aquifers for the construction of Delta Pier (Cole and others, as reported by Bovay Engineers, Inc., 1975). The effects of the actual pressure reduction on the ground-water flow system on SUBASE Bangor was summarized by Paterson (1981). The artesian pressure relief system used during construction was described by Kinner and Stimpson (1983). Noble (1989) summarized the generalized hydrogeologic framework and flow system of SUBASE Bangor on the basis of available hydrogeologic studies at that time. Many hydrologic studies were conducted from the late 1980s to the present at individual sites on SUBASE Bangor with shallow ground-water and soil contamination. Hydrogeologic and water-quality information were summarized in detail by Hart Crowser, Inc. (1988, 1989, 2000). The hydrogeology of SUBASE Bangor was summarized in the Comprehensive Water System Plan for SUBASE Bangor (Parametrix, Inc., 1994) and closely follows the earlier work of Noble (1976 and 1989).

Concurrent with the USGS Bangor studies, the hydrogeologic framework and water budget of the aquifers at and near SUBASE Bangor were updated by Becker (with Robinson and Noble, Inc., 1995a). The updated information was incorporated into a three-dimensional ground-water flow model to assess water availability in the area (Becker, 1995b). These studies were commissioned by the Kitsap County Public Utility District No. 1 (KPUD). This investigation simulated a larger area of the ground-water flow system than Becker's study, so that natural hydrologic boundaries could be selected as model boundaries. Outlines of both models are presented in the section "Modeling Approach."

Well-Numbering System and Well Data

In Washington, wells are assigned identifiers that describe their locations with respect to township, range, section, and 40-acre tract. For example, number 26N/01E-12Q01 (fig. 3) indicates that the well is in township 26 North (N) and Range 1 East (E) 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 in figure 3. The two-digit sequence number (01) following the letter indicates that the well was the first one inventoried by USGS personnel in that 40-acre tract. A "P" following the sequence number indicates that the well is a piezometer.

Physical and hydrologic data for wells used in this study are described by Kahle (1998) and in Appendix 1. Altitudes of land surface for selected wells described by Kahle (1998) were modified in this study as described in Appendix 2.

Acknowledgments

The authors thank Joseph E. Becker, Robinson and Noble, Inc., who provided original data for many aquifer tests throughout the study area and miscellaneous data related to the aquifer pressure reduction on SUBASE Bangor. Martin B. Sebren, Kitsap County Public Utility District No. 1, provided historical water-use and water-level data for various public-supply wells in the study area, as well as aquifer-test results. Morgan Johnson, Silverdale Water District No. 16; Gary Thompson, City of Poulsbo; and Michael Scott, Naval Undersea Warfare Center Keyport, provided historical water-use data. Arthur K. Schick, Beverly A. Pavlicek, and Patricia L. Kelly, at the time all with SUBASE Bangor, were invaluable resources for SUBASE Bangor environmental data and provided feedback throughout the study.

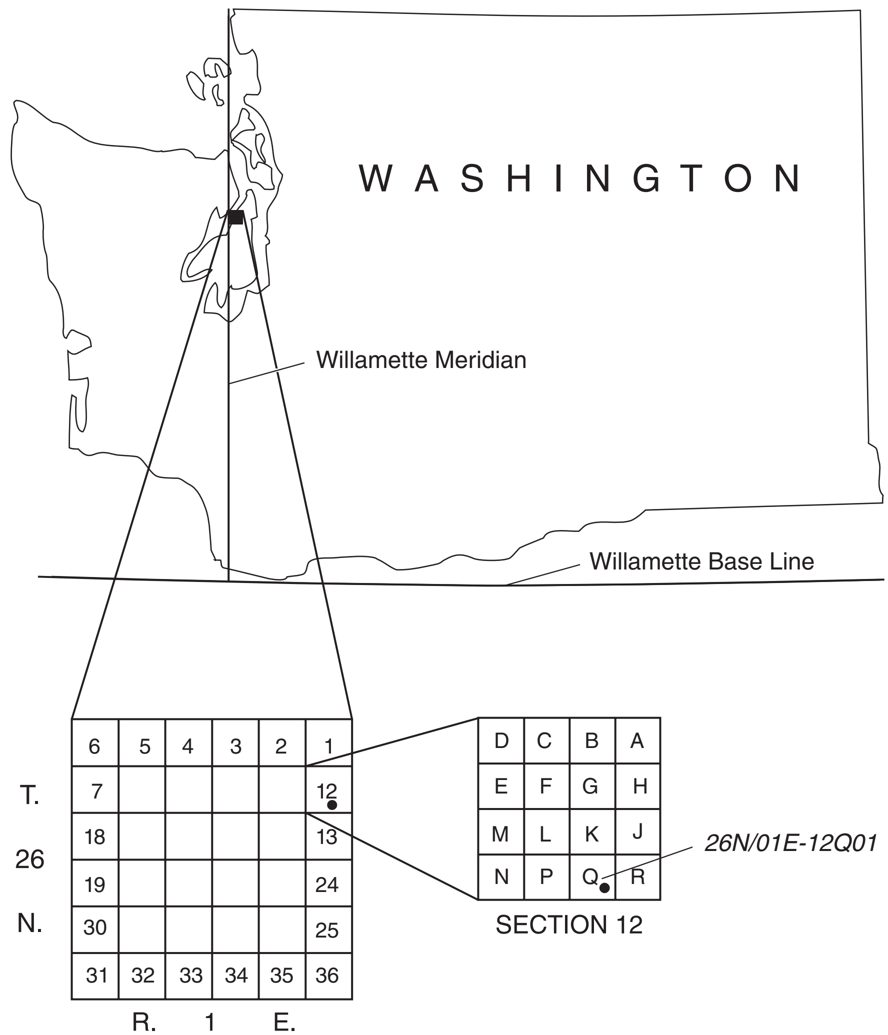


Figure 3. Well-numbering system used in Washington.

GROUND-WATER HYDROLOGY

Alternating layers of glacial and interglacial sediments with a wide range of hydraulic conductivities were deposited on top of bedrock to form the aquifers and confining units in the study area. An aquifer is a hydrogeologic unit that contains sufficient saturated permeable material to yield significant quantities of water to wells and springs, and a confining unit is a hydrogeologic unit of distinctly less permeable material bounding one or more aquifers. As part of the USGS Bangor studies, Kahle (1998) identified five aquifers and four confining units.

Precipitation is the source of almost all ground water in the study area. A fraction of the annual precipitation percolates vertically through the ground beneath the root zones of plants and recharges the ground-water system at the water table. The amount of recharge varies areally as a function of precipitation rate, vegetation type, land use, land slope, soil type, and near-surface geology. Bidlake and Payne (2001) estimated that the long-term average recharge from precipitation ranges from 0 to 21 in/yr and that most of the study area receives recharge ranging from 8 to 10 in/yr. Some of the ground-water recharge from precipitation leaves the flow system as discharge to springs, wells, streams, and seepage faces but some flows deeper into the system and recharges deeper aquifers. Deeper aquifers that lie at or below sea level may discharge ground water to saltwater bodies such as Hood Canal, Dyes Inlet, Liberty Bay, and Port Orchard (fig. 1). Because ground water is lost from the flow system at many depths, deeper aquifers receive less recharge than shallow aquifers.

Ground-water pumping in the study area has increased with population growth and increased activities on SUBASE Bangor. One of the largest measured changes in ground-water levels began in January 1977, when water levels on SUBASE Bangor were lowered for construction of the off-shore drydock, Delta Pier. Once construction was completed by the end of 1980, water levels recovered, although not to pre-1977 levels near Delta Pier. Water levels did not recover to pre-1977 levels because public-supply wells near Delta Pier that started pumping in 1977 continued to do so after construction ended, and artesian wells at Delta Pier were allowed to flow freely to maintain less-than-natural ground-water levels to ensure the integrity of the drydock.

Hydrogeologic Setting

Alternating layers of sediments of varying permeabilities were deposited on top of bedrock in the study area during a series of glacial and interglacial periods. The unconsolidated deposits in the study area fill the western part of a regional basin and range in thickness from less than 600 ft to more than 1,500 ft (Jones, 1996). The altitude of bedrock near the center of Hood Canal varies from north to south from about 600 ft to more than 900 ft below sea level and back to about 600 ft below sea level. The altitude of bedrock decreases to the east and is more than 1,100 ft below sea level within about 2 miles from the center of Hood Canal (Jones, 1996). Permeable deposits consisting of sands and gravels formed in meltwater river channels in front of advancing and retreating glaciers. While the area was covered by ice, a poorly sorted hard material with low permeability (till) was deposited by the glacier and lacustrine silt and clay were deposited in ice-dammed lakes. During interglacial periods, low permeability fine-grained materials such as clays and silts were deposited in lakes and swampy areas and coarse-grained alluvium was deposited in and along rivers. British Columbia generally has been the sediment source of the glacial deposits in the study area and the Olympic Mountains generally have been the sediment source of the interglacial deposits. Interglacial deposits are coarser in the western part of the study area due to the proximity to their source (Kahle, 1998).

Kahle (1998) obtained lithologic descriptions of more than 400 wells inventoried for the USGS Bangor studies and constructed a three-dimensional hydrogeologic framework for the study area. By grouping lithologies of similar permeabilities, Kahle identified 10 separate hydrogeologic units of either low or high permeability that are discernible on a regional scale. Becker (1995a) identified the same units with some differences as described by Kahle (1998). Glacial and interglacial sequences of deposits are heterogeneous, and correlating units over large distances includes a high degree of uncertainty in interpretation. Because fewer wells penetrate deeper deposits, the three-dimensional framework is known with more confidence near land surface than at depth. Deeper units frequently are more discontinuous or have large changes in thickness because the glacial deposits in older units were frequently reworked or eroded during later glacial and interglacial periods.

The hydrogeologic units identified by Kahle (1998) are shown in the conceptual hydrogeologic section in figure 4. This conceptual hydrogeologic section illustrates how the thickness and occurrence of the units vary considerably throughout the study area. Kahle (1998) provides a more detailed description of these units and how they correlate with prior identifications in the literature.

Aquifers in the study area (Qvr, Qva, QC1pi, QA1, and QA2) range in average thickness from 25 to 120 ft and confining units (Qvt, QC1, QC2, and QC3) range in average thickness from 45 to 210 ft (fig. 5).

Ground water occurs under water-table conditions in the Shallow aquifer and most of the Vashon aquifer. The Vashon aquifer is confined where it is fully saturated and overlain by the Vashon till confining unit. The permeable interbeds and the Sea-level and Deep aquifers are confined aquifers. The lithologic and hydrologic characteristics of the aquifers and confining units are summarized in figure 5.

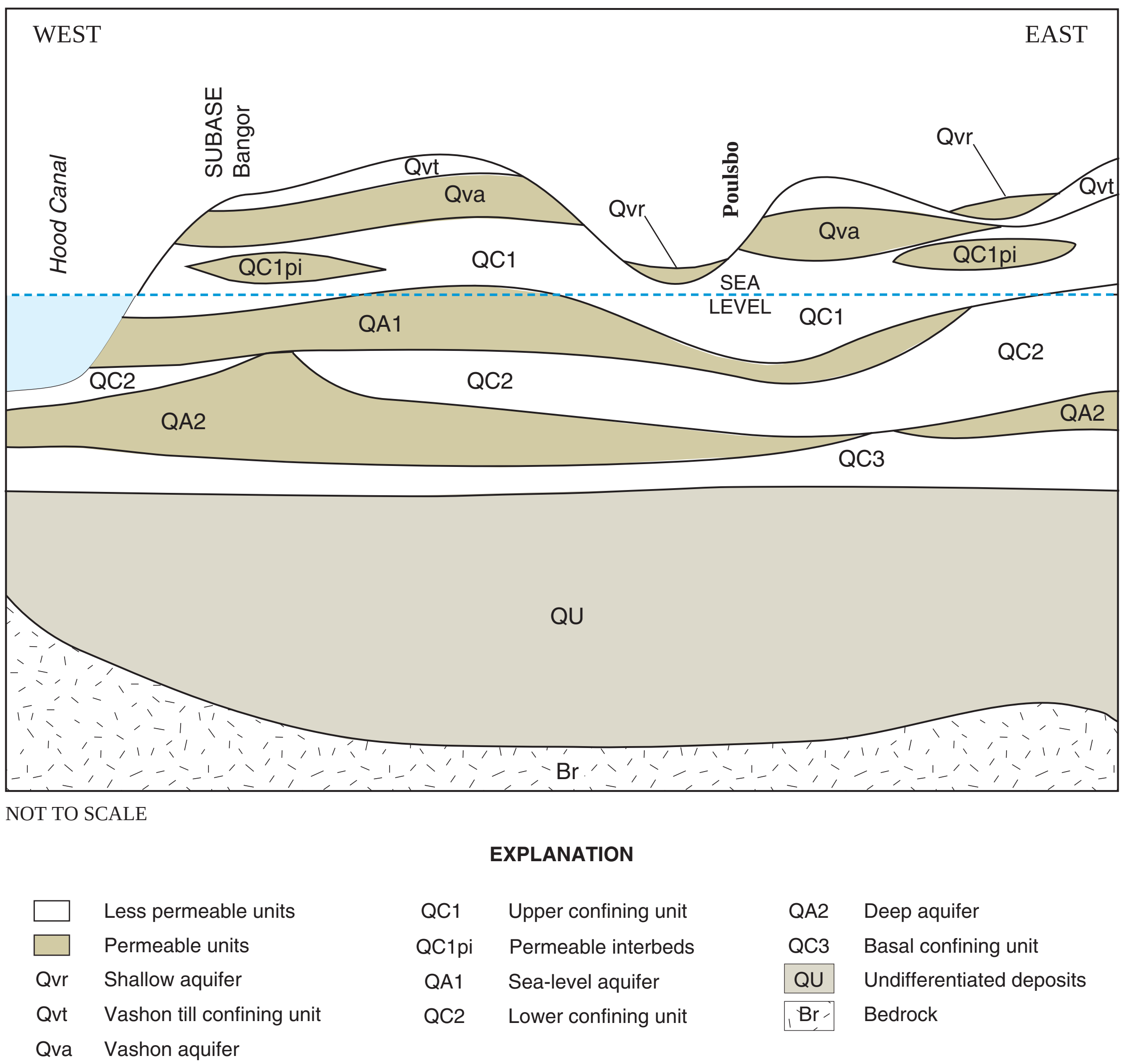


Figure 4. Conceptual hydrogeologic section through SUBASE Bangor and vicinity, Kitsap County, Washington.

Permeable units include sand and gravel outwash and alluvium; less permeable units may include till, silt, clay, and cemented silt, sand, and gravel. (Modified from Kahle, 1998.)

Hydrogeologic unit		Unit label	Range of thickness [average thickness] (feet)	Lithologic and hydrologic characteristics
Shallow aquifer		Qvr	4-74 [25]	Discontinuous unconfined aquifer consisting of sand, gravel, and silt. Unit includes lenses of silt and clay.
Vashon till confining unit		Qvt	3-134 [45]	Low-permeability unit consisting of compacted and poorly sorted silt, sand, and gravel (Vashon till) and a locally occurring sandy clay beneath the till. Unit includes water-bearing lenses of sand and gravel.
Vashon aquifer		Qva	5-497 [98]	Unconfined aquifer consisting of sand or sand and gravel. Unit is confined locally where it is fully saturated and overlain by till. Unit includes lenses of silt and clay.
Upper confining unit	Permeable interbeds	QC1 (QC1pi)	17-493 [200] 7-104 [29]	Low-permeability unit consisting mostly of glaciolacustrine silt and clay and underlying nonglacial iron-oxide cemented sand, silt, and gravel with lenses of silty peat and dispersed organic detritus. Permeable interbeds (QC1pi) are sand and gravel zones within QC1 that are sufficiently thick to delineate.
Sea-level aquifer		QA1	20-231 [110]	Confined aquifer consisting mostly of non-glacial sand and gravel with minor silt interbeds.
Lower confining unit		QC2	40-545 [140]	Low-permeability unit consisting of sandy silty clay and glacial sand and gravel with significant silt and clay layers. Where unit is absent, the Sea-level aquifer and the Deep aquifer are in direct hydraulic connection.
Deep aquifer		QA2	15-231 [120]	Confined aquifer consisting of sand and gravel outwash with minor amounts of silt.
Basal confining unit		QC3	170-300 [210]	Low-permeability unit consisting of blue clay and silt with some gravel.
Undifferentiated deposits		QU	unknown	Undifferentiated deposits overlying bedrock.

Figure 5. Lithologic and hydrologic characteristics of the hydrogeologic units of SUBASE Bangor and vicinity, Kitsap County, Washington. (Modified from Kahle, 1998.)

Hydraulic Properties of Aquifers and Confining Units

The hydraulic conductivity of the material in an aquifer or confining unit is a measure of the ease with which water can move through the material. It is a function of properties of both the matrix and the fluid. In this study, water in the regional flow system was assumed to have a uniform density and viscosity, and thus hydraulic conductivity only varies as the grain size, shape, sorting, and packing vary (Freeze and Cherry, 1979). Because matrix properties may vary over short distances, the hydraulic conductivity also may vary over short distances.

Horizontal hydraulic conductivities generally were greater than vertical hydraulic conductivities, as a result of the depositional history of the sediments. Horizontal hydraulic conductivities may be determined from single- or multiple-well aquifer tests. Single-well aquifer tests may be tests during which the pumping water level is measured at multiple time intervals or only once. The latter are referred to as specific-capacity tests. Results from multiple-well aquifer tests are usually more reliable because they usually integrate aquifer properties over a larger volume of the aquifer. Nonetheless, results of specific-capacity tests are the most common type of information available and considerable uncertainty remains in the interpretation of all aquifer-test data.

Kahle (1998) calculated horizontal hydraulic conductivities for a number of hydrogeologic units in the study area using specific-capacity data. Median horizontal hydraulic conductivities for the hydrogeologic units Qva, QC1, QC1pi, QA1, and QA2 were similar and ranged from 10 to 51 ft/d (table 1). No areal patterns in the horizontal hydraulic conductivities were detected by Kahle (1998).

Becker (1995a) summarized results of single- and multiple-well aquifer tests for wells on and off SUBASE Bangor. Off-base wells were usually public-supply wells tested by Robinson and Noble, Inc. Becker's results were reported as transmissivity, which is defined as

$$T = K_h\, b, \qquad (1)$$

where

T = transmissivity (ft^2/d),

K_h = horizontal hydraulic conductivity (ft/d), and

b = thickness of the unit (ft).

For a number of aquifer tests on SUBASE Bangor, Battelle (1977) reported lower transmissivities than those summarized by Becker (1995a). These differences are attributed to different interpretations of the same data. Using transmissivities reported by Battelle (1977) or Becker (1995a), horizontal hydraulic conductivities, K_h, were calculated using equation 1 by estimating the thicknesses, b, of the tested permeable units. The thickness was estimated as the length of the screened interval for single-well tests, and either the thickness of the permeable beds (if known) or four times the length of the screened interval for multiple-well tests, according to a technique outlined by Prudic (1991). The latter method for estimating thickness was used if the thickness of the permeable beds was unknown. The factor of 4 was calculated as the median ratio of permeable-bed thickness to length of the screened interval for wells where both were known.

Table 1. Median horizontal hydraulic conductivities and specific storages of selected hydrogeologic units of SUBASE Bangor and vicinity, Kitsap County, Washington

[**Hydrogeologic unit**: Qva, Vashon aquifer; QC1, Upper confining unit; QC1pi; Permeable interbeds; QA1, Sea-level aquifer; and QA2, Deep aquifer. Hydrogeologic designations are from Kahle (1998). **Specific-capacity tests**: Data from Kahle (1998). **Aquifer tests**: Source data from Becker (1995a) and Battelle (1977). Numbers in brackets are number of wells. –, not available]

Hydrogeologic unit	Median horizontal hydraulic conductivity (feet per day)		Median specific storage (per foot)
	Specific-capacity tests	Aquifer tests	Aquifer tests
Qva	51 [115]	223 [3]	–
QC1	10 [36]	–	–
QC1pi	34 [60]	288 [8]	–
QA1	43 [71]	26 [34]	1.4×10^{-6} [23]
QA2	21 [11]	122 [14]	4.8×10^{-5} [4]

The ratio calculated in this study was double the ratio calculated by Prudic (1991) for the Gulf Coast region in the south-central United States. The calculation of the ratio in this study used far fewer wells than Prudic (1991).

Median horizontal hydraulic conductivities estimated from aquifer tests are summarized in table 1 and range from 26 to 288 ft/d. Median horizontal hydraulic conductivities from aquifer tests were larger than those from specific-capacity tests, except for aquifer QA1. Prudic (1991) also estimated larger conductivities from aquifer tests than from specific-capacity tests. Areal patterns in horizontal hydraulic conductivities were not observed in the study area based on hydraulic conductivities estimated from aquifer tests.

Vertical hydraulic conductivities generally are not available for confining units, except for isolated laboratory measurements. Vertical hydraulic conductivities ranged from about 10^{-3} to 10^{-5} ft/d for laboratory measurements of the confining unit QC1 at Keyport in the eastern part of the study area (URS Consultants, Inc., and Science Applications International Corporation, 1993).

Results of multiple-well aquifer tests can be used to calculate storativities in addition to transmissivities. Storativity is a measure of the volume of water an aquifer or confining bed releases or takes into storage as the head changes and is defined as

$$S = S_S\, b, \qquad (2)$$

where

S = storativity (dimensionless), and
S_S = specific storage (ft^{-1}).

A limited number of storativities were reported by Battelle (1977) and Becker (1995a). Using the results reported by Battelle (1977) or Becker (1995a), specific storages, S_S, were calculated using equation 2 by estimating the thicknesses of the tested permeable units, b, with the same technique that was used to calculate the horizontal hydraulic conductivities from transmissivities. The resulting median specific storages are summarized in table 1.

Natural Recharge

Almost all ground-water recharge in the study area results from the percolation of a fraction of the total precipitation through the unsaturated zone beneath the root zones of plants. Leakage from selected stream reaches may provide a small fraction of the total recharge. Artificial recharge through wells was another source of water to the ground-water system. Any recharge from septic-system drainage was assumed to be largely offset by ground-water pumping by domestic wells.

As part of the USGS Bangor studies, Bidlake and Payne (2001) estimated direct recharge from precipitation as a function of annual precipitation and soil and land cover. They developed five equations (table 2), one for each soil and land-cover group, to estimate annual recharge. Bidlake and Payne's (2001) method was based on detailed water-budget measurements in four drainage basins in the study area. The measurements were used to simulate the water budget in each drainage basin on a daily basis using the Deep Percolation Model (DPM) (Bauer and Vaccaro, 1987; Bauer and Mastin, 1997), and to calculate percolation of precipitation below the root zone as a residual. Percolation of precipitation below the root zone was assumed to be the same as recharge to the ground-water system. In reality, some delay is expected between the time water percolates below the root zone and when it reaches the water table. In addition, not all percolated water may reach the water table (Bidlake and Payne, 2001). As part of the simulations, each drainage basin was subdivided into areas of similar soil, land cover, slope, and precipitation. On the basis of the results of the combined simulations, recharge to the ground-water system could be determined as a function of soil- and land-cover type and precipitation. Data were insufficient to determine recharge as a function of slope. The results of the combined simulations were interpolated over the entire study area. Considerable uncertainties are associated with this method, as discussed by Bidlake and Payne (2001); however, the recharge estimate based on the method likely represents the best estimate available to date, because it was estimated from actual measurements of components of the water budget.

Table 2. Equations for estimating annual recharge to ground water from annual precipitation for different soil and land-cover groups, SUBASE Bangor and vicinity, Kitsap County, Washington

[Data from Bidlake and Payne, 2001]

Soil and land-cover group	Annual recharge, *R*, in inches, as a function of annual precipitation, *P*, in inches
Nonforest vegetation on soils formed on glacial outwash and other alluvium	$R = 0.806P - 8.87$
Forest vegetation and soils formed on glacial outwash and other alluvium	$R = 0.633P - 6.96$
Forest and nonforest vegetation on soils formed on glacial till or fine-grained sediments	$R = 0.388P - 4.27$
Developed or urban land	$R = 0.194P - 2.13$
Water and wetlands	R assumed to equal 0

Using a long-term average precipitation at Bremerton of 52 in/yr (based on 1953-95 data) that was prorated over the study area, Bidlake and Payne (2001) estimated that long-term average recharge to the water table ranges from 0 to 21 in/yr over the study area (fig. 6). In most of the study area, however, long-term average recharge ranges from 8 to 10 in/yr. Most of this recharge occurs from late autumn through late spring during the time of maximum precipitation (fig. 7).

Historical Ground-Water Discharge and Artificial Recharge

Ground-water use in the study area has steadily increased since the beginning of the 20th century as the population increased and Naval activities on SUBASE Bangor expanded since they first started in 1944. Ground-water pumping prior to 1977, however, is believed to have been sufficiently small so that its effect on water levels was insignificant. This period of time is referred to as "prior to development" or "predevelopment."

A history of ground-water discharge from and recharge to wells on and off SUBASE Bangor was reconstructed for January 1977 through December 1995. Data for SUBASE Bangor wells were obtained from various sources that included miscellaneous records and published information from SUBASE Bangor and Robinson and Noble, Inc. (Paterson, 1981; Kinner and Stimpson, 1983). The off-base wells included in the history were those that were parts of water systems with at least 50 connections in 1996 (J.J. Welch, Washington Department of Health, written commun., 1996). These data were obtained from water-system managers and KPUD and any missing data were estimated.

On SUBASE Bangor

During Delta Pier Construction

From January 17, 1977 to October 16, 1980, large amounts of water were pumped from the Sea-level aquifer near the shore at SUBASE Bangor to reduce artesian water levels for construction of the off-shore drydock Delta Pier (fig. 8). Paterson (1981) estimated that during this period, 4,420 Mgal were pumped from the Sea-level aquifer, of which 3,240 Mgal were discharged to Hood Canal, 620 Mgal were used for water supply at SUBASE Bangor, and 560 Mgal were artificially recharged into the Sea-level and Deep aquifers to reduce water-level decreases inland from the construction project. Data presented by Kinner and Stimpson (1983) and miscellaneous records from SUBASE Bangor and Robinson and Noble, Inc. indicate that the total volume of water pumped from the Sea-level aquifer may have been 12 percent larger than reported by Paterson (1981).

Ground water initially was pumped from up to five wells along the shore (WRP-1, WRP-2, WRP-3, WRP-4, and WRP-5, also referred to in previous studies as the "Red Wells" and in this study as the on-shore pressure reduction wells; figs. 8 and 9). By May 20, 1978, pumping from these wells ceased, and pumping began for up to 12 wells located off-shore (the WCP/WTP wells, also referred to in previous studies as the "Purple Wells" and in this study as the off-shore pressure reduction wells). The WRP and WCP/WTP wells were installed to help reduce water levels, and water pumped from them was discharged into Hood Canal (Paterson, 1981). In addition to pumping from the WRP and WCP/WTP wells, ground water was pumped from at least one of four newly installed public-supply wells (501, 502, 503, and 504, also referred to in previous studies as the "Blue Wells") and two pre-existing public-supply wells (1181 and SWFPAC 6610) for most of the duration of the construction period. A new supplemental public-supply well (505 or TH18) was drilled in the spring of 1979. However, this well was little used because naturally occurring concentrations of iron and manganese were high in the well water (Arthur K. Schick, SUBASE Bangor, oral commun., 1996). During Delta Pier construction, part of the water pumped by the public-supply wells was used for consumption and part was used to artificially recharge the Sea-level and Deep aquifers. Pumping ceased from the off-shore pressure reduction wells on October 16, 1980, after the drydock construction was completed. All these wells (except for two which were replaced by two nearby wells) were allowed to continue to discharge by gravity flow in order to continue to provide some reduction in the artesian pressures at the drydock (Paterson, 1981; Kinner and Stimpson, 1983).

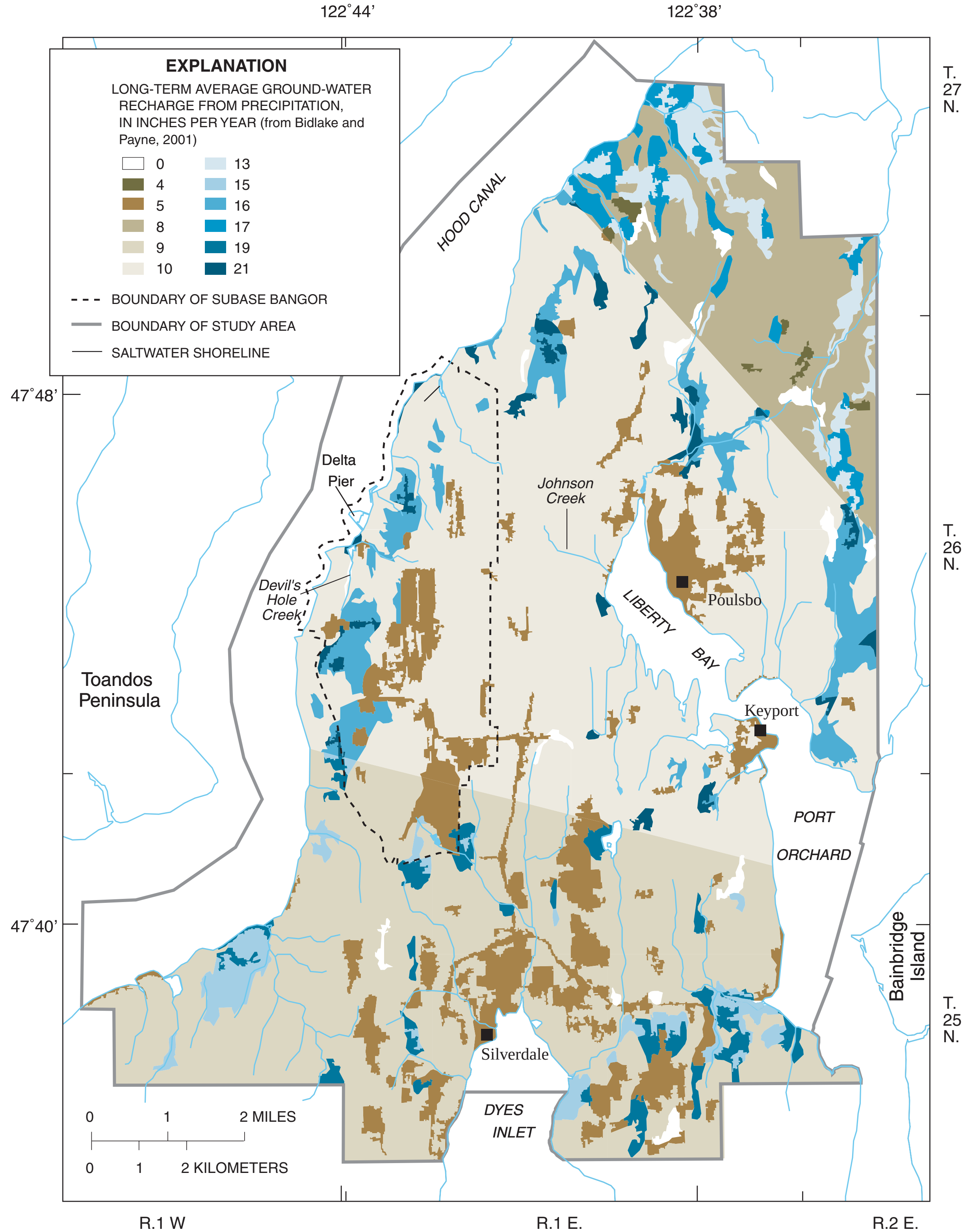


Figure 6. Long-term average ground-water recharge from precipitation for SUBASE Bangor and vicinity, Kitsap County, Washington. (From Bidlake and Payne, 2001.)

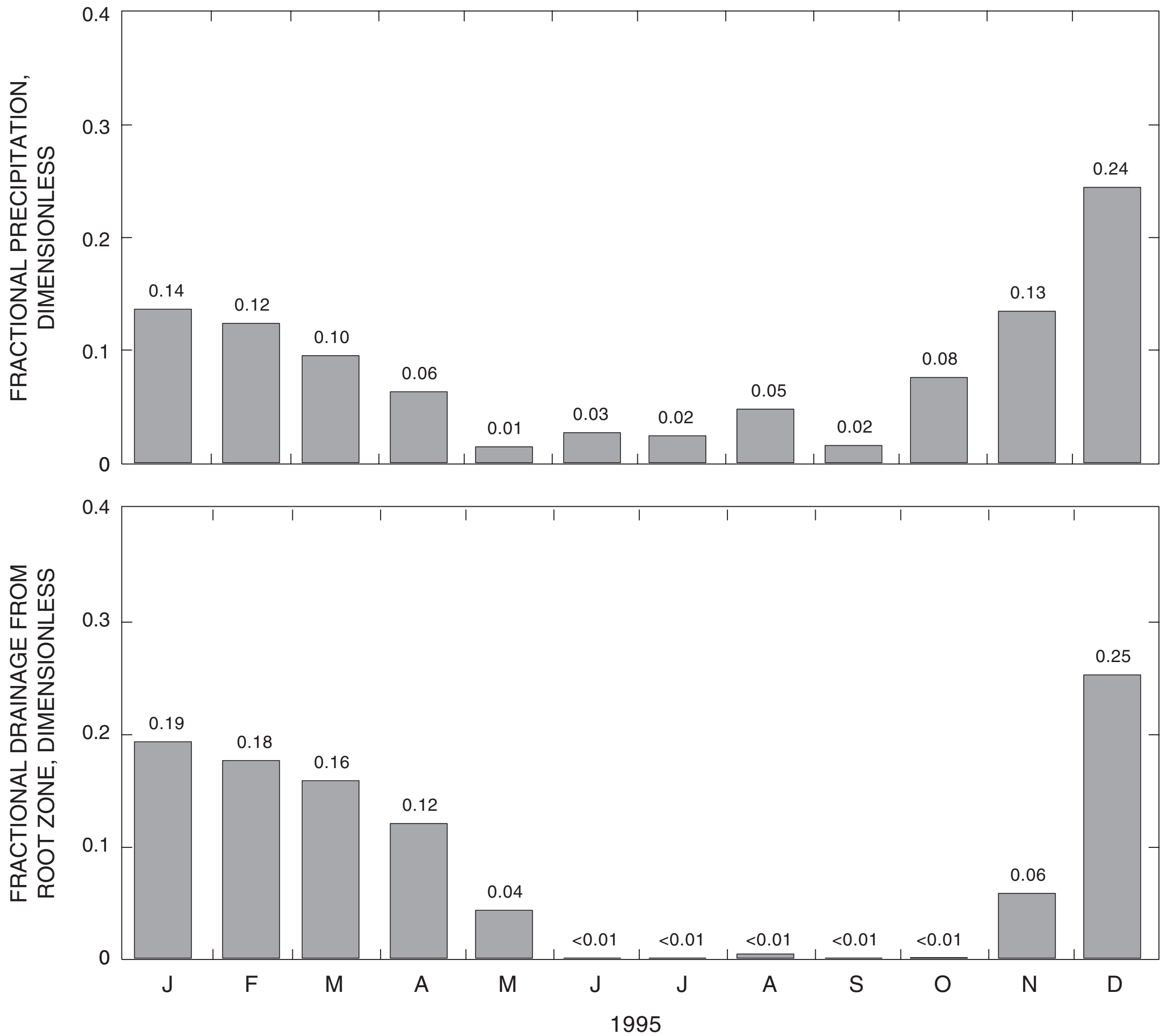


Figure 7. Monthly precipitation and simulated drainage from the root zone expressed as a fraction of the 12-month average for SUBASE Bangor and vicinity, Kitsap County, Washington.

(From Bidlake and Payne, 2001.)

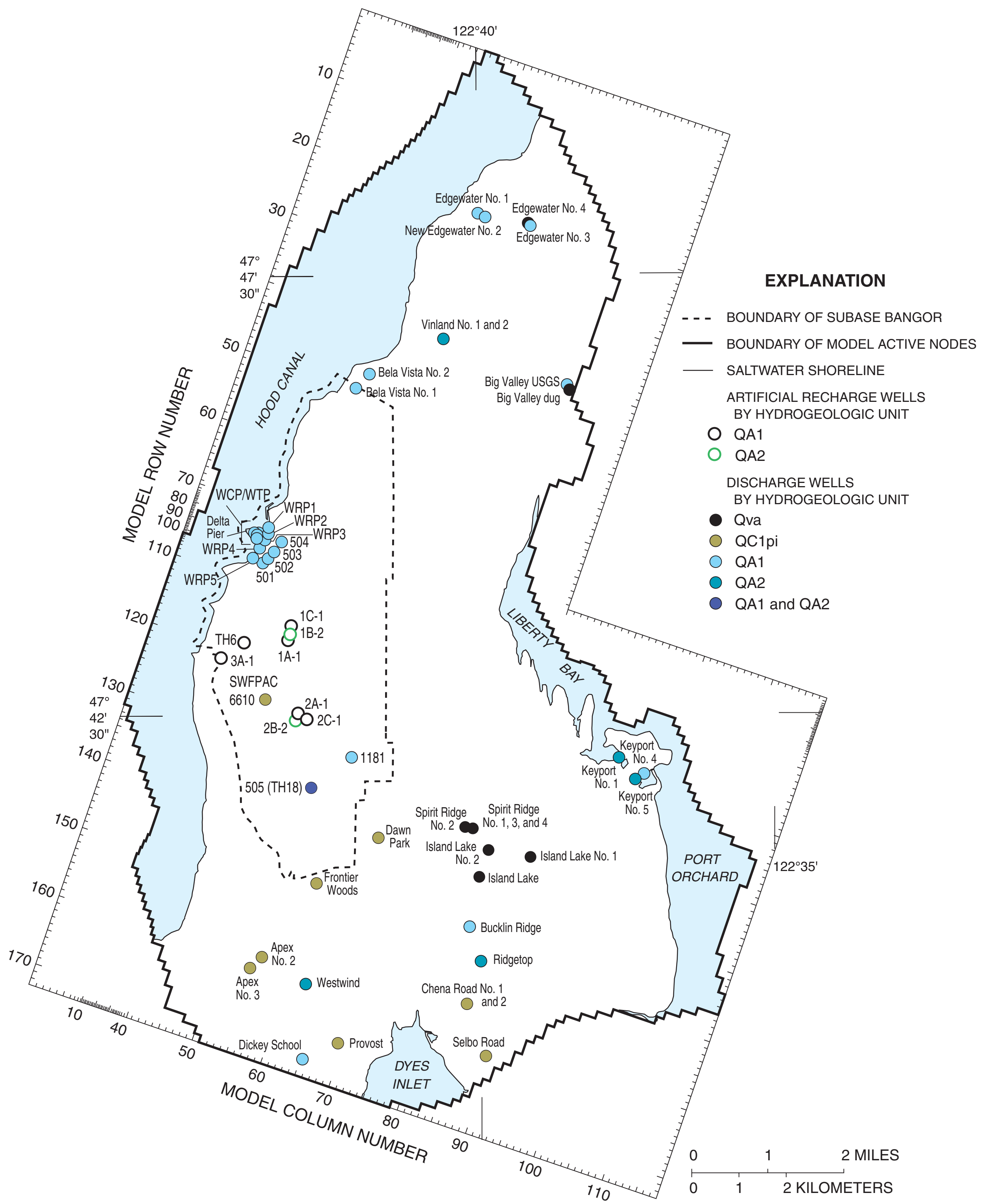


Figure 8. Locations of artificial recharge and discharge wells by hydrogeologic unit on SUBASE Bangor, Kitsap County, Washington.

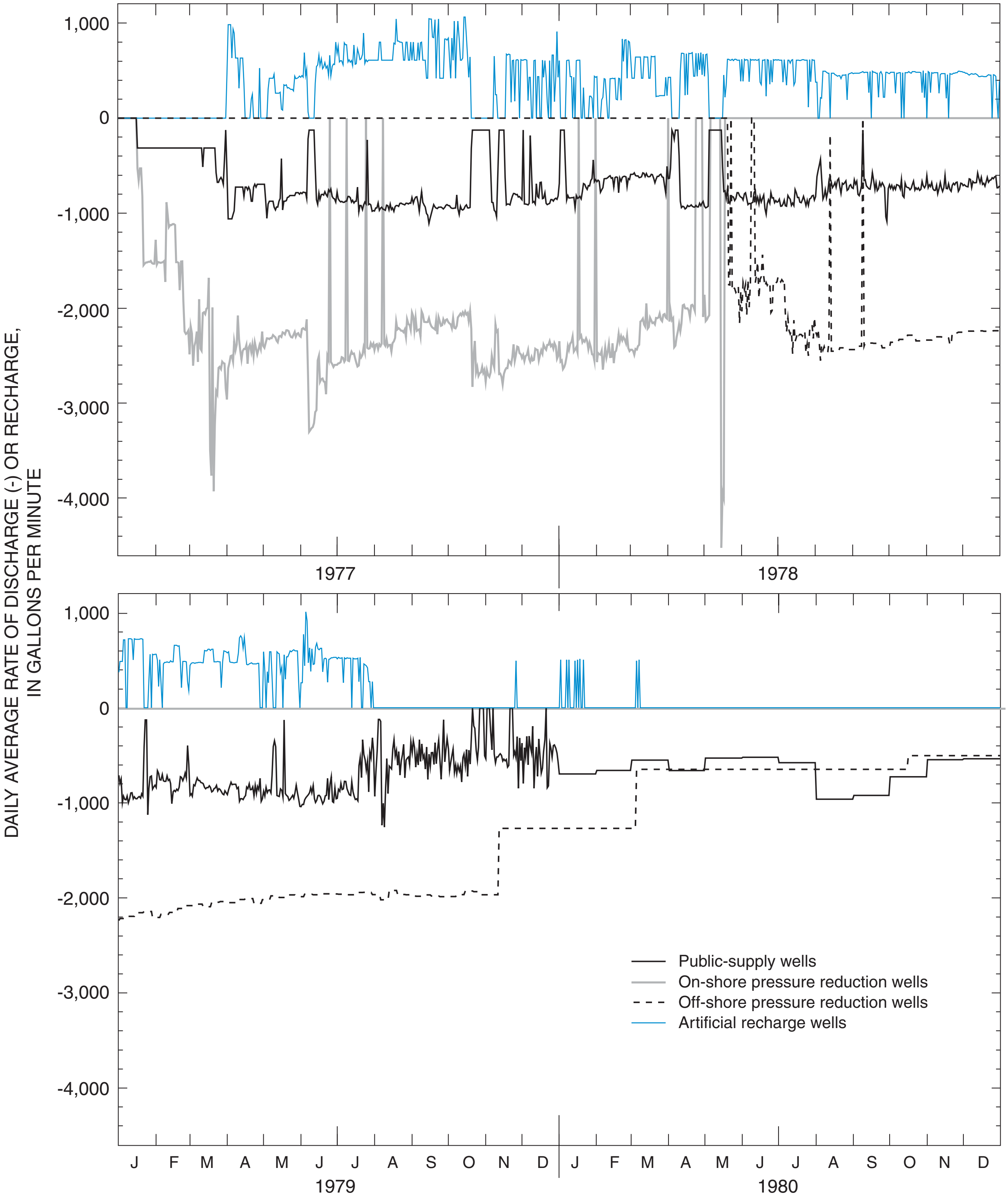


Figure 9. Daily average rates of discharge (-) from or recharge to wells on SUBASE Bangor, Kitsap County, Washington, 1977-80.

Artificial ground-water recharge occurred in several well fields (fig. 8). Well field 1 had three wells, two of which recharged the Sea-level aquifer (wells 1A-1 and 1C-1) and one recharged the Deep aquifer (well 1B-2). An alternate well (well TH6) was used to recharge the Sea-level aquifer when wells in well field 1 were off-line (Paterson, 1981). Well field 2 also had three wells, two of which recharged the Sea-level aquifer (wells 2A-1 and 2C-1) and one recharged the Deep aquifer (well 2B-2). A third well field had one well that recharged the Sea-level aquifer (well 3A-1).

Despite the data presented by Paterson (1981), Kinner and Stimpson (1983), and miscellaneous data obtained from SUBASE Bangor and Robinson and Noble, Inc. files, some missing data and discrepancies remained in the reconstructed history of ground-water discharge and artificial recharge. As a result, data were estimated and corrected for selected time periods (table 3).

As noted above, pumpage data for public-supply wells 1181 and SWFPAC 6610 during Delta Pier construction were not available. Because the first of the 500-series public-supply wells did not come on-line until March 23, 1977, pumpage for wells 1181 and SWFPAC 6610 was assumed to be 315 gal/min from January 17 through March 22, 1977, because this was the average rate of public consumption based on information presented by Paterson (1981). Wells 1181 and SWFPAC 6610 must have continued to pump after the 500-series came on-line, because total pumpage from wells 501 through 504 was insufficient to meet public-supply demands and documented artificial recharge. As a result, the combined pumpage from wells 1181 and SWFPAC 6610 was estimated to be 126 gal/min from March 23, 1977 through July 28, 1979, which is the last day the data indicated significant artificial recharge. Because separate pumpage for wells 1181 and SWFPAC 6610 was unknown, pumpage from well 1181 was assumed to be twice that of well SWFPAC 6610, to reflect the ratio between the capacities of these wells, which were estimated as 500 and 250 gal/min in 1973 (Becker, 1995a).

Because the 12 off-shore pressure reduction wells are screened in the same aquifer and are located close together in the off-shore drydock (fig. 8), pumpage from the 12 wells was totaled and the total pumpage was estimated for several periods of missing data. Neighboring time periods were used to interpolate the estimates.

Artificial recharge data were available for all recharge wells except well 3A-1. Because specific capacities were low in wells 3A-1 and 1B-2, recharge was assumed to be identical for both wells. A few short periods of recharge data were missing for recharge well TH6 based on a review of available water-level data; therefore, these data were estimated by correlating recharge rates and water levels during time periods when both data types were available. All estimated and known artificial recharge were increased by 5.4 percent so that total recharge from January 17, 1977 through October 15, 1980 would equal total recharge reported by Paterson (1981).

Most discharge and artificial recharge data were available for the period of Delta Pier construction. Some pumpage was estimated for public-supply wells 1181, SWFPAC 6610, and the off-shore pressure reduction wells as well as some artificial recharge for wells TH6 and 3A-1. All artificial recharge was increased by 5.4 percent to equal the total artificial recharge reported by Paterson (1981). Comparison of total discharge and artificial recharge for different groups of wells as used in this study and reported by Paterson (1981) and Kinner and Stimpson (1983) indicated that total discharge and artificial recharge data overall were in close agreement between this study and Kinner and Stimpson, and in slightly less agreement between this study and Paterson (1981) (table 4). The reading of discharge estimates from the graph in figure 11 of Kinner and Stimpson (1983) may have introduced some error.

Post Delta Pier Construction

After cessation of pumping for pressure relief during construction of Delta Pier, drinking water continued to be supplied by the 500 series of wells, which may have been occasionally supplemented by water from wells 1181 and SWFPAC 6610. However, discharge records do not exist for wells 1181 and SWFPAC 6610 prior to April 1, 1989 and June 1, 1989, respectively, and these wells were assumed not to have been pumped much after construction ended. For the period before April 13, 1981, gravity-flow discharge data for the off-shore pressure reduction wells were unavailable. As a result, these data and data for some other time periods were estimated (table 3).

Table 3. Discharge and recharge wells and selected time periods with estimates of or corrections to discharge or recharge data, SUBASE Bangor, Kitsap County, Washington

[**Well No.**: See figure 3 for explanation of well-numbering system. **Navy identifier**: Locations of wells are shown in figure 8. **Well type**: D, discharge; R, recharge. **Hydrogeologic unit**: QC1pi, Permeable interbeds; QA1, Sea-level aquifer; QA2, Deep aquifer. Hydrogeologic designations are from Kahle (1998). **Period of discharge or recharge estimate or correction**: –, no estimates or corrections needed]

Well No.	Navy identifier	Well type	Hydrogeologic unit	Period of discharge or recharge estimate or correction
		Public-supply wells		
26N/01E-18K01	504	D	QA1	–
26N/01E-18P03	501	D	QA1	–
26N/01E-18P04	502	D	QA1	–
26N/01E-18P05/06	503 Old/New	D	QA1	–
26N/01E-30L01	SWFPAC 6610	D	QC1pi	Jan. 17, 1977 to May 31, 1989
26N/01E-31R01	505 (TH18)	D	QA1 and QA2[1]	–
26N/01E-32L05	1181	D	QA1	Jan. 17, 1977 to Mar. 31, 1989
		On-shore pressure reduction wells		
26N/01E-18L04	WRP-1	D	QA1	–
26N/01E-18L05	WRP-2	D	QA1	–
26N/01E-18L06	WRP-3	D	QA1	–
26N/01E-18N03	WRP-5[2]	D	QA1	–
26N/01E-18P02	WRP-4	D	QA1	–
		Off-shore pressure reduction wells		
Not numbered	WCP and WTP wells	D	QA1	Oct. 28, 1979 to April 12, 1981 May 28, 1982 to Jan. 2, 1983 July 27, 1984 to Apr. 10, 1985 Mar. 16, 1987 to Apr. 15, 1987 Mar. 30, 1988 to Apr. 5, 1988
		Artificial recharge wells[3]		
26N/01E-19Q01	1B-2	R	QA2	–
26N/01E-19Q02	1A-1	R	QA1	–
26N/01E-19Q03	1C-1	R	QA1	–
26N/01E-30D01	TH6	R	QA1	July 27, 1977 to Oct. 17, 1977 Feb. 22, 1978 to Mar. 21, 1978
26N/01E-31A03	2C-1	R	QA1	–
26N/01E-31B02	2B-2	R	QA2	–
26N/01E-31B03	2A-1	R	QA1	–
26N/01W-25A02	3A-1	R	QA1	Mar. 23, 1977 to July 28, 1979

[1]Kahle (1998) used hydrogeologic unit "multiple."

[2]Well description given in appendix 1.

[3]Recharge was increased by 5.4 percent for all recharge wells.

Table 4. Comparison of total discharge and artificial recharge for different groups of wells as used in this study (2002) and as previously reported by Paterson (1981) and Kinner and Stimpson (1983), SUBASE Bangor, Kitsap County, Washington

[Recharge and discharge are reported as totals for different time periods for groups of wells that serve similar functions. –, not reported]

Well type	Time period	Total recharge or discharge (-), in millions of gallons, as reported in			Difference in recharge or discharge (in percent) between this study (2002) and Paterson (1981) or Kinner and Stimpson (1983)
		Paterson (1981)	Kinner and Stimpson (1983)	This study (2002)	
Artificial recharge	Jan. 17, 1977 to Oct. 15, 1980	560	–	560	0
Total		560	–	560	0
Public supply	Jan. 17, 1977 to Oct. 15, 1980	-1,180	–	-1,362	13
On-shore and off-shore pressure reduction	Jan. 17, 1977 to Oct. 15, 1980	-3,240	–	-3,575	9
Total		-4,420	–	-4,937	11
On-shore pressure reduction	April 15, 1977 to May 19, 1978	–	-1,373	-1,293	-6
Off-shore pressure reduction	May 20, 1978 to Oct. 15, 1980	–	-2,201	-2,266	3
Total		–	-3,574	-3,559	-0.4

Except for some year-to-year variability, annual average pumping rates for public-supply wells on SUBASE Bangor increased after 1980 (fig. 10) except for 1994-95 when this trend reversed. As the pumping rate for the public-supply wells increased, the rate of gravity flow from the off-shore pressure reduction wells decreased, as first noted by Becker (1995a). Conversely, with the decrease in pumping rate from 1994 to 1995, the rate of off-shore gravity flow increased. The cause of the lower rates of ground-water pumping from 1994 to 1995 is unknown, although a possible explanation is that water-conservation measures started to take effect (Arthur K. Schick, SUBASE Bangor, oral commun., 1996). The trend in decreasing ground-water pumping rates continued through 1996 (not shown) but reversed again in 1997 (Arthur K. Schick, SUBASE Bangor, oral commun., 1998).

There has been no artificial recharge on SUBASE Bangor since construction of Delta Pier was completed, and wastewater from the base has always been routed off-base for sewage treatment.

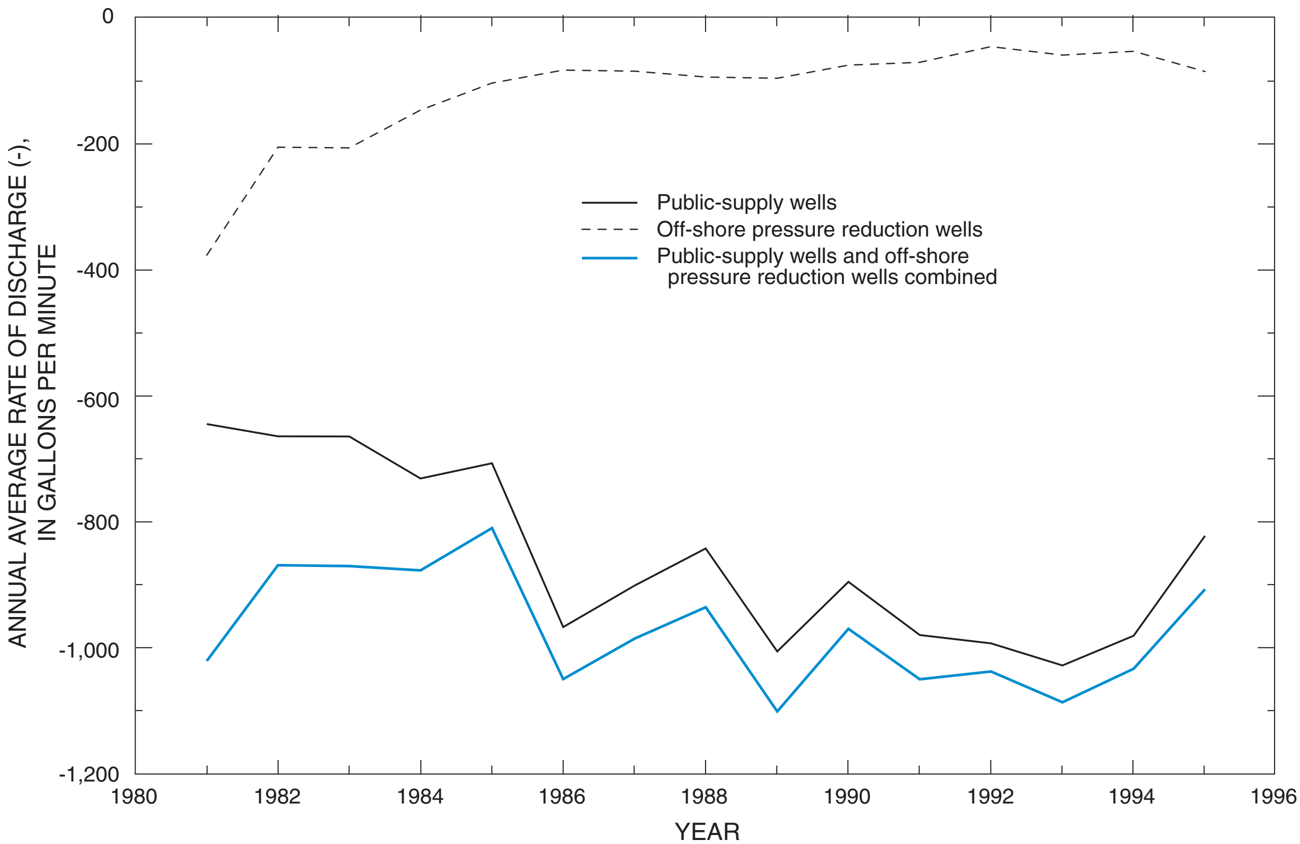


Figure 10. Annual average rates of discharge (-) on SUBASE Bangor, Kitsap County, Washington, 1981-95.

Off SUBASE Bangor

In 1996, there were seven water systems off-base within the study area with at least 50 connections (J.J. Welch, Washington Department of Health, written commun., 1996). The seven water systems presented in order from largest to smallest rates of pumping from the study area in 1995 are Silverdale Water District No. 16 (referred to as Silverdale in this report), Poulsbo, Naval Undersea Warfare Center (NUWC) Keyport, KPUD Keyport, Vinland, Island Lake, and Apex Airport (table 5 and fig. 11). Wells in water systems with fewer connections (including domestic wells with only one connection) were not included in the reconstruction of historical water use because smaller systems in the study area usually return a large fraction of pumped ground water through septic-system drainage back into the same shallow water-bearing unit from which water was pumped; therefore, the net effect on the regional hydrology is negligible. For example, assuming that the average October through April pumping rate by Silverdale for 1987-89 represents the average non-consumptive water use throughout the year, then calculations based on the average annual water use show that 73 percent of pumped ground water is returned as recharge from septic-system drainage. The overall rate of return would be even higher, if excess water use from April through October is assumed to be used for irrigation of which a fraction also may recharge the water table.

Table 5. Discharge wells in public-supply water systems with 50 or more connections in 1996 and selected time periods with estimates of or corrections to discharge data, vicinity of SUBASE Bangor, Kitsap County, Washington

[Water systems are presented in order from largest to smallest rates of pumping from the study area in 1995. **Well No.**: See figure 3 for explanation of well-numbering system. **Common name**: Locations of wells are shown in figure 8. **Hydrogeologic unit**: Qva, Vashon aquifer; QC1pi, Permeable interbeds; QA1, Sea-level aquifer; QA2, Deep aquifer; QU, Undifferentiated deposits. Hydrogeologic designations are from Kahle (1998). **Period of discharge estimate or correction**: Only periods longer than 1 month

Well No.	Common name	Hydro-geologic unit	Period of discharge estimate or correction
	Silverdale Water District No. 16[1]		
25N/01E-03E01	Spirit Ridge No.4	Qva	–
25N/01E-03E02	Spirit Ridge No.3	Qva	Nov. 1977 to Dec. 1981
25N/01E-03E03	Spirit Ridge No.1	Qva	Jan. 1977 to Oct. 1977
25N/01E-03E04	Spirit Ridge No.2	Qva	Jan. 1977 to Oct. 1977
25N/01E-05J01	Dawn Park[2]	QC1pi	Jan. 1977 to Dec. 1989
25N/01E-07A01	Frontier Woods	QC1pi	–
25N/01E-10D01	Island Lake	Qva	–
25N/01E-10N01	Bucklin Ridge	QA1	Jan. 1977 to Dec. 1981
25N/01E-15D01	Ridgetop[3]	QA2	–
25N/01E-16J01	Chena Road No.2	QC1pi	–
25N/01E-16R01[4]	Chena Road No.1	QC1pi	Jan. 1977 to Oct. 1979
			Aug. 1980 to Feb. 1981
25N/01E-18H01	Westwind	QA2	–
25N/01E-19H02	Dickey School	QA1	July 1978 to July 1981
25N/01E-19P02[5]	Wixson	QA2	–
25N/01E-20F01	Provost	QC1pi	Jan. 1977 to July 1981
25N/01E-22F02	Selbo Road	QC1pi	Jan. 1977 to July 1984
25N/01E-29D01[5]	Hess	QA2	–
	Poulsbo[6]		
26N/01E-02L04	Big Valley dug	Qva	Jan. 1977 to May 1982
			May 1990 to May 1991
26N/01E-02L05	Big Valley USGS	QA1	Jan. 1977 to Apr. 1982
			Mar. 1985 to June 1985
			Feb. 1991 to May 1991
	NUWC Keyport[7]		
26N/01E-36P04	Keyport No.4	QA1 and QU[3,8]	Jan. 1977 to Dec. 1988
			Jan. 1991 to Dec. 1991
26N/01E-36P05	Keyport No.5	QA2	Jan. 1977 to Dec. 1988
			Apr. 1989 to May 1989
			Jan. 1991 to Dec. 1991

Table 5. Discharge wells in public-supply water systems with 50 or more connections in 1996 and selected time periods with estimates of or corrections to discharge data, vicinity of SUBASE Bangor, Kitsap County, Washington—*Continued*

Well No.	Common name	Hydro-geologic unit	Period of discharge estimate or correction
		KPUD Keyport	
25N/01E-02J03[9]	Keyport No.2	QU	Oct. 1993 to Dec. 1993
26N/01E-36M01	Keyport No.1	QA2	Oct. 1977 to Apr. 1983
		Vinland	
26N/01E-04B01	Vinland No.2	QA2	June 1992 to Sept. 1993
26N/01E-04B02	Vinland No.1	QA2[3]	Jan. 1977 to Dec. 1984
26N/01E-05K01	Bela Vista No.1	QA1	Jan. 1977 to Feb. 1985
26N/01E-05K02	Bela Vista No.2	QA1	Jan. 1977 to Feb. 1985
27N/01E-27E01	Edgewater No.1	QA1	Jan. 1977 to June 1987
27N/01E-27E04	New Edgewater No.2[2]	QA1	Jan. 1977 to Jan. 1980
27N/01E-27J01	Edgewater No.4	Qva	–
27N/01E-27J02	Edgewater No.3	QA1	Dec. 1988 to Dec. 1991
		Island Lake	
25N/01E-03P01[4]	Island Lake No.2	Qva	Jan. 1984 to Dec. 1995
25N/01E-03R01[4]	Island Lake No.1	Qva	Jan. 1977 to Dec. 1983
		Apex Airport	
25N/01E-18D03	Apex No.2	QC1pi	Jan. 1977 to Dec. 1995
25N/01E-18E01[4]	Apex No.3	QC1pi	Jan. 1993 to Dec. 1995

[1] Miscellaneous months of estimated discharge during years for which annual totals were available have not been included in this table.

[2]Kahle (1998) used hydrogeologic unit "QC1."

[3]Kahle (1998) used hydrogeologic unit "Multiple."

[4]Well description given in appendix 1.

[5]Well is outside model area.

[6] Months for which the reported discharge was adjusted by up to 10 percent to match the reported total of the wells and a spring have not been included in this table.

[7] Monthly pumpage for these wells (except April and May 1989 for Keyport No.5) was estimated from the reported total pumpage of both wells according to the number of hours each well pumped and by assuming that the discharge rate was identical for both wells.

[8]Hydrogeologic unit designation "QU" not shown in figure 8.

[9]Location of well not shown in figure 8.

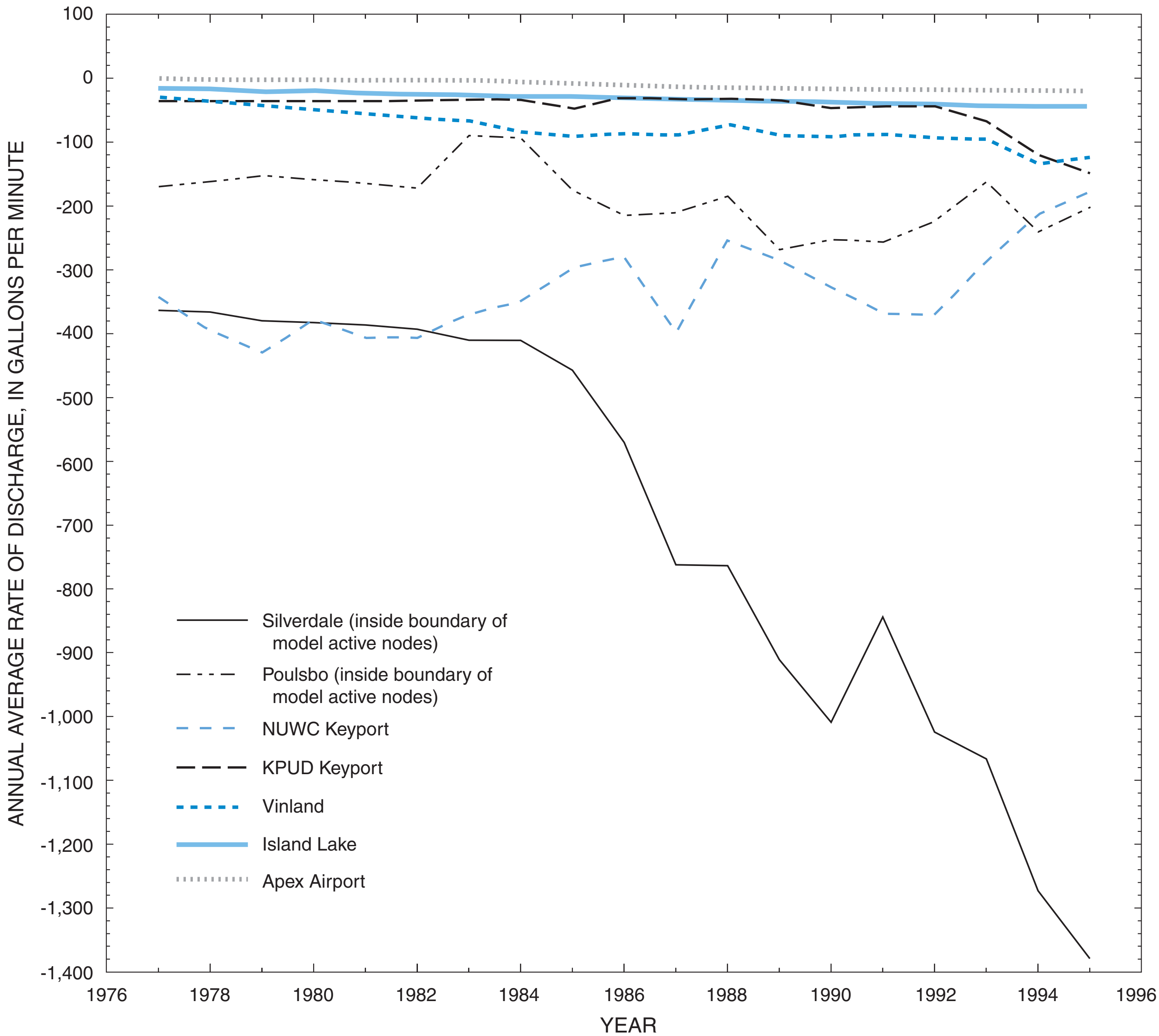


Figure 11. Annual average rates of discharge (-) for public-supply systems with 50 or more connections in 1996 off SUBASE Bangor, Kitsap County, Washington, 1977-95.

Ground-water discharge data were estimated or corrected during different time periods for several wells in the selected off-base water systems (table 5). For all water systems except Island Lake and Apex Airport, estimates were interpolated from measured pumping rates for neighboring time periods. The need to estimate or correct discharge data was evaluated for all wells of the Silverdale system including two wells that were outside the model boundaries. For the Poulsbo system, only the two wells that were within the model boundaries were considered. Discharge was estimated for all wells in the Island Lake and Apex Airport water systems, because pumpage data were not available for those systems. Discharge was estimated using miscellaneous historical data on the number of connections for each system (Judy E. Passey, Washington Department of Health, oral commun., 1996) and by assuming that each connection used 300 gal/d. This rate was the average usage per connection for the Vinland system, which serves a mostly residential population, similar to the Island Lake and Apex Airport water systems.

Annual average rates of ground-water pumping steadily increased since 1984 for the part of the Silverdale system inside the model boundaries (fig. 11) as Silverdale expanded its service area and added more wells. Annual average pumping rates for the remaining water systems (except for NUWC Keyport) also increased over time, although at a lesser rate. NUWC Keyport pumpage decreased as a result of water-conservation measures (Michael Scott, Naval Undersea Warfare Center Keyport, oral commun., 1996).

Ground water pumped by larger water systems may have been distributed away from the area where the water was pumped. Whether this distributed ground water was available as ground-water recharge at the point of delivery would have depended on whether wastewater is discharged to a sewer or septic system. Most of the ground water pumped by the seven off-base water systems was distributed to connections that discharged wastewater to individual septic systems. However, wastewater generated at points of delivery serviced by the Poulsbo and NUWC Keyport systems discharged almost entirely to sewers (Gary Thompson, City of Poulsbo, and Michael Scott, Naval Undersea Warfare Center Keyport, oral commun., 1996). Based on sewer- and water-distribution information for the Silverdale area (Chad Dean, Kitsap County Public Works, and Henry Aus, Silverdale Water District No. 16, written commun., 1996), it was estimated that about 50 percent of Silverdale connections discharged to sewers in 1996. The first sewers in the Silverdale service area were installed in the mid-1950s (Richard E. Gagnon, Kitsap County Public Works, oral commun., 2002).

Historical Water Levels

Predevelopment water levels in the study area were available from measurements of static water levels that drillers made at the time of well installation. In this study, all static water levels prior to January 17, 1977 (the start of water-level decrease on SUBASE Bangor) were assumed to represent predevelopment conditions. During the time of water-level decrease (1977 through 1980), representatives of SUBASE Bangor regularly measured water levels in about 30 monitoring wells on-base and several wells off-base. After 1980, water-level measurements were continued for most of the on-base monitoring wells, although time intervals between measurements usually were increased.

Around July 1, 1979, a mass water-level measurement was conducted of the monitoring network (Paterson, 1981). During a mass water-level measurement, water levels are measured in many wells in a short period of time to obtain a synopsis of ground-water flow conditions. The July 1979 measurements were made at the time of maximum stress on the flow system, and thus the time of maximum drawdown (defined as the change in water level) since predevelopment (Paterson, 1981). Compared to predevelopment conditions, water levels in the Sea-level aquifer had decreased over about one-half of SUBASE Bangor. Maximum drawdowns exceeded 65 ft on land and 110 ft off-shore (Paterson, 1981).

As part of the USGS Bangor studies, two mass water-level measurements were conducted throughout the study area in August 1994 and April 1995 (Kahle, 1998). In 1995, water levels in the Sea-level aquifer were lower than predevelopment over about one-quarter of SUBASE Bangor. The maximum drawdown since predevelopment was between 30 and 40 ft. KPUD has been monitoring ground-water levels off-base throughout Kitsap County on a mostly monthly basis since about 1991. In 2002, the monitoring network included about 150 wells (Martin B. Sebren, Kitsap County Public Utility District No. 1, oral commun., 2002).

Ground-water levels measured in wells with open intervals below sea level and located near the shore may be affected by tides in Puget Sound. Paterson (1981) reported tidal coefficients for the Sea-level aquifer on SUBASE Bangor that indicate that ground-water levels may fluctuate about 4 to 5 ft near the shore of Hood Canal near Delta Pier and less than 0.1 ft about 1 to 2 miles inland, depending on location. For lack of information, predevelopment and April 1995 water levels used in this study were not adjusted for tidal effects. Water-level data collected by representatives of SUBASE Bangor from 1977 through 1980 were adjusted for tides. Adjustments for tidal effects did not appear to have been applied to water levels measured in on-base monitoring wells after about 1980. Historical water levels and drawdowns are discussed in more detail in the section "Model Calibration."

Ground-Water Discharge to Streams

Streamflow in streams originates as surface runoff from storms and ground-water discharge that may occur throughout the year. The part of streamflow that originates from ground-water discharge is baseflow. In the study area, baseflow sustains streamflow during the summer, when precipitation is low. Springs and ground-water seeps may provide indirect ground-water discharge to streams as surface runoff.

Baseflow in the study area was estimated for water year 1995 (WY95, which begins October 1, 1994 and ends September 30, 1995) by one of two methods. Baseflows were determined by hydrograph separation (Bidlake and Payne, 2001) for streams for which continuous records were available (Devil's Hole and Johnson Creeks, fig. 6). Average baseflow for WY95 for other streams was assumed to be equal to the discharge obtained from a miscellaneous measurement during a period without direct storm runoff in May 1995. (For a complete set of miscellaneous and continuous surface-water measurements made as part of the USGS Bangor studies, see Wiggins and others, 1996, 1997, and 1998; and Bidlake and Payne, 2001.) A miscellaneous measurement in May was selected as representative of the entire water year because it is prior to summer low flows but later than April, when mean flows approximately equal mean annual streamflow in most basins in the Puget Sound Lowland (Vaccaro and others, 1998) and when baseflows probably exceed annual average baseflows. When all miscellaneous measurements (which were made on an almost-monthly basis during stable streamflow conditions) were averaged for the entire water year and a weight of 0.8 was assigned to November through April measurements to allow for the removal of possible surface-runoff components of the measurements, the water-year averages approximated the miscellaneous measurements in May. Estimated baseflows are presented and discussed in more detail in the section "Ground-Water Discharge to Streams, Springs, and Seeps."

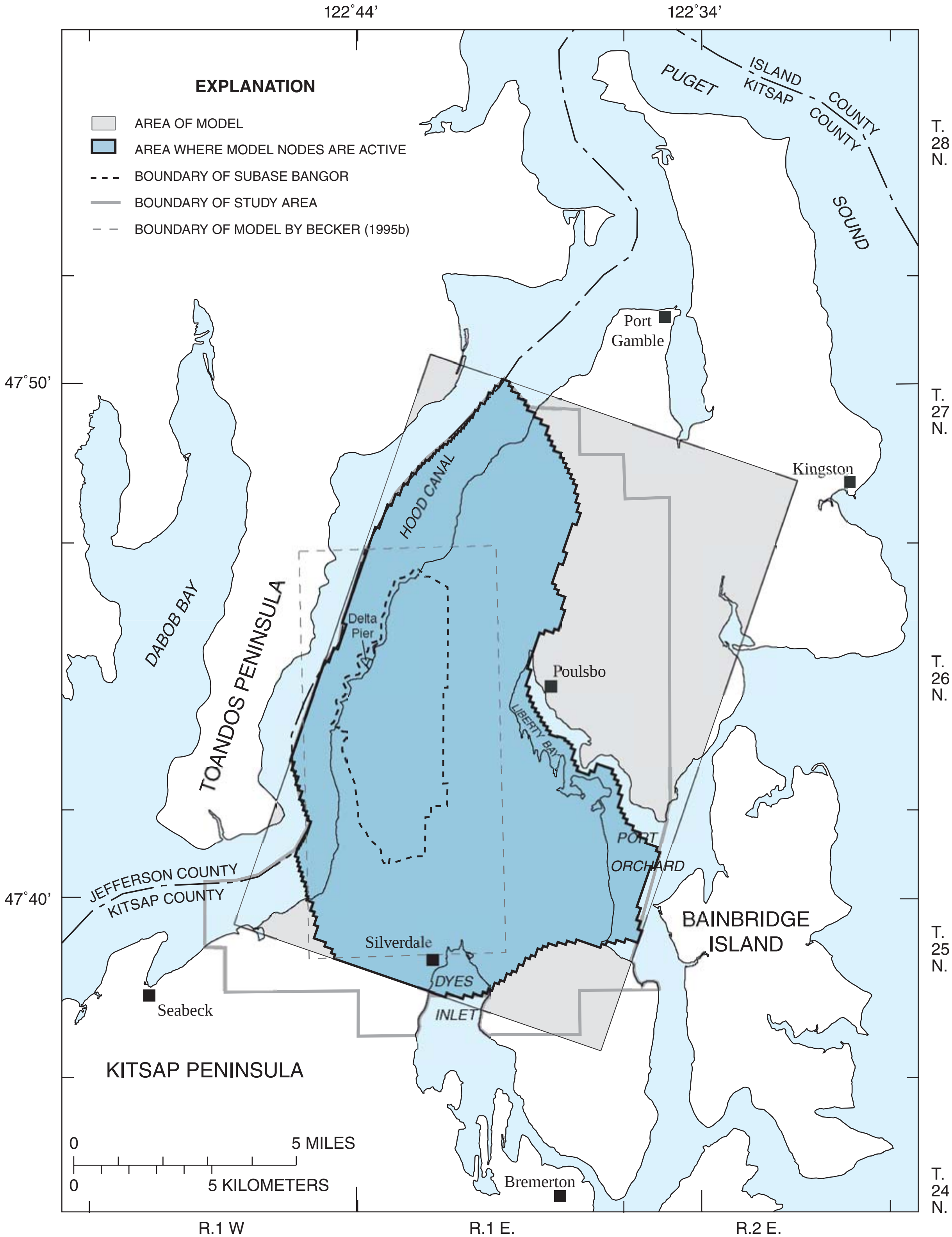
Precipitation in the study area during WY95 and also during the year ending in May 1995 was estimated to be about 35 and 30 percent above the long-term average (1953-95), respectively (Bidlake and Payne, 2001; William R. Bidlake, U.S. Geological Survey, written commun., 2002). Because shallow ground-water levels may have been higher than average as a result, estimated WY95 baseflows probably represent upper limits of long-term average baseflows.

SIMULATION OF THE GROUND-WATER FLOW SYSTEM

The ground-water flow system of the study area was numerically simulated to evaluate how ground-water flow on SUBASE Bangor interacts with the regional flow system and how possible future ground-water pumping may affect the system. Specifically, the numerical simulations were used to (1) determine how selected alternatives of ground-water pumping may affect the advective transport of on-base ground-water contamination to selected off-base wells and (2) evaluate the potential for future saltwater encroachment. Simulated output such as water levels in aquifers, streamflow, and ground-water residence times were compared to measured or estimated values to verify the validity of the numerical approximations.

Modeling Approach

The ground-water flow system was numerically simulated in three dimensions using MODFLOW, a widely used modular finite-difference model that simulates the flow of ground water of uniform density (McDonald and Harbaugh, 1988). The modeled area included most of the study area (fig. 12) but was designed to focus on conditions at SUBASE Bangor. The model was calibrated in a steady-state mode with predevelopment water levels (prior to January 17, 1977) and in a transient (time-varying) mode with drawdowns measured at different times between January 17, 1977 and April 1995; with streamflows measured during WY95; and with ground-water residence times estimated by isotopic methods (Stephen E. Cox, U.S. Geological Survey, written commun., 2002). Hydraulic parameters were iteratively adjusted by trial-and-error between steady-state and transient modes of the model until satisfactory matches to measured variables were achieved in the steady-state and transient simulations.



Base map modified from U.S. Geological Survey.
Scale 1:24,000 Digital Data
Projection: Universal Transverse Mercator, Zone 10 North American Datum 1927

Figure 12. Location and extent of the ground-water flow model for SUBASE Bangor and vicinity, Kitsap County, Washington.

Four hypothetical pumping alternatives were simulated to estimate potential long-term effects on the flow system. Particle flowpaths and traveltimes in the 1995 and future flow systems were estimated by using flows from the calibrated MODFLOW model as input to the particle-tracking program MODPATH (Pollock, 1994), and projected saltwater encroachment patterns were calculated using the Ghyben-Herzberg approximation (for example, Bear, 1979, p. 385).

Description of Model

Grid Design

The ground-water system on and near SUBASE Bangor was simulated by choosing vertical and horizontal extents of the model that would capture parts of the regional ground-water flow system that may affect the flow system on SUBASE Bangor. Centers of saltwater bodies east and west of SUBASE Bangor—Liberty Bay/Port Orchard and Hood Canal, respectively—were selected as extents of the model off-shore (fig. 12). The centers of these saltwater bodies were selected because ground-water flow is likely to be near vertical and upward here and therefore approximately defines an areal boundary of the flow system under study, beyond which ground-water flow to the saltwater body is contributed by a separate and distinct ground-water flow system (fig. 13). Extents of the model north and south of SUBASE Bangor were selected approximately parallel to April 1995 ground-water flow paths, as reported by Kahle (1998). More detailed descriptions of model boundaries are provided in the section "Boundary Conditions."

The modeled area was overlain by a numerical grid of rectangular cells with block-centered nodes. Cell sizes vary horizontally from 500 to 100 ft on a side, with the smallest-sized cells near Delta Pier, because this area has the highest resolution of data and is an area of interest for evaluating the potential for saltwater encroachment. The active-node area of the model covers 68 mi^2, of which 51 mi^2 is on land. The orientation of the grid was selected to be approximately parallel to the coast and perpendicular to the horizontal ground-water flow direction near Delta Pier. For lack of information, regional horizontal anisotropy was assumed to be non-existent in the hydrogeologic units and, on the basis of this assumption, the orientation of the grid should not affect numerical results.

The hydrogeologic system was vertically represented by 11 model layers (table 6; fig. 14). The top layer, layer 1, represented a combination of the till that drapes the surface of much of the study area (Qvt) and locally occurring recessional outwash and alluvium (Qvr). The layer represented a confining unit, unless Qvt is absent, in which case it represented an aquifer. Layer 2 represented the Vashon aquifer (Qva). Layers 3 and 5 represented the upper and lower parts of the Upper confining unit (QC1) respectively, and layer 4 represented permeable beds within QC1 (QC1pi). The Sea-level aquifer (QA1) was represented by three model layers (6, 7, and 8) to obtain better vertical resolution of the aquifer. The three layers were each of equal, but regionally varying thicknesses. The Lower confining unit (QC2) is below the Sea-level aquifer and was simulated as model layer 9. The Deep aquifer (QA2) is below the Lower confining unit and was simulated by two model layers (10 and 11). Layer 11 formed the bottom of the model, because ground-water flow between QA2 and the Basal confining unit (QC3) below was believed to be insignificant compared to other fluxes in the flow system.

Table 6. Conceptualization of model layers 1-11, SUBASE Bangor and vicinity, Kitsap County, Washington

[**Hydrogeologic unit**: Qvt, Vashon till confining unit; Qvr, Shallow aquifer; Qva,Vashon aquifer; QCl, Upper confining unit; QC1pi, Permeable interbeds; QA1, Sea-level aquifer; QC2, Lower confining unit; and QA2, Deep aquifer. Hydrogeologic designations are from Kahle (1998]

Model layer No.	Hydro-geologic unit	Hydrologic characteristics
1	Qvt/Qvr	Confining unit; aquifer if Qvt is absent
2	Qva	Aquifer
3	QC1	Confining unit
4	QC1pi	Aquifer
5	QC1	Confining unit; exists only if QC1pi is present
6, 7, 8	QA1	Aquifer
9	QC2	Confining unit
10, 11	QA2	Aquifer

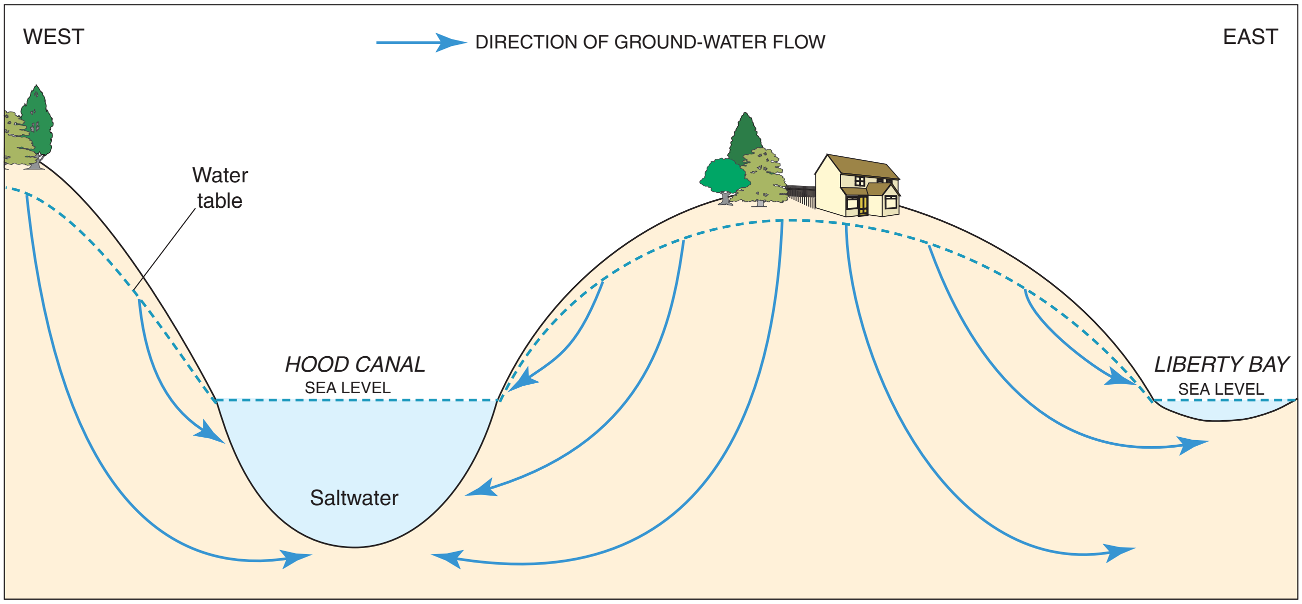
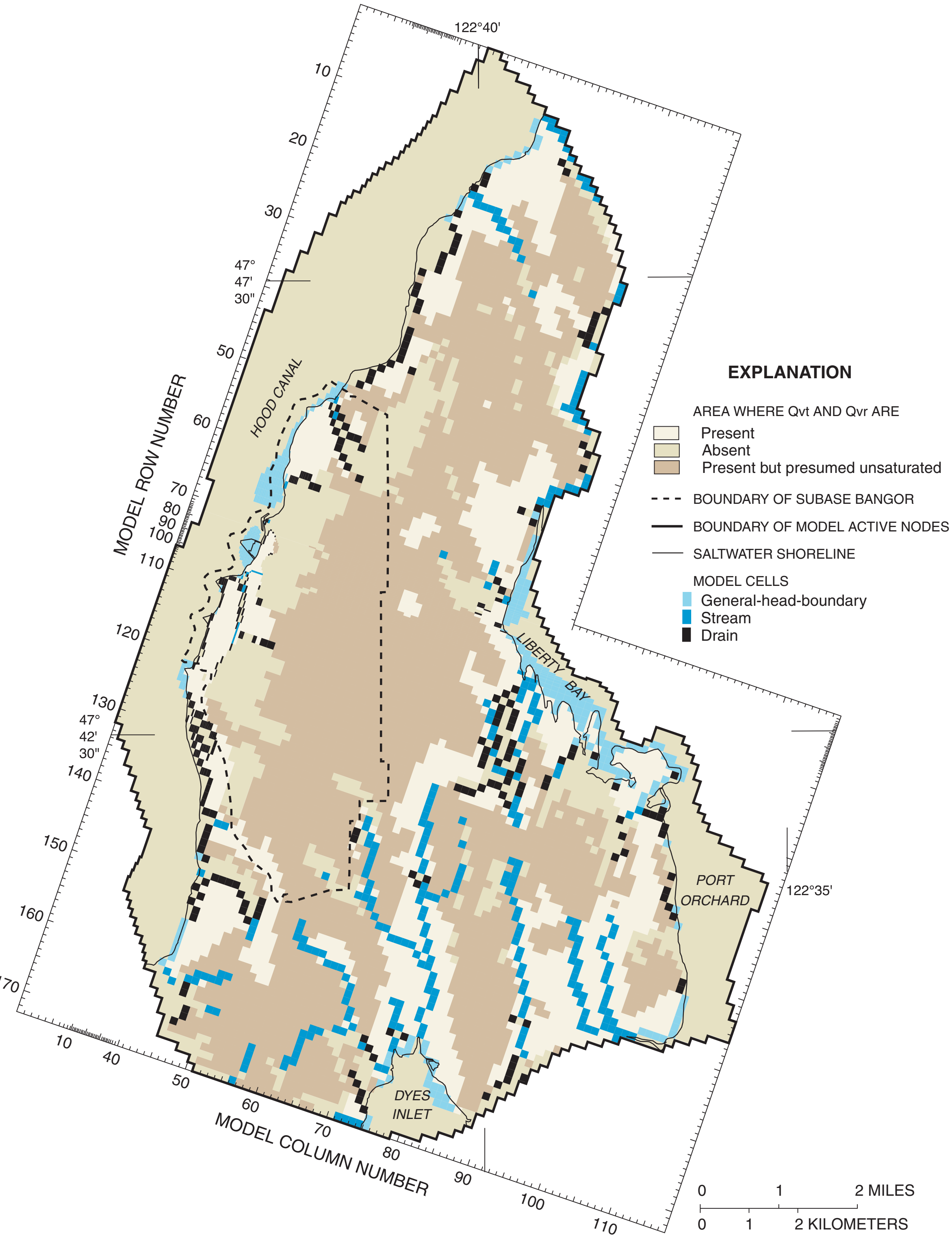


Figure 13. Schematic cross-section of ground-water flow for SUBASE Bangor and vicinity, Kitsap County, Washington.

The areal extents of layers 1, 2, 4, and 5 (fig. 14) match those of the corresponding hydrogeologic units mapped by Kahle (1998). However, Kahle was unable to map the areal extents of units corresponding to layers 3 and 6 through 11 off-shore, except in a small area near Delta Pier where lithologic information was available. Hydrogeologic units QC1, QA1, QC2, and QA2 were projected off-shore with the same approximate thickness and dip as on-shore to obtain an estimate of the areal extents of layers 3 and 6 through 11. The projection of each unit ended where it intersected the bathymetry or the model boundary, whichever came first.

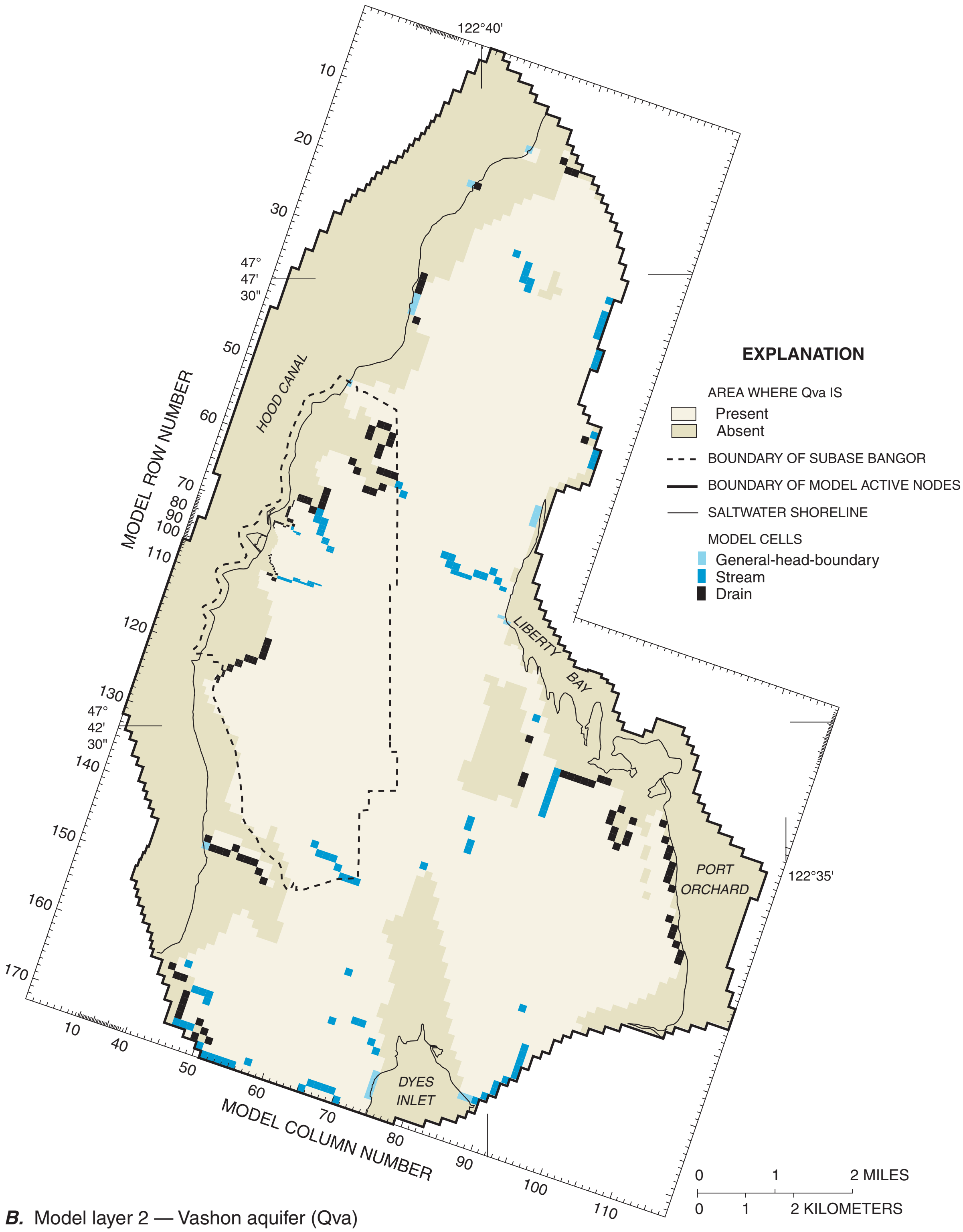
All model layers were simulated as confined units, even though in reality, model layer 1 is unconfined everywhere and layer 2 is unconfined over much of its areal extent. This assumption means that the transmissivity and storativity remained constant for each layer for the duration of the simulation and model cells were not allowed to become inactive, even if the simulated water level decreased below the bottom of the layer. To minimize errors due to this assumption, the saturated thickness instead of the layer thickness of layers 1 and 2 was used to calculate transmissivities of the layers (the product of thickness and hydraulic conductivity; eq. 1). This simplification greatly improved the numerical stability of the model and does not adversely affect the simulations, as long as simulated water levels are not significantly less than the assumed saturated top of the units.

The saturated thickness of layer 2 was calculated by subtracting the bottom altitude of layer 2 from the measured April 1995 water levels in that layer (Kahle, 1998). The saturated thickness of layer 1 was calculated by subtracting the bottom altitude of layer 1 from the measured April 1995 water level in layer 2. This effectively assumes that the water level in layer 1 is the same as the water level measured in layer 2. Where layer 2 has zero thickness and thus April 1995 water levels for the layer were absent (Kahle, 1998), the saturated thickness of layer 1 was assumed to be equal to the thickness of the hydrogeologic unit. Using this technique to define the saturated thickness of layer 1 resulted in large unsaturated areas in the interior of layer 1. The simulated transmissivity and storativity in these areas was zero and, effectively, these cells were not part of the flow model (fig. 14*A*).



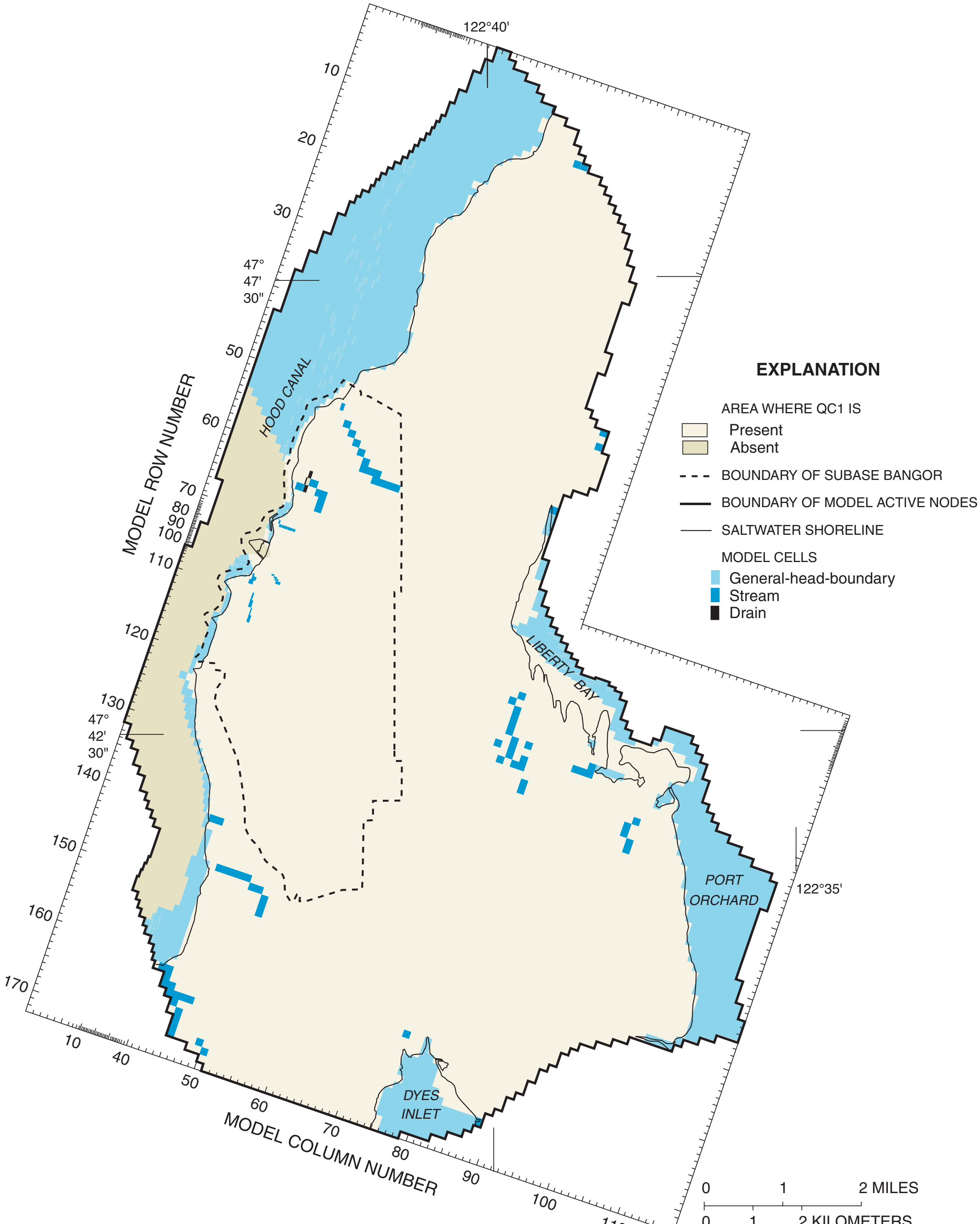
A. Model layer 1 — Vashon till confining unit and Shallow aquifer (Qvt and Qvr)

Figure 14. Areal extents of model layers 1-11 and locations of stream, drain, and general-head-boundary cells, SUBASE Bangor and vicinity, Kitsap County, Washington.



B. Model layer 2 — Vashon aquifer (Qva)

Figure 14.—*Continued.*

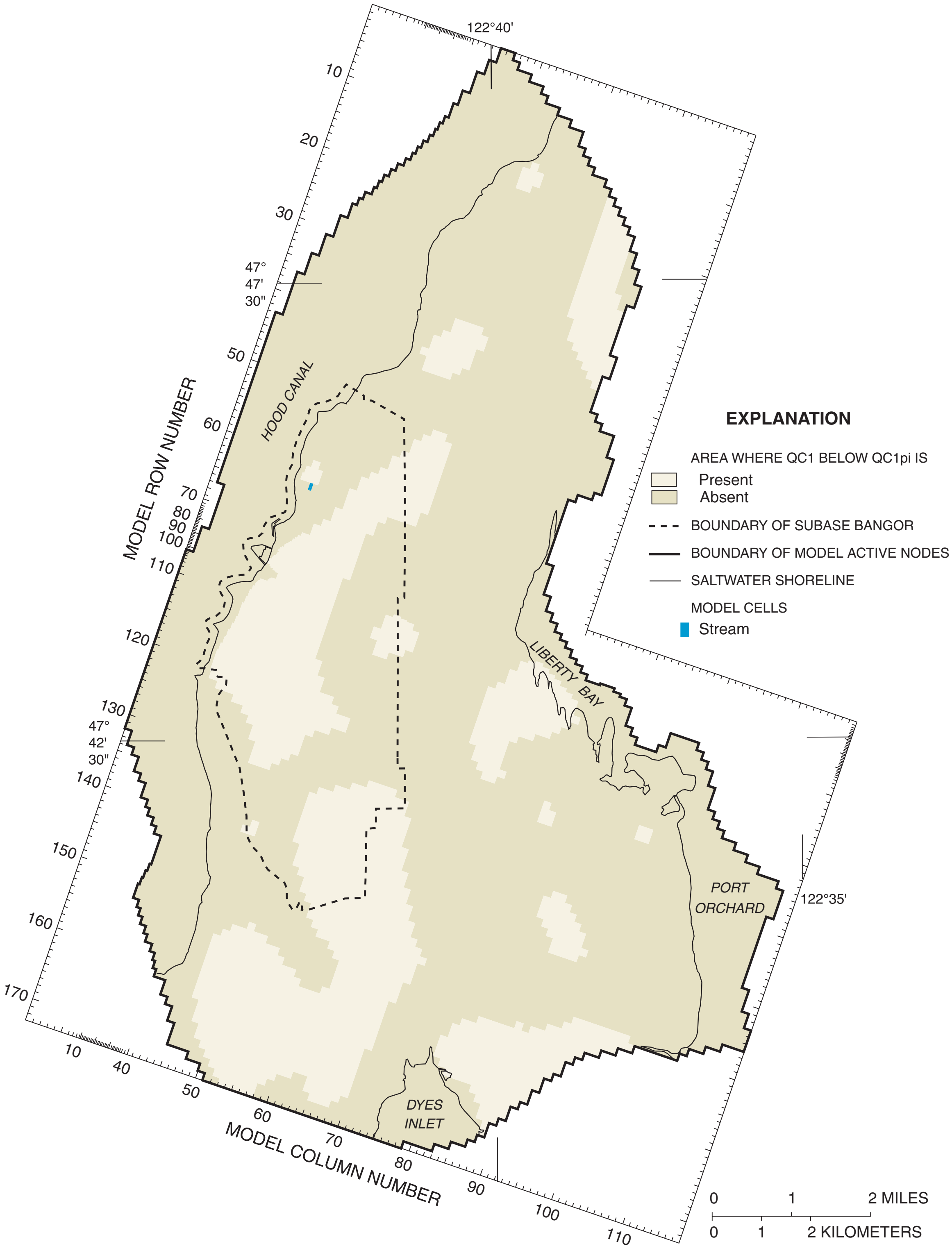


C. Model layer 3 — Upper confining unit (QC1)

Figure 14.—*Continued.*

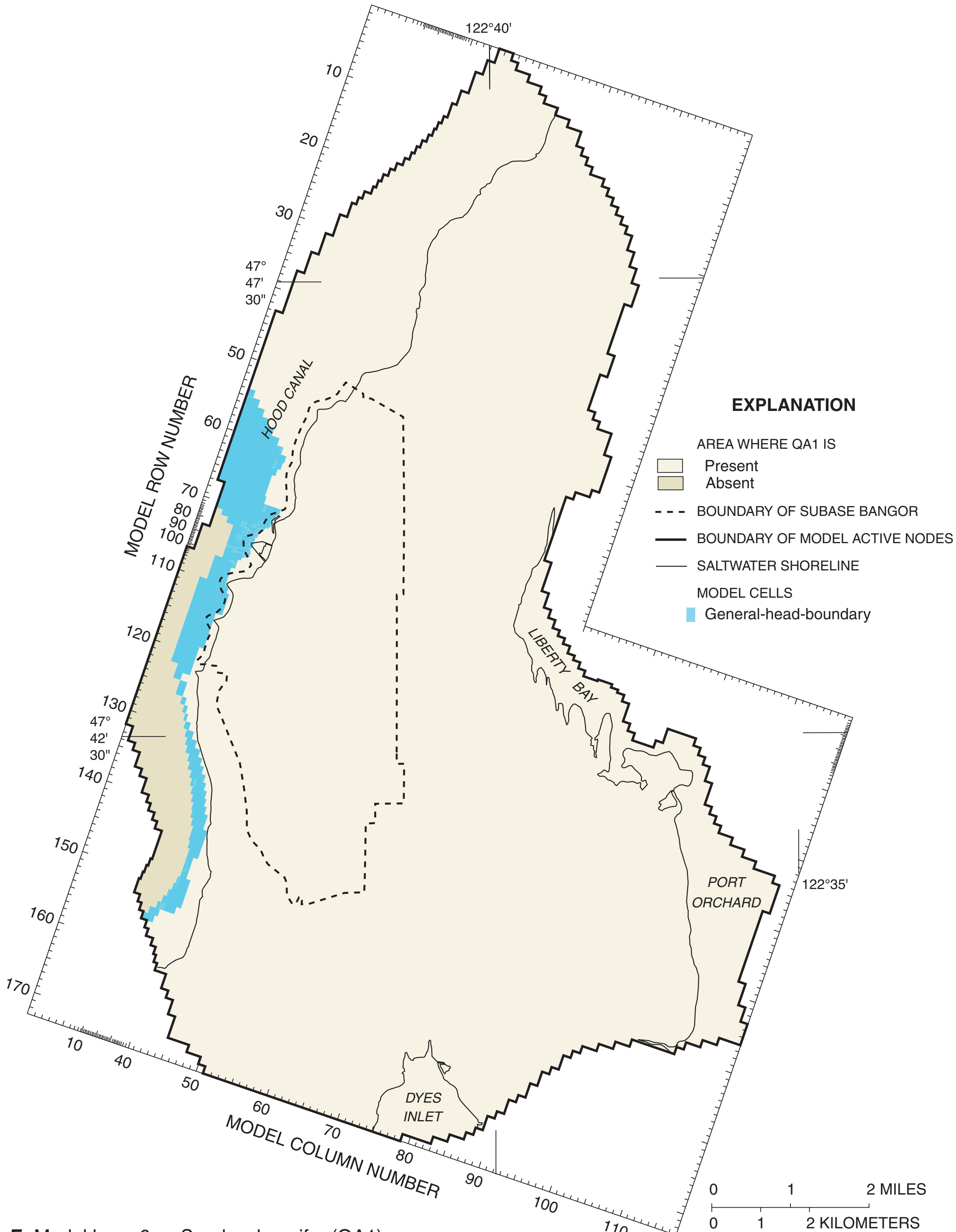
D. Model layer 4 — Permeable interbeds (QC1pi)

Figure 14.—*Continued.*



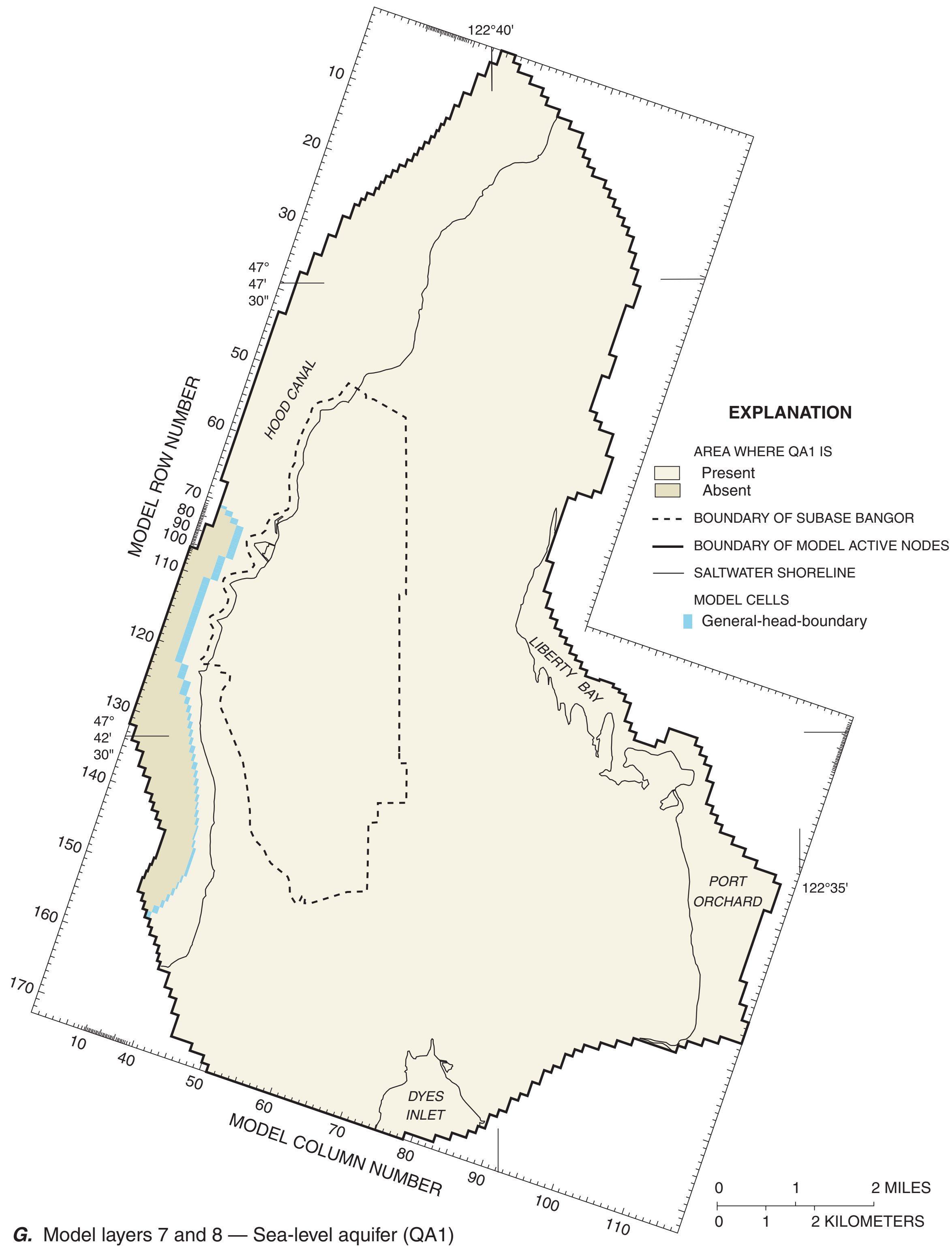
E. Model layer 5 — Upper confining unit (QC1; exists if QC1pi is present)

Figure 14.—*Continued.*



F. Model layer 6 — Sea-level aquifer (QA1)

Figure 14.—*Continued.*



G. Model layers 7 and 8 — Sea-level aquifer (QA1)

Figure 14.—*Continued.*

H. Model layer 9 — Lower confining unit (QC2)

Figure 14.—*Continued.*

I. Model layers 10 and 11 — Deep aquifer (QA2)

Figure 14.—*Continued.*

Boundary Conditions

The choice in type and location of model boundaries is important, as this may affect the simulation results. Ideally, model boundaries represent actual hydrologic boundaries, but this objective cannot always be met. If model boundaries do not represent actual hydrologic boundaries, it is important that they are located far enough away from the area of interest so they do not affect the simulation results.

Boundaries may be of three general types. One type is a specified-flux boundary, of which a no-flow boundary is a special case. A second type is a specified-head boundary, which was not used in this study. The third type is a head-dependent-flux boundary, for which the boundary flux is the product of a specified factor and the difference between the simulated head at the boundary and a specified head of an external source/sink.

The areal boundaries of the model (fig. 14) are either no-flow or head-dependent flux boundaries. All areal boundaries on land are no-flow and represent ground-water flow lines far from SUBASE Bangor so they do not affect the simulation results in the area of interest, even if effects of ground-water pumping encroach on these boundaries. All areal boundaries off-shore are head-dependent flux boundaries, and were simulated with the general-head-boundary (GHB) module of MODFLOW (McDonald and Harbaugh, 1988). Due to the choice of off-shore boundary conditions, any simulated flux in or out of general-head-boundary cells represents flow from saltwater bodies into the simulated ground-water system or flow from the simulated system into saltwater bodies, respectively. Once flow is simulated from the saltwater body into the model, MODFLOW treats the water as if it were freshwater because MODFLOW cannot simulate variable-density fluids.

Each model cell in direct contact with saltwater was assumed to be a general-head-boundary cell. If this contact is through a side face, the head assigned to the cell was the freshwater-equivalent head of the height of the saltwater column above the bottom of the cell. Using the bottom altitude assures that worst-case conditions for saltwater encroachment were simulated. If contact between a general-head-boundary cell and saltwater is through a top face only, however, the head assigned to the cell was the freshwater-equivalent head of the height of the saltwater column above the top of the cell. The freshwater-equivalent head was calculated according to

$$h_f = (\gamma_s/\gamma_f - 1)\, h_s, \qquad (3)$$

where

h_f = freshwater head above sea level (ft),
γ_s = specific weight of saltwater (63.864 lb/ft^3 in this study),
γ_f = specific weight of freshwater (62.428 lb/ft^3), and
h_s = height of the saltwater column (ft).

If equation 3 is rearranged so that h_s is expressed as a function of h_f, it represents the Ghyben-Herzberg approximation that describes the depth to a saltwater interface in a coastal aquifer as a function of freshwater head (for example, Bear, 1979, p. 385). This approximation will be used later in this report to estimate the possible extent of saltwater encroachment in the study area for four hypothetical alternatives of future ground-water pumping. The specific weight of saltwater in Hood Canal (63.864 lb/ft^3) was estimated from data reported by Collias and others (1974) and was assumed to prevail in Liberty Bay, Port Orchard, and Dyes Inlet. When this specific weight was substituted into equation 3, the freshwater-equivalent head equaled 0.023 times the height of the saltwater column.

The top boundary of the model includes both specified-flux and head-dependent-flux boundary cells. The specified-flux boundary is areally applied ground-water recharge, and the head-dependent boundaries represent either streams, springs, or ground-water seeps. Recharge was specified and simulated with the recharge (RCH) module (McDonald and Harbaugh, 1988) and is discussed in more detail in the section "Stresses and Stress Periods." Streams were simulated with the stream (STR) module of MODFLOW (Prudic, 1989) and springs and ground-water seeps were simulated with the drain (DRN) module (McDonald and Harbaugh, 1988). The bottom boundary of the model is a specified no-flow boundary (bottom of layer 11).

Numerous small streams are present in the study area. However, only perennial streams as identified on 1:24,000-scale USGS topographic maps were simulated except for one small stream with measured streamflow data southwest of SUBASE Bangor (referred to as Stream #129 later in this report in the section “Ground-Water Discharge to Streams, Springs, and Seeps”). Perennial streams were included because they may exchange water with the ground-water flow system throughout the year. A total of 21 streams were simulated with the STR module (fig. 14), which allows water to flow from the ground-water system to the stream or vice versa, depending on the relative stream and ground-water levels. If the specified stream stage is lower than the simulated ground-water level in the cell, water will discharge from the ground-water flow system to the stream. The reverse happens if the assigned stage in the stream cell is higher than the simulated water level in the cell. The rate at which the recharge to or discharge from the flow system occurs depends on the magnitude of the water-level difference and the streambed conductance. The latter is defined as the hydraulic conductivity of the streambed multiplied by the product of the width of the stream and its length divided by the thickness of the streambed (Prudic, 1989). The general definition of conductance is the hydraulic conductivity of the material in the direction of flow multiplied by the cross-sectional area perpendicular to the flow and divided by the length of the flow path (McDonald and Harbaugh, 1988). The STR module calculates the amount of water in the stream. Discharge from the stream to the flow system is possible as long as water remains in the stream.

In the model, stream stages were assigned on the basis of digital elevation model (DEM) data. The data that were used have a 30-meter horizontal resolution (resampled to 15 meters) with a vertical root-mean-square error of 7 meters, and were produced by the National Mapping Program of the USGS. Each assigned stage is the average of the altitude where the stream enters and exits the model cell. If by chance this average altitude exceeded the altitude of land surface at the center of the cell, the stream stage was set equal to 1 ft below land surface. Streams in the study area were assumed to be 1 ft deep and lakes were assumed to range from 1 to 16 ft deep. Streambed altitudes were used to determine in which model layer the stream was present. Stream cells in model layer 1 that traverse areas presumed to be unsaturated (fig. 14*A*) were assigned a streambed conductance equal to zero. As a result, streams in these cells do not exchange water with the ground-water system.

Springs and ground-water seeps occur throughout the study area in bluffs along the coast and also along streams. The locations of these features were determined by assuming that a spring or seep was present where the vertical edge of a model-simulated hydrogeologic unit was exposed to air. Springs and ground-water seeps thus identified were simulated with the DRN module, and primarily occur in the Shallow aquifer and Vashon till confining unit (model layer 1) and Vashon aquifer (model layer 2) (figs. 14*A* and 14*B*). The DRN module allows discharge from the ground-water flow system as long as the simulated water level in the cell is greater than the specified altitude of the drain. The drain altitude was assumed to be the altitude of the bottom of the cell at the node, unless a cell adjacent to the drainage face and belonging to the next layer down has a top altitude greater than the bottom altitude of the drain cell. In this case, the top altitude of the adjacent cell was selected as the drain altitude. In the case of multiple drainage faces, the lowest top altitude of the adjacent cells was selected. Similarly, if a stream cell was adjacent to a cell with a drain, the drain altitude was set equal to the stream stage if the stage was higher than the lowest top of adjacent cells and higher than the altitude of the bottom of the drain cell. The rate at which ground water discharges from a drain cell depends on the height of the simulated water level above the drain altitude and the drain conductance.

Hydraulic Properties

Transmissivity

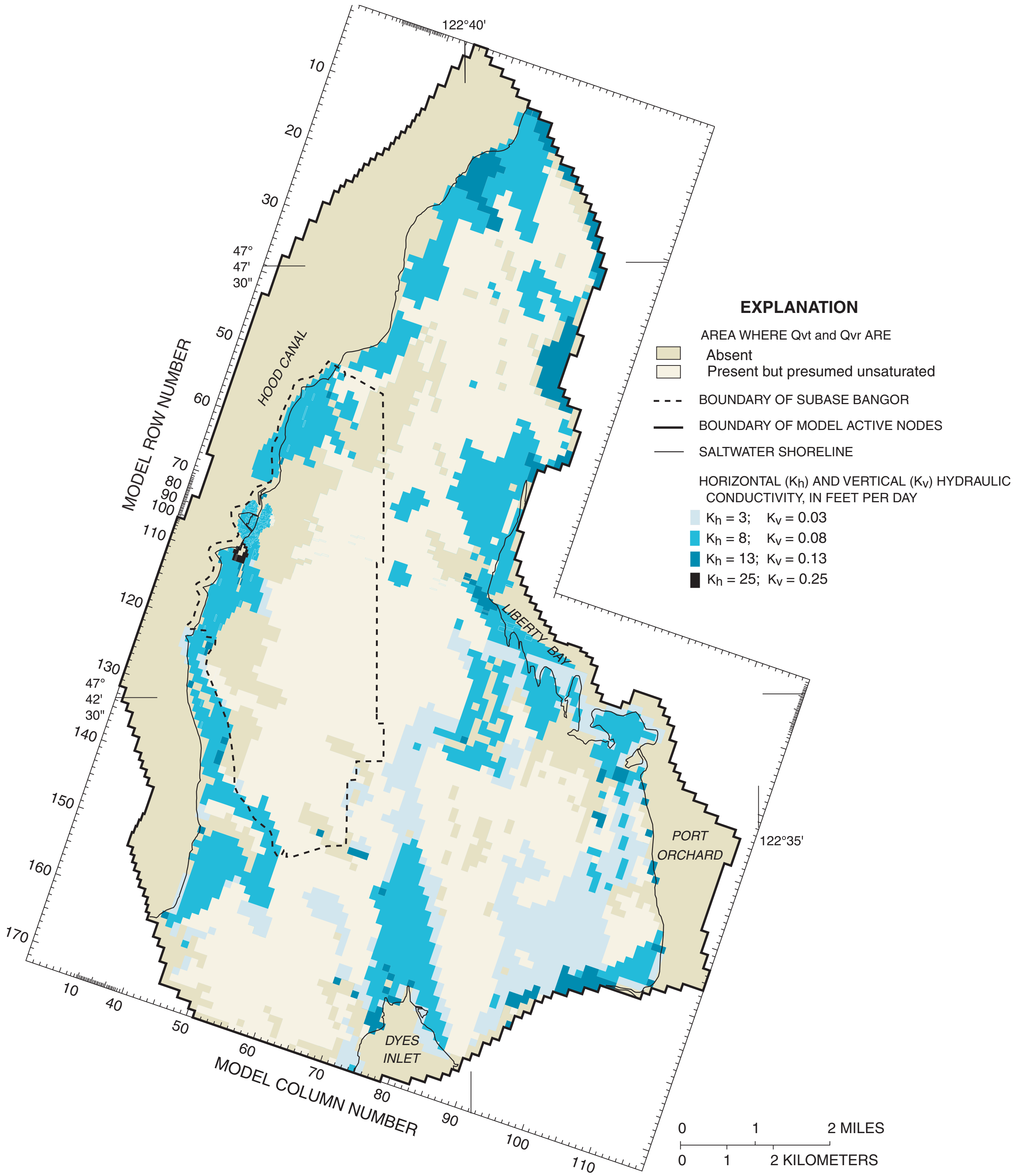
Transmissivity is the product of horizontal hydraulic conductivity and the thickness of a hydrogeologic unit (eq. 1). Transmissivity is an important parameter that controls the rate at which water is transmitted horizontally through an aquifer, and therefore, also the rate at which water may be pumped from an aquifer. As explained previously, the thicknesses of hydrogeologic units in the model were based on the interpretations by Kahle (1998). Initial hydraulic conductivities estimated from well hydraulic tests were modified during the process of trial-and-error model calibration to minimize simulation errors. The resulting horizontal hydraulic conductivities ranged from 0.003 ft/d for confining units to 25 ft/d for aquifers (fig. 15).

The simulated horizontal hydraulic conductivities resulted in transmissivities that range from about 3×10^{-3} to 4,700 ft^2/d in the on-shore parts of aquifers. Statistics for simulated horizontal hydraulic conductivities in the on-shore parts of hydrogeologic units are summarized in table 7. Simulated horizontal hydraulic conductivities of aquifers are smaller than median values obtained from specific-capacity and aquifer tests (table 1). The reason for this difference is that specific-capacity and aquifer-test values are based on local-scale measurements that are expected to be biased toward higher values, because generally the wells in which the measurements were made are designed to be open to the most permeable parts of hydrogeologic units. The simulated horizontal hydraulic conductivities, however, are representative of values on a regional scale. Because all model parameters are representative of hydraulic properties on a regional scale, the model should only be used to gain insight into ground-water flow on a regional scale. Attempts to use the model to predict ground-water flow on a local scale could lead to erroneous results.

Model layer 1 (a combination of hydrogeologic units Qvt and Qvr) was conceptualized as a combination of confining and aquifer materials. The modeling results, however, demonstrate that this layer is best simulated with aquifer characteristics (fig. 15*A*). The reason for this may be that multiple lenses of permeable material within unit Qvt allow for a significant component of horizontal flow on a regional scale. A significant component of horizontal flow was expected in unit Qvr. Simulated horizontal hydraulic conductivities for the off-shore parts of the Upper and Lower confining units (figs. 15*C* and 15*G*) are more typical of aquifers than confining units. This means that even though these confining units were projected to extend off-shore, in reality they are either not present or, if they are present, large parts of the low-permeability materials have eroded away and been replaced with more permeable materials. The Lower confining unit (QC2) is thought to be absent or breached in larger areas than originally inferred by Kahle (1998). This is indicated by the larger simulated hydraulic conductivities in the area of mapped absences of the Lower confining unit (fig. 15*G*). The Sea-level aquifer (fig. 15*F*) has areas of high horizontal hydraulic conductivities on SUBASE Bangor, with smaller horizontal hydraulic conductivities off-shore.

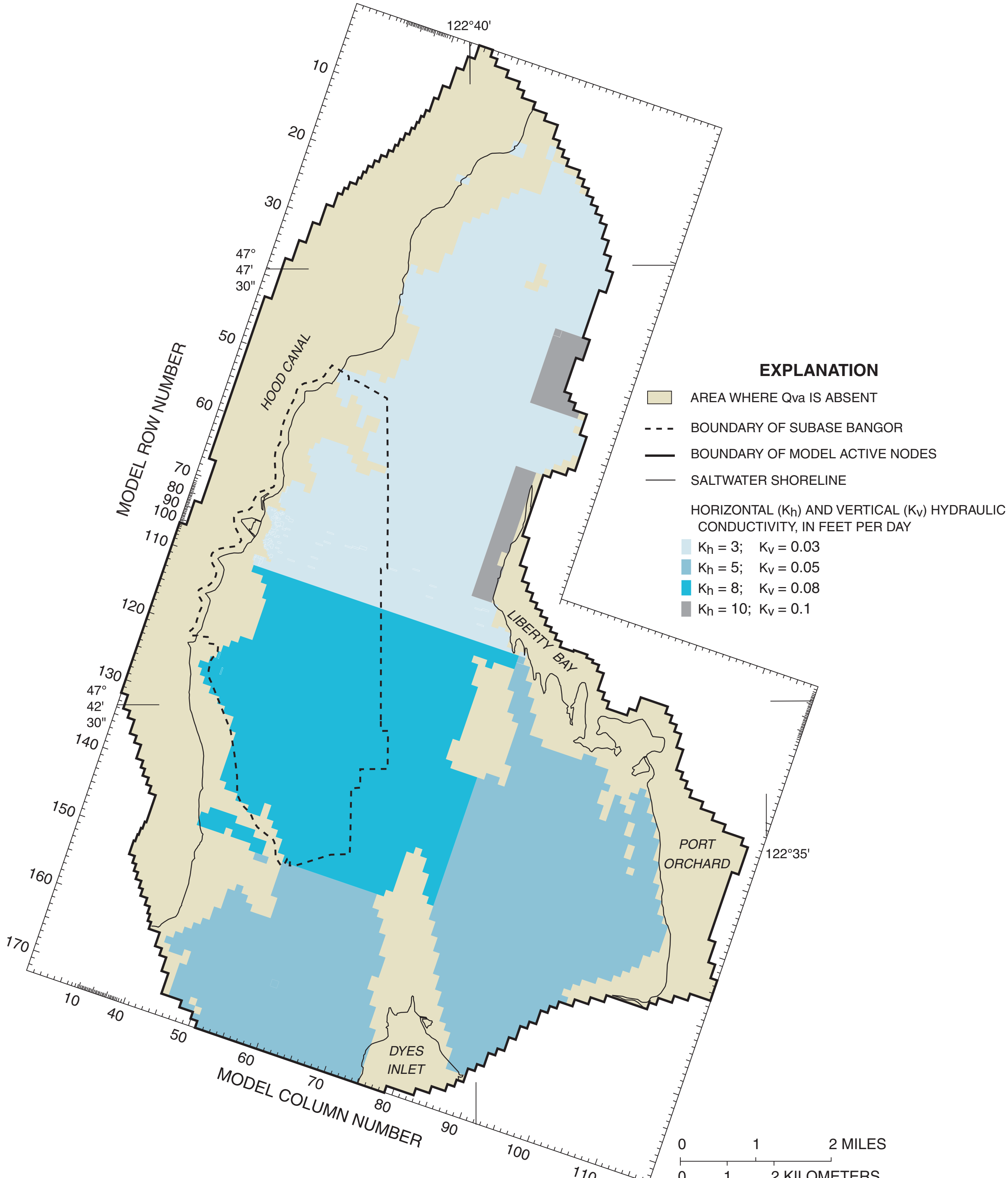
Vertical Conductance

The ease with which water moves in the vertical direction between adjacent model layers is controlled by vertical conductance (McDonald and Harbaugh, 1988). In this study, vertical conductance was calculated using layer thickness and vertical hydraulic conductivity. Vertical hydraulic conductivities were calculated by assuming ratios between horizontal and vertical hydraulic conductivities and adjusting horizontal hydraulic conductivities to achieve model calibration. The ratios were assumed to be 10 for horizontal hydraulic conductivities less than 1 ft/d (those representative of confining units) and 100 for horizontal hydraulic conductivities greater than or equal to 1 ft/d (those representative of aquifers). The ratio of 100 for horizontal hydraulic conductivities was larger than what commonly is used for aquifers (for example, Todd, 1980) and the ratio also was larger than what was estimated from aquifer tests conducted of the Vashon aquifer in the southeastern part of SUBASE Bangor (Thomas Goodlin, Foster Wheeler Environmental Corporation, written commun., 1999). The larger ratio was selected to try to simulate vertical water-level gradients measured in the Sea-level and Deep aquifers, which were represented by multiple model layers. Vertical water-level gradients were measured in the Sea-level aquifer between TH5 shallow and TH5 deep observation wells. For simplicity purposes, the same ratio was used for all aquifer materials.



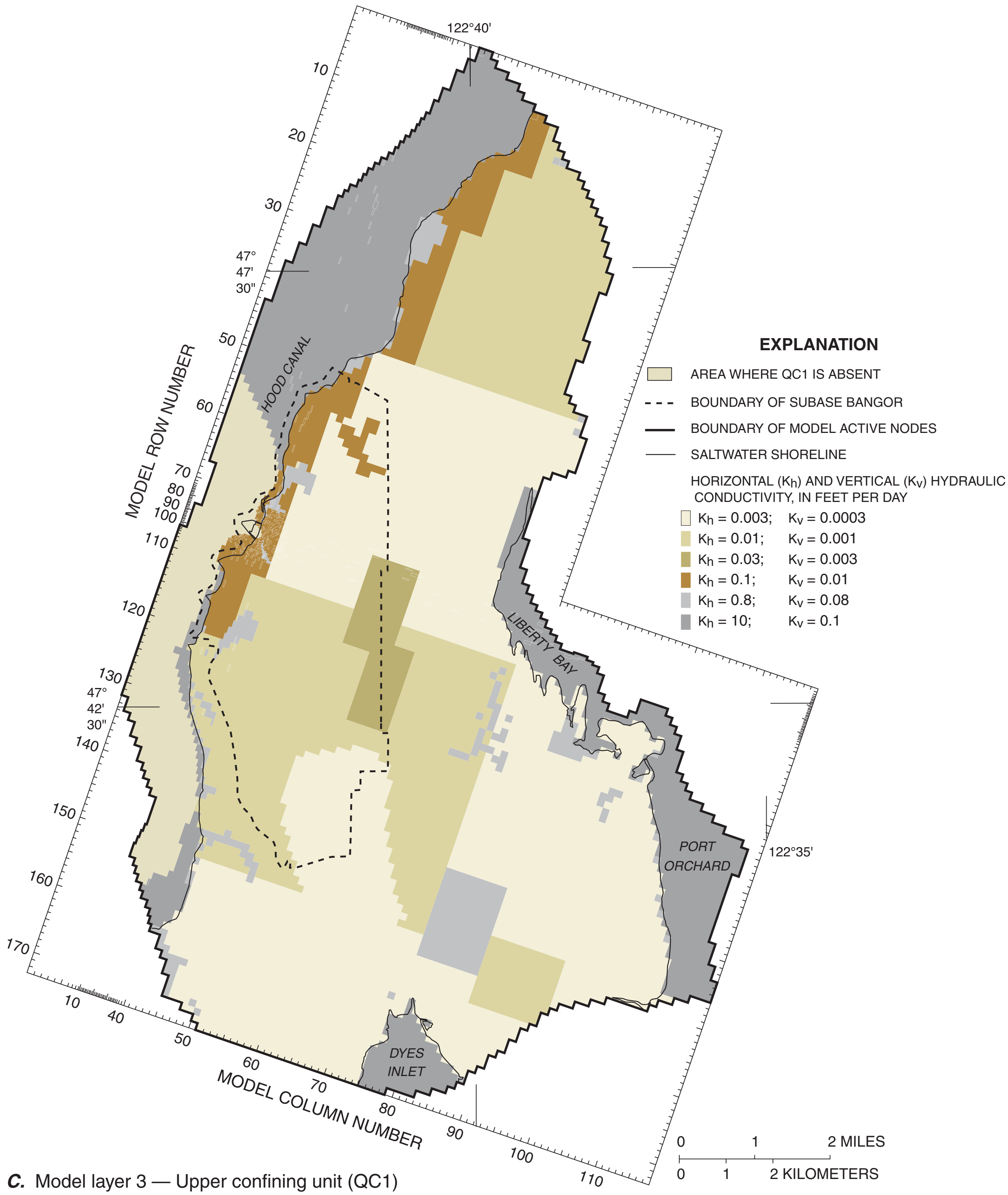
A. Model layer 1 — Vashon till confining unit and Shallow aquifer (Qvt and Qvr)

Figure 15. Simulated horizontal and vertical hydraulic conductivities for model layers 1-11, SUBASE Bangor and vicinity, Kitsap County, Washington.



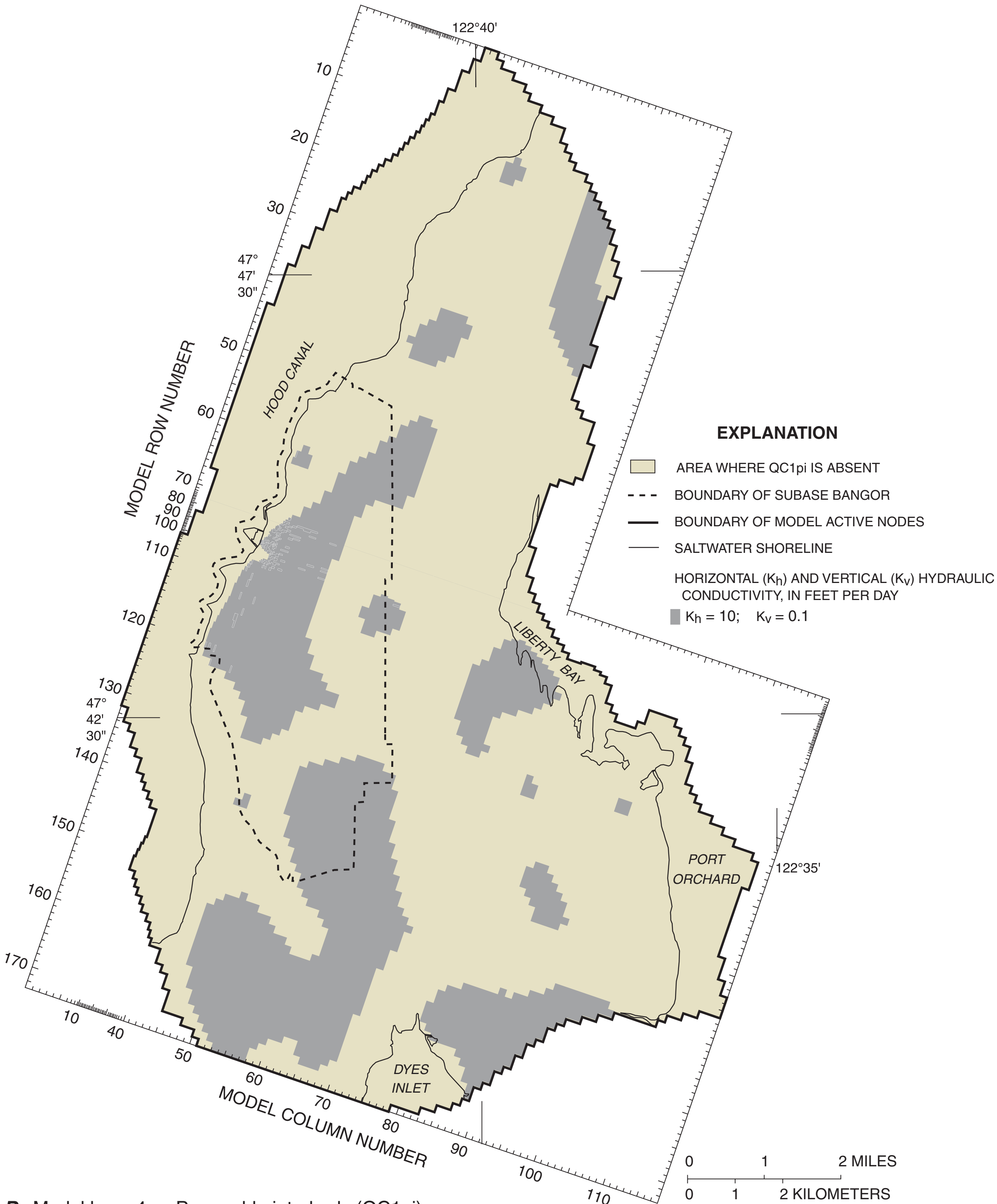
B. Model layer 2 — Vashon aquifer (Qva)

Figure 15.—*Continued.*



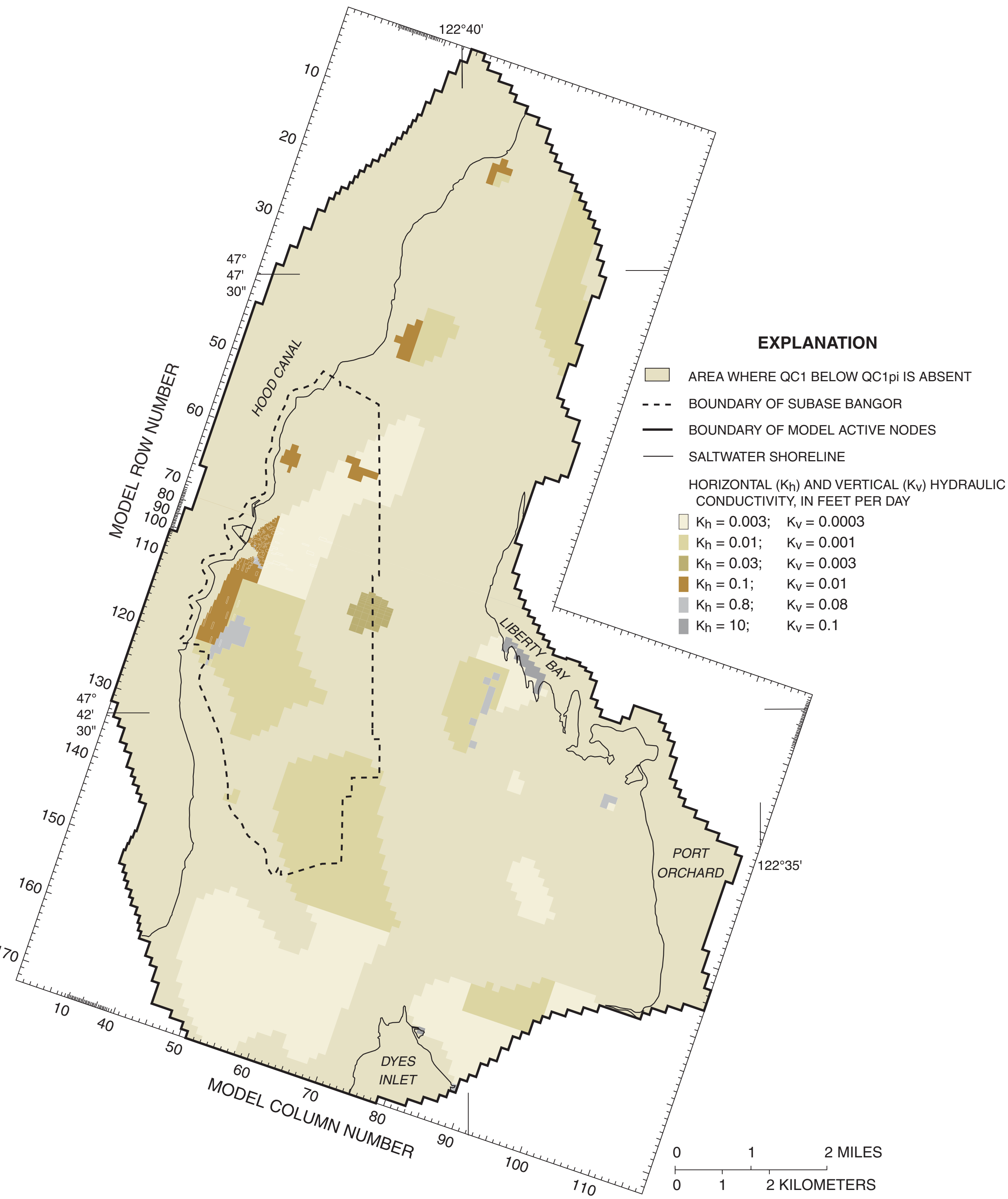
C. Model layer 3 — Upper confining unit (QC1)

Figure 15.—*Continued.*



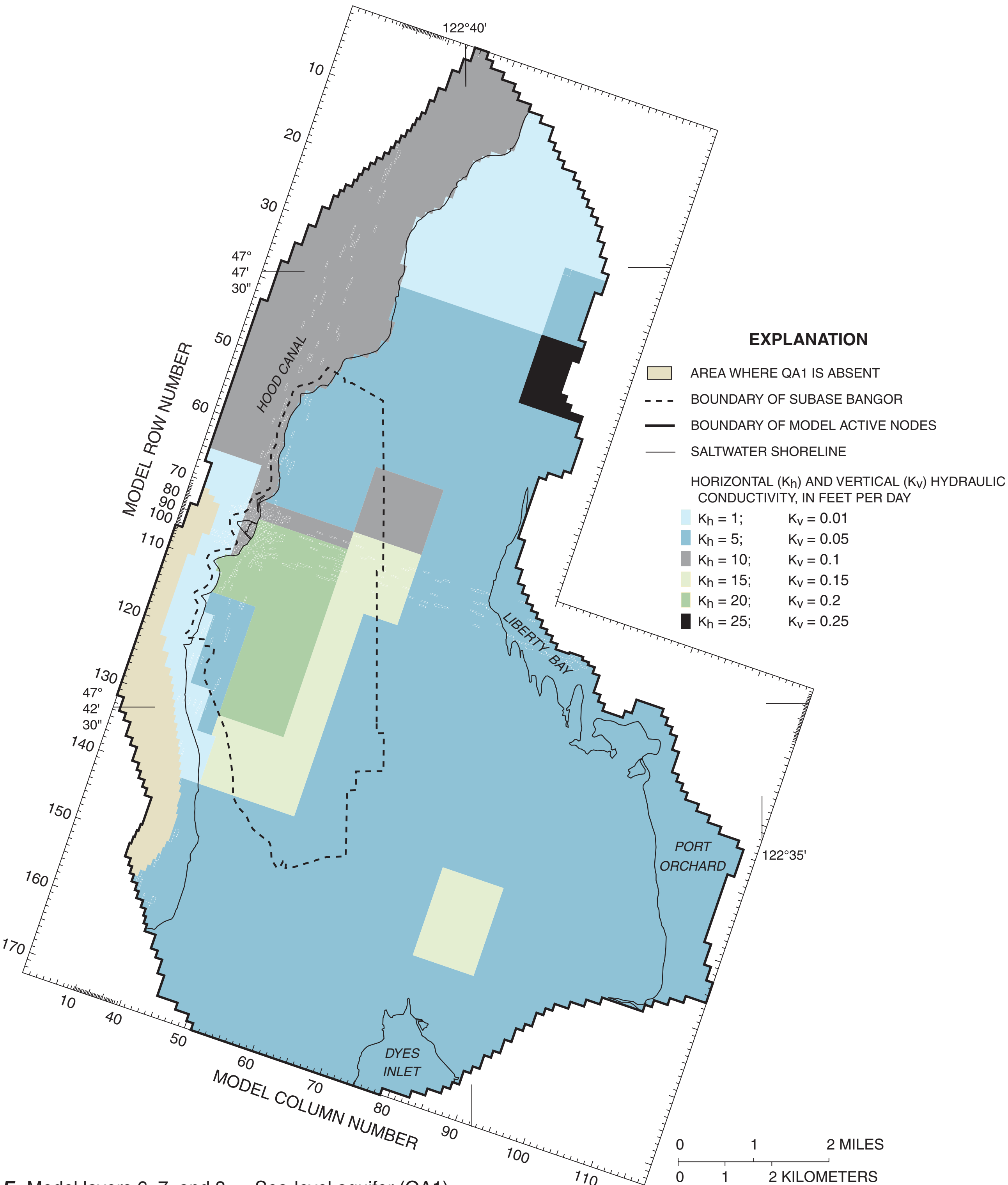
D. Model layer 4 — Permeable interbeds (QC1pi)

Figure 15.—*Continued.*



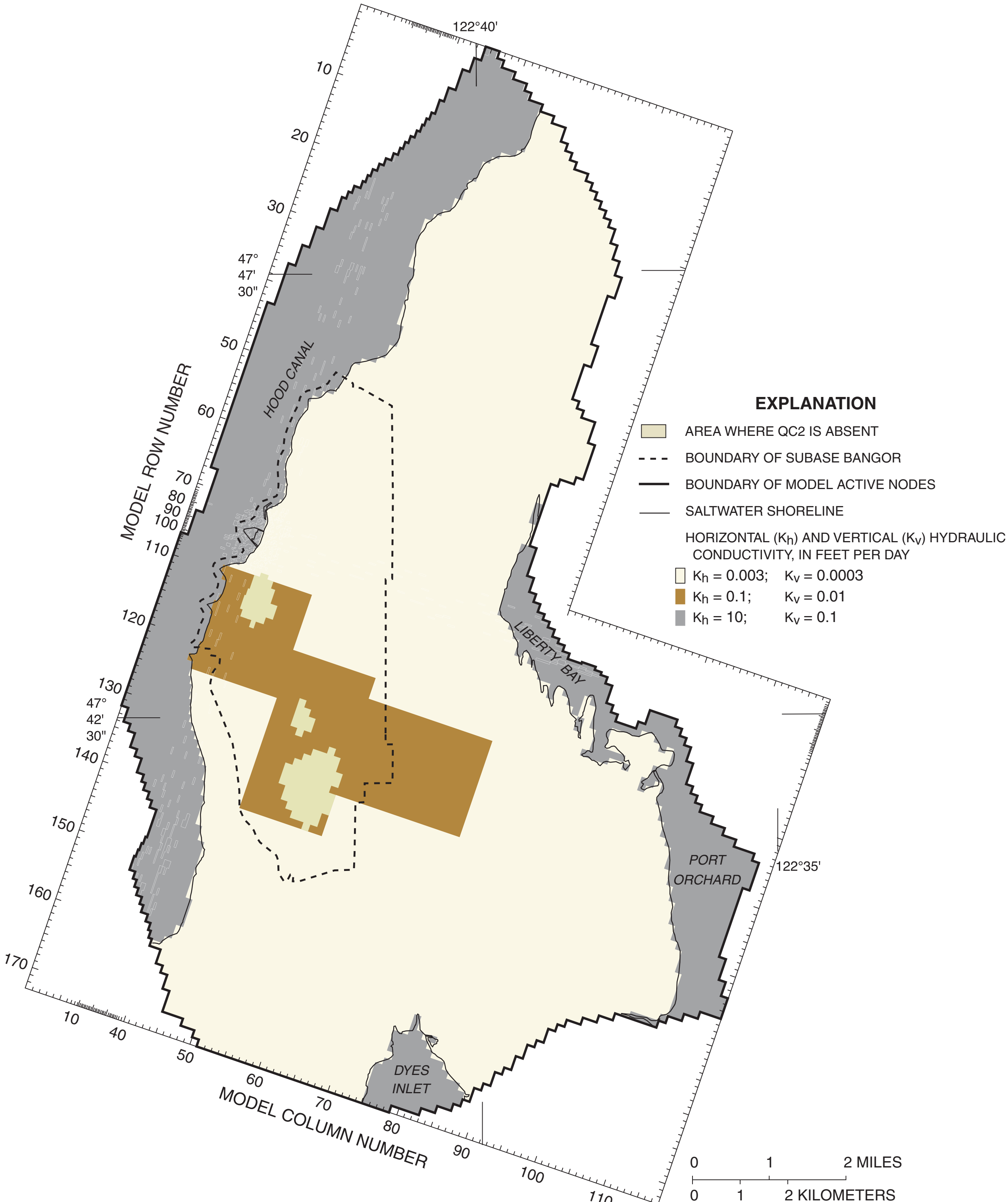
E. Model layer 5 — Upper confining unit (QC1; exists if QC1pi is present)

Figure 15.—*Continued.*



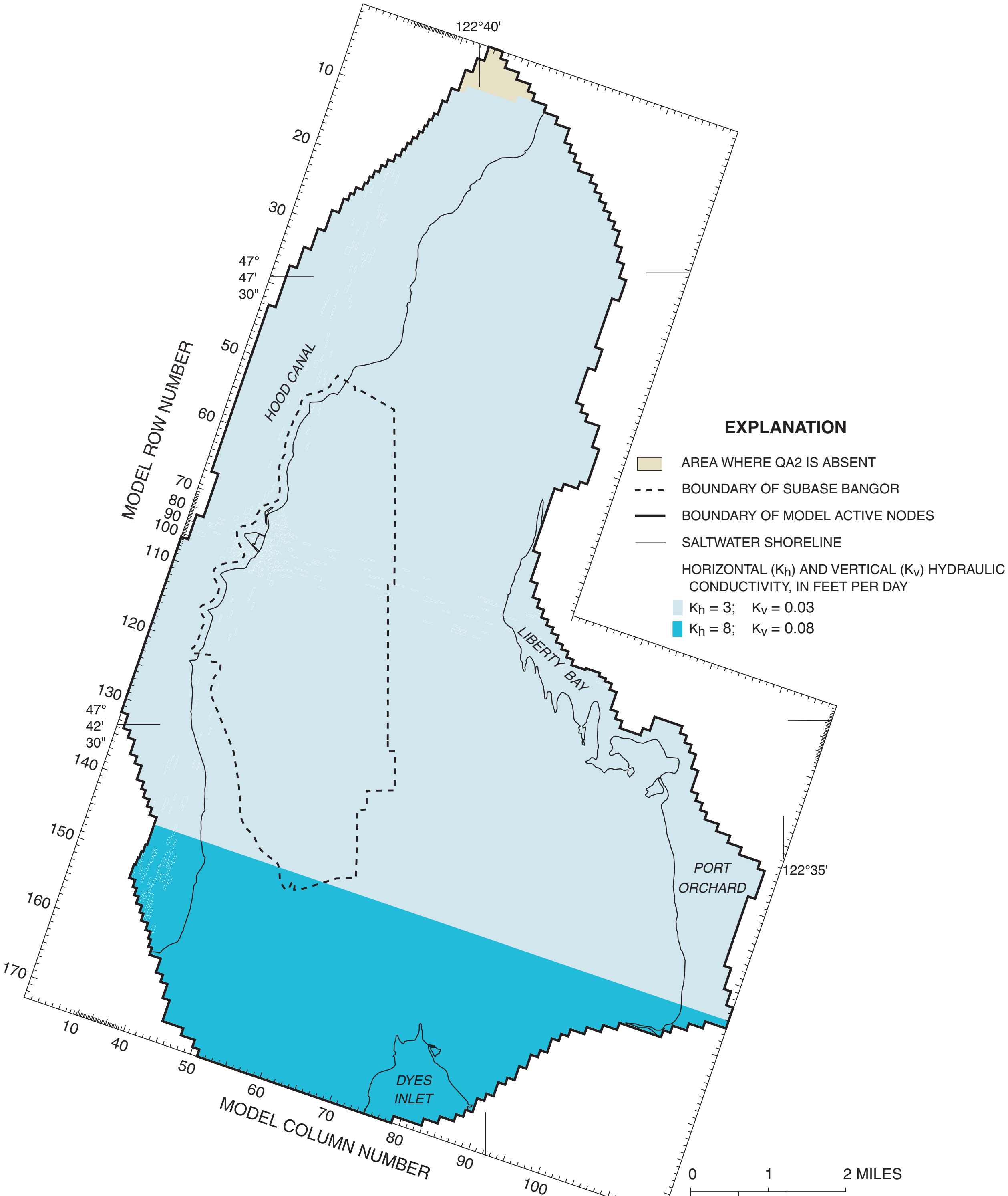
F. Model layers 6, 7, and 8 — Sea-level aquifer (QA1)

Figure 15.—*Continued.*



G. Model layer 9 — Lower confining unit (QC2)

Figure 15.—*Continued.*



H. Model layers 10 and 11 — Deep aquifer (QA2)

Figure 15.—*Continued.*

Table 7. Summary statistics for simulated horizontal hydraulic conductivities in the on-shore parts of the hydrogeologic units, SUBASE Bangor and vicinity, Kitsap County, Washington

[**Hydrogeologic unit**: Qvt, Vashon till confining unit; Qvr, Shallow aquifer; Qva,Vashon aquifer; QCl, Upper confining unit; QC1pi, Permeable interbeds; QA1, Sea-level aquifer; QC2, Lower confining unit; and QA2, Deep aquifer. Hydrogeologic designations are from Kahle (1998). **Simulated horizontal hydraulic conductivity**: Mean and standard deviation weighted by model-cell area]

Model layer No.	Hydro-geologic unit	Simulated horizontal hydraulic conductivity (feet per day)				
		Median	Mean	Standard deviation	Minimum	Maximum
1	Qvt/Qvr	8.0	7.0	3.1	3.0	25.0
2	Qva	5.0	5.3	2.1	3.0	10.0
3	QC1	0.01	0.08	0.54	0.003	10.0
4	QC1pi	10.0	10.0	0	10.0	10.0
5	QC1	0.01	0.024	0.1	0.003	0.8
6, 7, 8	QA1	5.0	6.6	5.0	1.0	25.0
9	QC2	0.003	0.014	0.03	0.003	0.1
10, 11	QA2	3.0	4.2	2.1	3.0	8.0

Ground-water flow in aquifers that were represented by one model layer, such as the Vashon aquifer and Permeable interbeds, was only affected by vertical anisotropy insofar as it affects the calculation of the vertical conductance between the aquifer and confining units immediately above or below. Because this conductance is primarily determined by the small vertical hydraulic conductivity of confining units, the value of the vertical anisotropy selected for aquifers that were simulated by one model layer was not significant.

Vertical water-level gradients in aquifers in the study area indicate that the aquifers may contain multiple layers and lenses of less permeable materials such as clay, which increase the vertical anisotropy. Todd (1980) notes that even though vertical anisotropy for alluvium usually ranges from 2 to 10, values up to 100 or more can occur if clay layers are present. Statistics for vertical hydraulic conductivities in the on-shore parts of hydrogeologic units are summarized in table 8.

Storativity

An additional parameter, storativity, S, has to be specified when simulating transient flow. Storativity is a dimensionless parameter defined as the change in volume of water stored in an aquifer or confining bed per unit horizontal area per unit change in head. When heads in a confined unit change, the volume of stored water changes due to compression or expansion of the granular matrix and water. When heads in an unconfined unit change, a change in storage also occurs due to the same processes, but a much larger change in storage occurs by filling or draining water from pores at the water table. As a result, the storativity for unconfined units is almost identical to the specific yield, S_y, which is usually several orders of magnitude greater than the storativity of confined units.

Even though model layers 1 and 2 were simulated as confined, they are in fact largely unconfined, and were therefore assigned storativities equal to their specific yields, 0.15 and 0.30, respectively. Model layers 3 through 11 represent confined units. Confined conditions persisted in these units during the large-scale water-level decreases that occurred during the construction of Delta Pier.

Table 8. Summary statistics for simulated vertical hydraulic conductivities in the on-shore parts of the hydrogeologic units, SUBASE Bangor and vicinity, Kitsap County, Washington

[**Hydrogeologic unit**: Qvt, Vashon till confining unit; Qvr, Shallow aquifer; Qva,Vashon aquifer; QCl, Upper confining unit; QC1pi, Permeable interbeds; QA1, Sea-level aquifer; QC2, Lower confining unit; and QA2, Deep aquifer. Hydrogeologic designations are from Kahle (1998). **Simulated vertical hydraulic conductivity**: Mean and standard deviation weighted by model-cell area]

Model layer No.	Hydro-geologic unit	Simulated vertical hydraulic conductivity (feet per day)				
		Median	Mean	Standard deviation	Minimum	Maximum
1	Qvt/Qvr	0.08	0.07	0.031	0.03	0.25
2	Qva	0.05	0.053	0.021	0.03	0.1
3	QC1	0.001	0.0057	0.018	0.0003	0.1
4	QC1pi	0.1	0.1	0	0.1	0.1
5	QC1	0.001	0.0024	0.01	0.0003	0.08
6, 7, 8	QA1	0.05	0.066	0.05	0.01	0.25
9	QC2	0.0003	0.0013	0.003	0.0003	0.01
10, 11	QA2	0.03	0.042	0.021	0.03	0.08

Assuming layers 3 through 11 are largely unconsolidated granular material, storativity may be calculated as $S = S_S\, b$ (previously defined in equation 2) and specific storage as (Lohman, 1979):

$$S_S = \gamma\,(\alpha + n\,\beta), \qquad (4)$$

where

S = storativity (dimensionless),
S_S = specific storage (ft^{-1}),
b = layer thickness (ft),
γ = specific weight of freshwater [0.434 (lb/in^2)/ft],
α = compressibility of the granular matrix (in^2/lb),
n = porosity of the granular matrix (dimensionless, decimal fraction), and
β = compressibility of freshwater (3.30×10^{-6} in^2/lb).

To calculate storativity at each model cell for layers 3 through 11, the specific storage and layer thickness were substituted into equation 2. Specific storage was calculated by substituting representative porosities (table 9) into equation 4. This left the compressibility of the granular matrix, α, as the only remaining unknown. Freeze and Cherry (1979) summarized published ranges of matrix compressibility for sedimentary materials as follows (converted to English units):

Clay	$7 \times 10^{-3} - 7 \times 10^{-5}$ in^2/lb
Sand	$7 \times 10^{-4} - 7 \times 10^{-6}$ in^2/lb
Gravel	$7 \times 10^{-5} - 7 \times 10^{-7}$ in^2/lb

Table 9. Porosities and effective porosities assigned to model layers, SUBASE Bangor and vicinity, Kitsap County, Washington

[**Porosity**: Freeze and Cherry (1979); Fetter (1988). Effective porosities were assumed equal to specific yields (Fetter, 1988) for similar materials]

Model layer No.	Most abundant material	Porosity	Effective porosity
1	Till	0.20	0.15
2, 4, 6 ,7, 8, 10, 11	Sand and gravel	0.30	0.30
3, 5, 9	Clay and silt	0.40	0.20

Layers that represent confined aquifers (layers 4, 6, 7, 8, 10, 11) were assigned compressibilities of granular matrices of 7×10^{-6} in^2/lb, and layers that represent fully saturated confining units (layers 3, 5, 9) were assigned compressibilities of 7×10^{-5} in^2/lb. These values resulted in a specific storage of 3.5×10^{-6} ft^{-1} for confined aquifers and 3.1×10^{-5} ft^{-1} for fully saturated confining units. The compressibility and resulting specific storage was greater for the confining units than for the confined aquifers because the confining units contain more clay. The contribution of compressibility of the granular matrix to storativity was several times that of the compressibility of water for both confined aquifers and fully saturated confining units. Storativities calculated as described here were used in the model and not changed during the calibration process. Simulated and reported specific storages were similar for the Sea-level aquifer (QA1), which is the unit with the largest number of measured storativities (table 1).

Stream, Drain, and General-Head-Boundary Conductance

The initial conductances for stream, drain, and general-head-boundary cells were calculated using layer thickness and simulated horizontal and vertical hydraulic conductivities. Drain conductances were calculated using an assumed, saturated height of a drainage face of 1 ft. Similarly, stream conductances were calculated using an assumed streambed thickness of 10 ft. If a general-head-boundary or drain cell had multiple faces exposed to saltwater or air, respectively, the maximum conductance calculated for each cell was used as an initial estimate of the conductance. Initial conductances were adjusted by trial-and-error during model calibration.

The general-head-boundary conductance immediately off-shore of SUBASE Bangor was simulated to be very small, which could be caused by a low-permeability deposit that is draped over the off-shore extent of the Sea-level aquifer. Kahle (1998) mapped a till unit (Qvt) draped over at least part of the off-shore extent of the Sea-level aquifer. Additional, unmapped, low-permeability units also may extend off-shore. Such low-permeability deposits would be important for maintaining high water levels in the Sea-level aquifer and may have helped prevent significant saltwater encroachment during the construction of Delta Pier. These deposits would continue to be important to prevent saltwater encroachment, if future water levels decrease as a result of increased ground-water pumping.

Stresses and Stress Periods

Transient ground-water flow conditions occur as the flow system adjusts to changes in stresses to the system, such as ground-water pumping, artificial recharge, and natural recharge. Transient flow conditions existed in the flow system from predevelopment (January 17, 1977) to April 1995, when the second and final mass water-level measurements were conducted as part of the USGS Bangor studies (Kahle, 1998). Simulations of transient conditions require starting water levels and in this study, simulated steady-state water levels for predevelopment stress conditions were used for this purpose.

A series of time periods of constant stress (stress periods) were selected from predevelopment to April 15, 1995 to represent transient conditions in the flow system. From predevelopment through December 31, 1980, stress periods were selected on the basis of pumping and artificial recharge patterns on SUBASE Bangor (fig. 16). New stress periods were selected when groups of wells came on- and off-line and when pumping or artificial recharge rates for those groups of wells significantly changed. Stress periods were numbered sequentially with predevelopment labeled stress period 0 (table 10). The ends of stress periods 12 and 40 were selected to coincide with mass water-level measurements on SUBASE Bangor around July 1, 1979 (Paterson, 1981) and throughout the study area during the week of April 15, 1995 (Kahle, 1998), so that simulated water levels at the ends of these stress periods could be compared with measured water levels on those dates. Stress periods of 1 year were selected for the time period from January 1, 1981 through December 31, 1992 to represent gradual changes in on- and off-base pumping and to adequately represent when different wells came on- and off-line. Stress periods of about 3 months were selected for the time period from January 1, 1993 through April 15, 1995 to represent possible seasonal changes in the flow system.

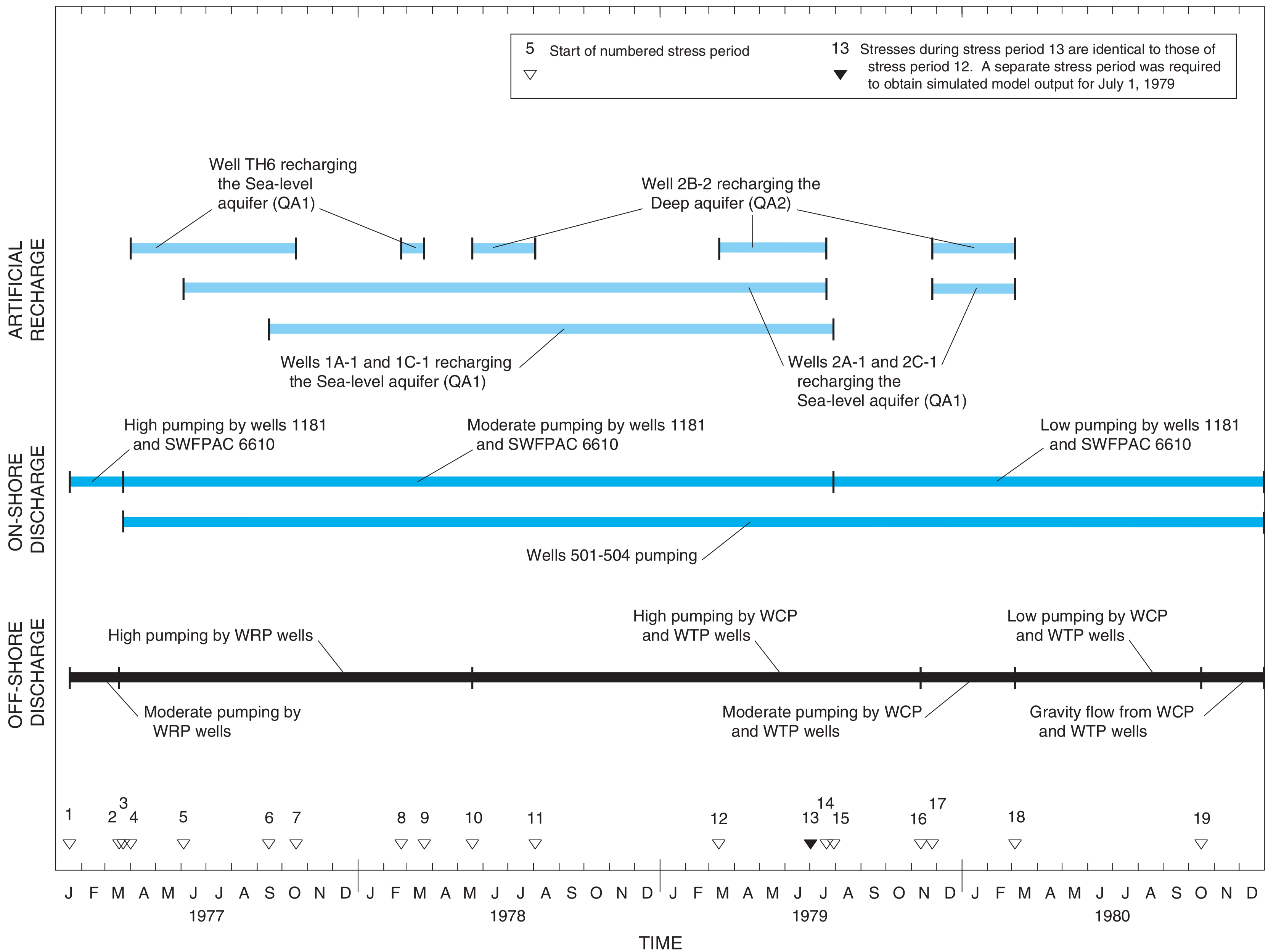


Figure 16. Stress periods and patterns of ground-water discharge and artificial recharge on SUBASE Bangor, Kitsap County, Washington, Jan. 17, 1977 through Dec. 31, 1980. (Starting dates and lengths of stress periods are shown in table 2; locations of wells are shown in figure 3.)

Table 10. Stress periods simulated in the model for SUBASE Bangor and vicinity, Kitsap County, Washington

[–, not applicable]

Stress period No.	Start of stress period	Length of stress period (days)
0[1]	Predevelopment	–
1	01-17-1977	60
2	03-18-1977	5
3	03-23-1977	9
4	04-01-1977	64
5	06-04-1977	103
6	09-15-1977	33
7	10-18-1977	127
8	02-22-1978	28
9	03-22-1978	58
10	05-19-1978	76
11	08-03-1978	222
12[1]	03-13-1979	111
13	07-02-1979	19
14	07-21-1979	9
15	07-30-1979	105
16	11-12-1979	14
17	11-26-1979	100
18	03-05-1980	225
19	10-16-1980	76
20-31	01-01-1981 through 1992[2]	365
32	01-01-1993	90
33	04-01-1993	91
34	07-01-1993	92
35	10-01-1993	92
36	01-01-1994	90
37	04-01-1994	91
38	07-01-1994	92
39	10-01-1994	92
40[1]	01-01-1995[3]	105

[1]At the end of the stress period, simulated and measured water levels were compared.

[2]Twelve stress periods, each 365 days long, except during leap years when length is 366 days.

[3]Stress period ends on April 15, 1995.

Ground-water pumping and artificial recharge rates were simulated using the WEL module (McDonald and Harbaugh, 1988), which simulates constant rates of well discharge or recharge per stress period at user-selected model cells. Pumping and artificial recharge rates were assigned to the node of each model cell in which a pumping or recharging well is located (table 11). If multiple wells were pumping from or recharging to the same model cell, pumpage and artificial recharge were combined. When a well was open to more than one model layer, pumpage or recharge were distributed proportional to aquifer thickness. Simulated pumpage for wells within 1,500 ft of a model boundary was decreased to 50 percent of actual pumpage because these wells are expected to draw ground water from outside the model boundaries and thus simulating their actual pumpage would overestimate simulated drawdowns. Affected wells were: 25N/01E-19H02 (Dickey School), 25N/01E-22F02 (Selbo Road), 26N/01E-02L04 (Big Valley dug), and 26N/01E-02L05 (Big Valley USGS).

Ground-water recharge from precipitation was calculated using the results from Bidlake and Payne (2001). Recharge was applied to the top active model layer at each cell using the RCH module (McDonald and Harbaugh, 1988). Recharge during predevelopment was assumed to equal long-term average recharge (see section "Natural Recharge"). The procedure outlined by Bidlake and Payne allows for the calculation of annual recharge in the model area as a function of annual precipitation. However, because most stress periods are fractions of years, annual recharge was prorated for shorter time periods according to the monthly fractional drainage from the root zone (fig. 7) on the assumption that the timing of drainage from the root zone coincides with ground-water recharge from precipitation. Depending on the length and timing of simulated stress periods, ground-water recharge may vary seasonally and may be larger or smaller than the long-term average recharge (fig. 17).

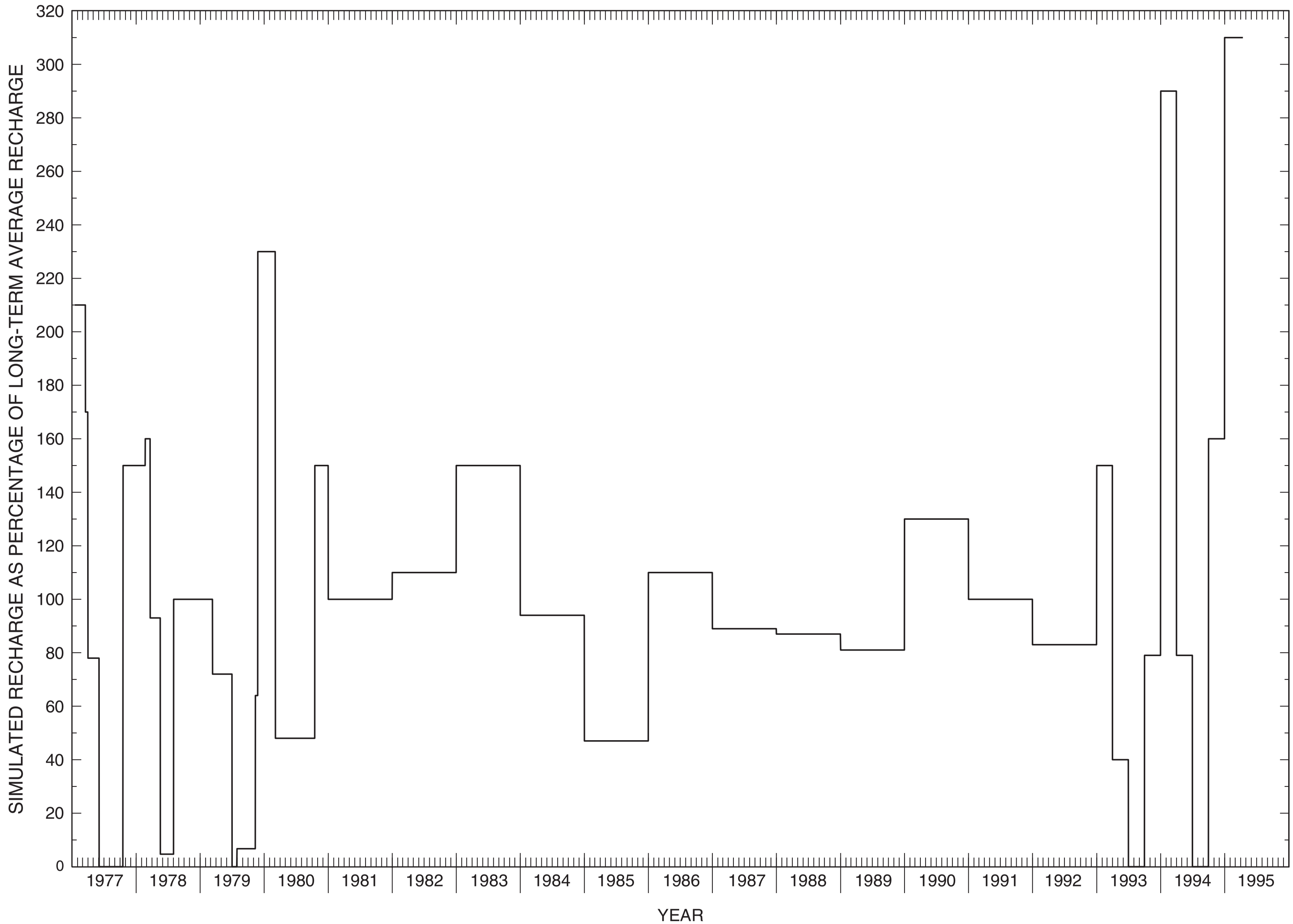


Figure 17. Simulated recharge as percentage of long-term average recharge for SUBASE Bangor and vicinity, Kitsap County, Washington, Jan. 17, 1977 through April 15, 1995.

Table 11. Wells used to simulate ground-water discharge or artificial recharge in the model, and fractional allocation of discharge or recharge by model layer, SUBASE Bangor and vicinity, Kitsap County, Washington

[**Well No.**: See figure 3 for explanation of well-numbering system. **Navy identifier**: Locations of wells shown in figure 8. **Acronyms**: KPUD, Kitsap County Public Utility District No. 1; NUWC, Naval Undersea Warfare Center. –, not applicable]

Well No.	Navy identifier	Common name	Model node (row, column, layer)	Fraction from layer
SUBASE Bangor, public-supply wells				
26N/01E-18K01	504	–	87, 38, 7	1
26N/01E-18P03	501	–	104, 32, 6	0.5
			104, 32, 7	0.5
26N/01E-18P04	502	–	101, 34, 6	0.334
			101, 34, 7	0.333
			101, 34, 8	0.333
26N/01E-18P05	503 Old	–	95, 36, 6	0.5
			95, 36, 7	0.5
26N/01E-30L01	SWFPAC 6610	–	125, 45, 4	1
26N/01E-31R01	505 (TH18)	–	135, 55, 6	0.22
			135, 55, 7	0.22
			135, 55, 8	0.22
			135, 55, 10	0.34
26N/01E-32L05	1181	–	129, 59, 8	1
SUBASE Bangor, on-shore pressure reduction wells				
26N/01E-18L04	WRP-1	–	82, 27, 6	0.5
			82, 27, 7	0.5
26N/01E-18L05	WRP-2	–	85, 27, 6	0.5
			85, 27, 7	0.5
26N/01E-18L06	WRP-3	–	89, 27, 6	0.5
			89, 27, 7	0.5
26N/01E-18N03	WRP-5	–	103, 23, 6	0.5
			103, 23, 7	0.5
26N/01E-18P02	WRP-4	–	96, 26, 6	0.5
			96, 26, 7	0.5
SUBASE Bangor, off-shore pressure reduction wells				
–	WCP and WTP wells – not numbered	–	85, 20, 6	1
			85, 21, 6	1
			86, 20, 6	1
			86, 21, 6	1
			87, 20, 6	1
			88, 20, 6	1
			89, 20, 6	1
			90, 20, 6	1
			91, 20, 6	1

Table 11. Wells used to simulate ground-water discharge or artificial recharge in the model, and fractional allocation of discharge or recharge by model layer, SUBASE Bangor and vicinity, Kitsap County, Washington—*Continued*

Well No.	Navy identifier	Common name	Model node (row, column, layer)	Fraction from layer
SUBASE Bangor, artificial recharge wells				
26N/01E-19Q01	1B-2	–	116, 45, 11	1
26N/01E-19Q02	1A-1	–	116, 45, 6	0.334
			116, 45, 7	0.333
			116, 45, 8	0.333
26N/01E-19Q03	1C-1	–	115, 45, 6	0.334
			115, 45, 7	0.333
			115, 45, 8	0.333
26N/01E-30D01	TH6	–	119, 37, 6	0.334
			119, 37, 7	0.333
			119, 37, 8	0.333
26N/01E-31A03	2C-1	–	126, 51, 7	0.5
			126, 51, 8	0.5
26N/01E-31B02	2B-2	–	127, 50, 10	1
26N/01E-31B03	2A-1	–	126, 50, 6	0.334
			126, 50, 7	0.333
			126, 50, 8	0.333
26N/01W-25A02	3A-1	–	122, 25, 6	0.334
			122, 25, 7	0.333
			122, 25, 8	0.333
Silverdale Water District No. 16, public-supply wells				
25N/01E-03E01	–	Spirit Ridge No.4	133, 78, 2	1
25N/01E-03E02	–	Spirit Ridge No.3	133, 78, 2	1
25N/01E-03E03	–	Spirit Ridge No.1	133, 78, 2	1
25N/01E-03E04	–	Spirit Ridge No.2	133, 77, 2	1
25N/01E-05J01	–	Dawn Park	138, 66, 4	1
25N/01E-07A01	–	Frontier Woods	147, 60, 4	1
25N/01E-10D01	–	Island Lake	139, 81, 2	1
25N/01E-10N01	–	Bucklin Ridge	146, 82, 6	0.5
			146, 82, 7	0.5
25N/01E-15D01	–	Ridgetop	150, 85, 10	1
25N/01E-16J01	–	Chena Road No.2	156, 85, 4	1
25N/01E-16R01	–	Chena Road No.1	156, 85, 4	1
25N/01E-18H01	–	Westwind	161, 63, 10	0.5
			161, 63, 11	0.5
25N/01E-19H02[1]	–	Dickey School	171, 66, 7	0.5
			171, 66, 8	0.5
25N/01E-20F01	–	Provost	167, 70, 4	1
25N/01E-22F02[1]	–	Selbo Road	162, 90, 4	1

Table 11. Wells used to simulate ground-water discharge or artificial recharge in the model, and fractional allocation of discharge or recharge by model layer, SUBASE Bangor and vicinity, Kitsap County, Washington—*Continued*

Well No.	Navy identifier	Common name	Model node (row, column, layer)	Fraction from layer
Poulsbo, public-supply wells				
26N/01E-02L04[1]	–	Big Valley dug	41, 71, 2	1
26N/01E-02L05[1]	–	Big Valley USGS	41, 71, 8	1
NUWC Keyport, public-supply wells				
26N/01E-36P04[2]	–	Keyport No.4	118, 98, 6	0.27
			118, 98, 7	0.27
			118, 98, 8	0.27
26N/01E-36P05	–	Keyport No.5	119, 97, 10	0.5
			119, 97, 11	0.5
KPUD Keyport, public-supply wells				
26N/01E-36M01	–	Keyport No.1	117, 94, 10	0.5
			117, 94, 11	0.5
Vinland, public-supply wells				
26N/01E-04B01	–	Vinland No.2	40, 52, 10	1
26N/01E-04B02	–	Vinland No.1	40, 52, 10	1
26N/01E-05K01	–	Bela Vista No.1	51, 43, 6	1
26N/01E-05K02	–	Bela Vista No.2	48, 44, 6	0.334
			48, 44, 7	0.333
			48, 44, 8	0.333
27N/01E-27E01	–	Edgewater No.1	22, 51, 6	1
27N/01E-27E04	–	New Edgewater No.2	22, 52, 6	1
27N/01E-27J01	–	Edgewater No.4	21, 58, 2	1
27N/01E-27J02	–	Edgewater No.3	21, 58, 6	0.334
			21, 58, 7	0.333
			21, 58, 8	0.333
Island Lake, public-supply wells				
25N/01E-03P01	–	Island Lake No.2	135, 81, 2	1
25N/01E-03R01	–	Island Lake No.1	134, 87, 2	1
Apex Airport, public-supply wells				
25N/01E-18D03	–	Apex No.2	159, 56, 4	1
25N/01E-18E01	–	Apex No.3	161, 55, 4	1

[1]Simulated discharge was 50 percent of actual discharge, because the well is within 1,500 feet of a model boundary.

[2]Total of fractions does not add to 1, because well also is screened below layer 11.

Model Calibration

Model calibration was achieved by trial-and-error adjustments of selected hydraulic parameters to obtain the best agreements between simulated and measured or estimated variables in steady-state and transient simulations. Initially, each model layer was assigned a single horizontal hydraulic conductivity based on estimated values and a vertical anisotropy of 10. Transmissivities, vertical conductances, and general-head-boundary, drain, and stream conductances were calculated from these initial values. During the first phase of the calibration, simulated and measured predevelopment water levels were matched by decreasing the initial horizontal hydraulic conductivities of confining units until simulated water levels approximated measured water levels. Horizontal hydraulic conductivities of confining units were small and their adjustment was essentially an adjustment of confining-unit impedance to vertical ground-water flow. The calibration of steady-state, predevelopment conditions was fine-tuned by making some local adjustments in horizontal hydraulic conductivities of aquifers and confining units. Also as part of this process, general-head-boundary, drain, and stream conductances were recalculated using the updated hydraulic conductivities.

Once reasonable predevelopment water levels were simulated, additional fine-tuning of the calibration was achieved by independently adjusting the general-head-boundary, stream, and drain conductances. Of these, general-head-boundary conductances in Hood Canal near Delta Pier were lowered in order to simulate sufficiently high water levels in the Sea-level aquifer on SUBASE Bangor. Isolated stream conductances were set equal to zero to solve some localized numerical stability problems. This effectively removed the affected stream segments as potential ground-water sources or sinks. Once a reasonable calibration had been achieved in steady-state, predevelopment mode, the adequacy of the calibration was checked in transient mode by comparing simulated and historical water levels and water-level drawdowns from January 1977 through April 1995.

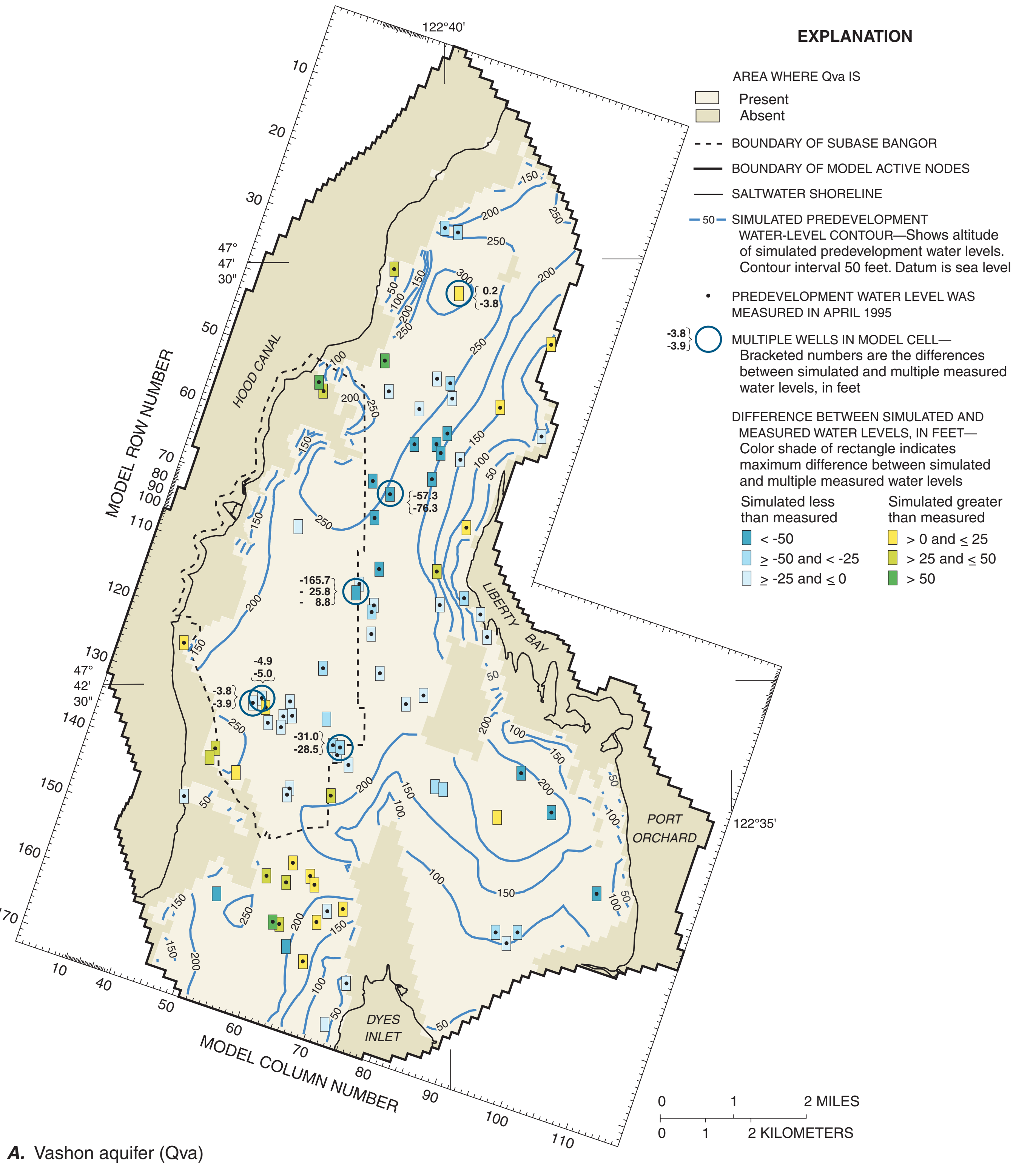
For the transient simulation, each of model layers 3 through 11 were assigned a single specific storage that was estimated from published ranges of compressibility for sedimentary materials (Freeze and Cherry, 1979) and storativities were calculated from these values. Model layers 1 and 2 were assigned storativities equal to their specific yields. Storativities were not adjusted during the calibration process. To improve the calibration results in transient mode, additional adjustments were made to horizontal hydraulic conductivities and the vertical anisotropy of aquifers was increased to simulate vertical water-level gradients within the Sea-level and Deep aquifers. Errors in the calibrated model were significant. The poor agreement between simulated and measured values could be improved by making many local changes to hydraulic parameters but these changes were not supported by other data.

Predevelopment Steady-State Conditions

Water Levels

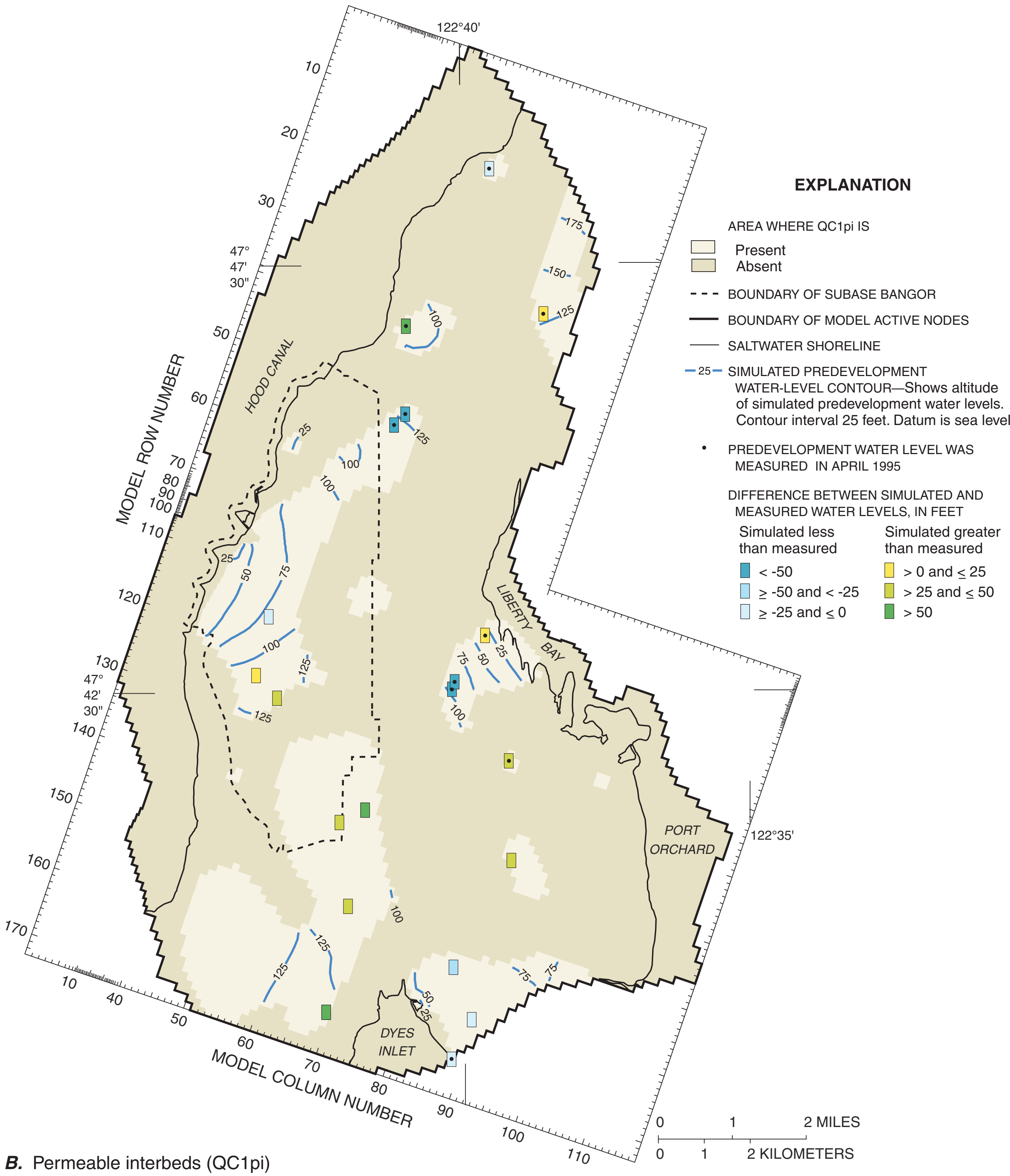
Simulated predevelopment water levels were compared with measured predevelopment and selected April 1995 water levels. The 1995 data were included to increase the sparse number of predevelopment data points, but only if transient simulations indicated that the water levels changed less than 5 ft from predevelopment until April 15, 1995. Patterns in simulated predevelopment water-level contours (fig. 18) were consistent with those measured in April 1995 (Kahle, 1998). Water levels were highest in shallow aquifers and follow the general pattern of the topography. Ground-water flows horizontally from the center of the peninsula toward saltwater bodies and vertically downward in most of the on-shore regions and upward in the off-shore regions (fig. 13).

The limited number of predevelopment water levels were contoured for the Sea-level aquifer and compared with simulated water-level contours (fig. 18*C*). In areas where measured water-level data were available, simulated and measured water-level contours matched reasonably well. Simulated and measured water levels also were compared at individual points in the Vashon aquifer, the Permeable interbeds, and the Sea-level and Deep aquifers (fig. 18) and all units (fig. 19 and table 12). The root-mean-square error (RMSE) of all units (41.9 ft) is 9.3 percent of the range of measured water levels in the flow system (450 ft).



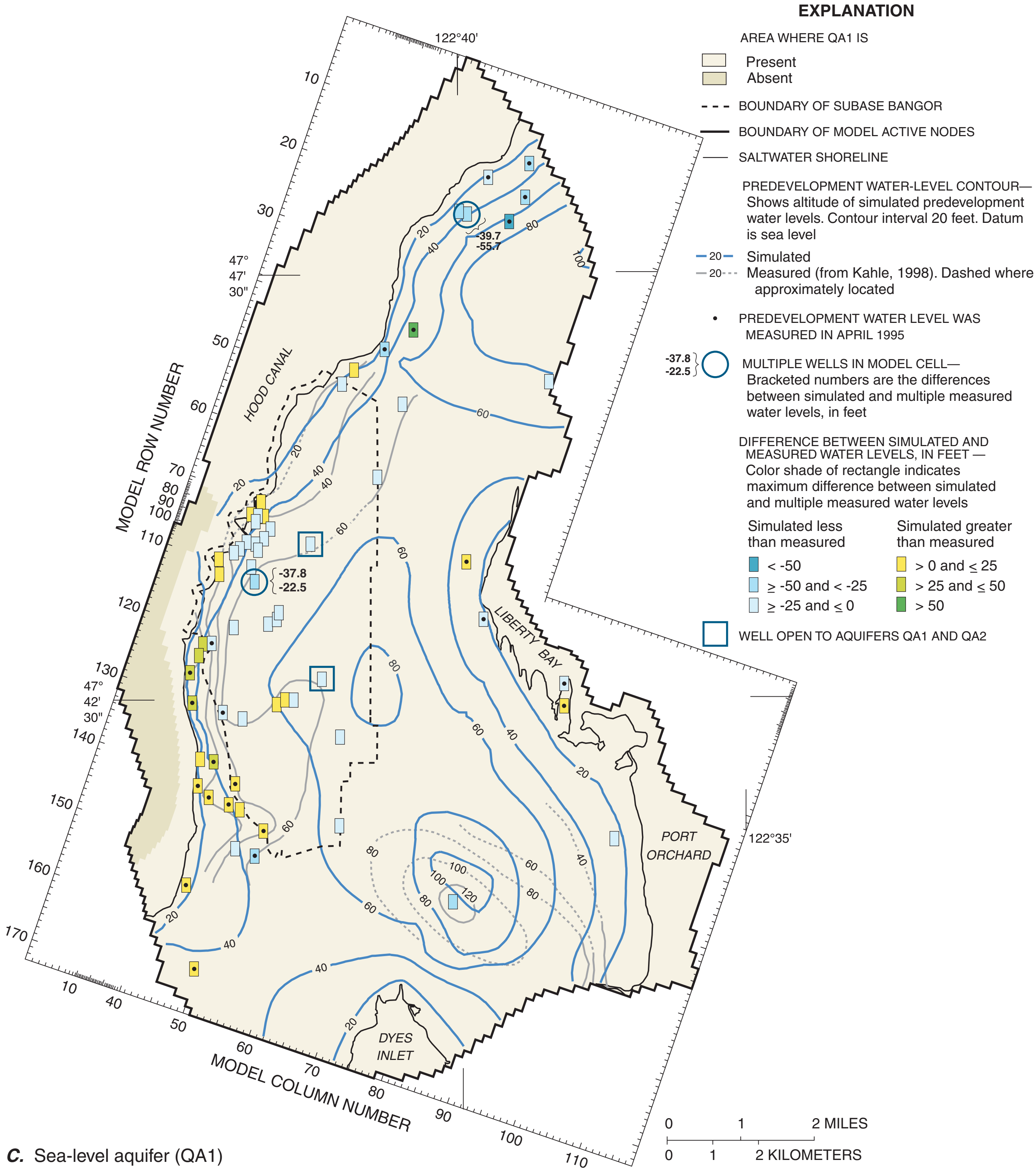
A. Vashon aquifer (Qva)

Figure 18. Simulated predevelopment water-level altitudes and differences between simulated and measured predevelopment water-level altitudes for the Vashon aquifer (Qva) and Permeable interbeds (QC1pi), SUBASE Bangor and vicinity, Kitsap County, Washington.



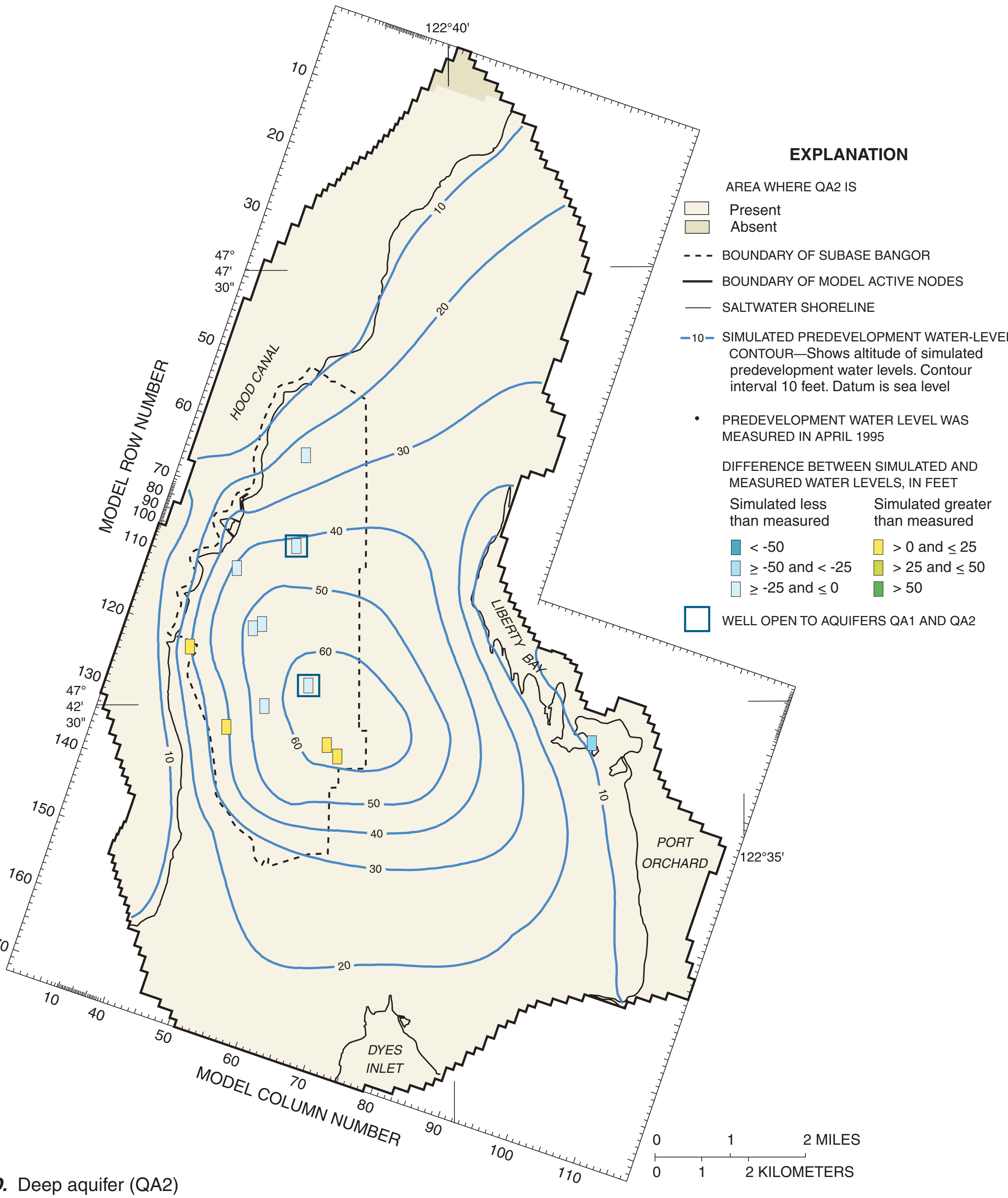
B. Permeable interbeds (QC1pi)

Figure 18—*Continued.*



C. Sea-level aquifer (QA1)

Figure 18—*Continued.*



D. Deep aquifer (QA2)

Figure 18—*Continued.*

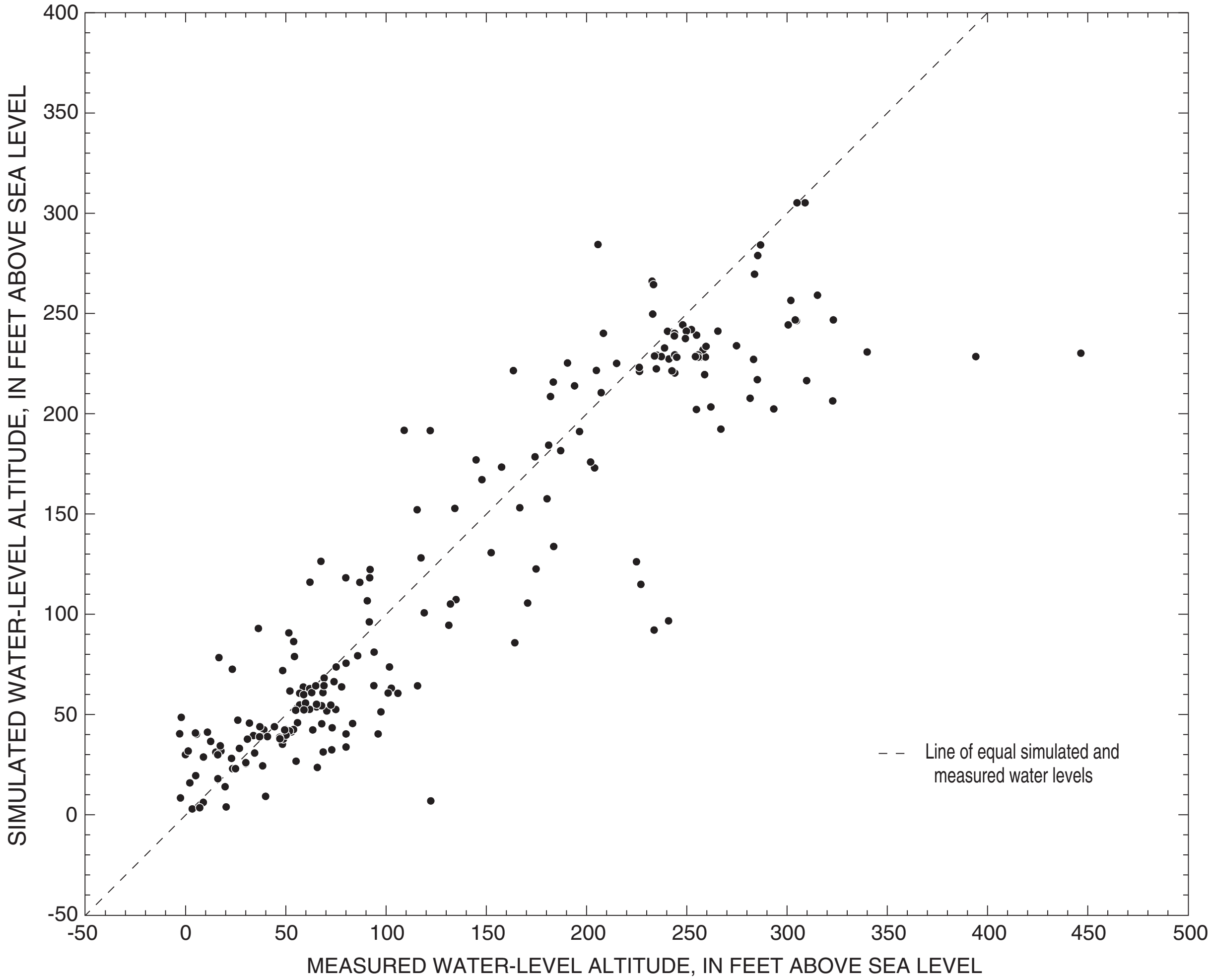


Figure 19. Simulated and measured predevelopment water-level altitudes, SUBASE Bangor and vicinity, Kitsap County, Washington.

Measured altitudes include some April 1995 water levels that are believed to be representative of predevelopment conditions.

Table 12. Statistics for differences between simulated and measured predevelopment water levels, SUBASE Bangor and vicinity, Kitsap County, Washington

[**Hydrogeologic unit**: Qvt, Vashon till confining unit; Qvr, Shallow aquifer; Qva, Vashon aquifer; QCl, Upper confining unit; QClpi, Permeable interbeds; QA1, Sea-level aquifer; and QA2, Deep aquifer. Hydrogeologic designations are from Kahle (1998). **Difference between simulated and measured water level**: A positive difference means the simulated water level is greater than the measured water level. A negative difference means the opposite. **Root-mean-square error (RMSE)** = $\sqrt{(\text{Mean})^2+(\text{Standard deviation})^2}$. –, statistic not computed because the number of values is small. Measured water levels include some measurements made in April 1995 which were believed to be representative of predevelopment conditions]

Hydrogeologic unit	Difference between simulated and measured water level (feet)						Number of values
	RMSE	Median	Mean	Standard deviation	Minimum	Maximum	
Qvt/Qvr	56.5	-25.1	-42.0	37.8	-115.4	-0.9	8
Qva	47.8	-10.3	17.8	44.3	-216.4	78.7	93
QC1	47.8	-5.0	-4.4	47.6	-78.4	82.7	16
QC1pi	61.8	12.5	-8.3	61.2	-144.2	61.8	20
QA1	22.1	-2.6	-3.5	21.9	-55.7	50.8	65
QA2	15.7	-5.7	-5.0	14.8	-30.7	19.9	10
QA1 and QA2	–	-12.0	-12.0	–	-14.0	-9.9	2
All units	41.9	-6.3	-11.8	40.2	-216.4	82.7	214

Overall, the calibrated model has a negative bias: the median simulated water level for all units is about 6 ft less than measured water levels. Excluding the Permeable interbeds, the RMSE generally is smaller for deeper than shallower aquifers. The same pattern is not true, however, if the error is expressed as a percentage of measured water levels.

One reason RMSEs generally decrease for deeper aquifers may be that at a particular row and column location, the model simulates average water levels for each layer, based on uniform properties assigned to each layer that are representative of average conditions in the field. A measured water level, however, may not be representative of vertically averaged water levels in the hydrogeologic unit at that location. If a well is open to multiple intervals within a hydrogeologic unit, a measured water level would be representative of averaged effects of vertical heterogeneity within a unit. If a well is open to only one discrete interval, however, a measured water level most likely does not represent averaged effects of vertical heterogeneity. Generally, wells completed in deep aquifers were public-supply wells that were open to multiple intervals within an aquifer. Shallow wells, however, were usually domestic wells that were open to only discrete intervals. As a result, simulated and measured water levels were expected to match more closely for deeper aquifers.

An extreme example of vertical variability in a shallow aquifer is demonstrated by two wells (26N/01E-20R01 and 26N/01E-20R03) that are open to the Vashon aquifer in the same model cell (row 110, column 57). The measured predevelopment water level in one well is 394.2 ft and 254.3 ft in the other; a difference of almost 140 ft. The simulated water level is 228.5 ft, which is closer to the lower measured water level. The well with the highest water level is open to the top of the Vashon aquifer and the other is open to the bottom half of the aquifer. The thickness of the unit is about 300 ft at this location. Differences between simulated and measured water levels for both wells were included to calculate the summary statistics in table 12 and they also are shown in figure 18*A* (the third difference shown at row 110, column 57 is for a water level measured in April 1995). This example illustrates that especially in the shallow units, large simulated differences are not that meaningful. What is important, however, is that the regional flow pattern is correct and that on average, the simulated water levels are representative of the hydrogeologic unit that is being simulated.

For the Vashon aquifer, most simulated water levels in the center of the peninsula were less than measured water levels (fig. 18*A*). Near the coast, the differences between simulated and measured water levels were smaller and simulated water levels were greater than measured water levels at some locations. In some coastal areas, simulated water levels were above land surface. Attempts to increase the horizontal gradient in simulated water levels by increasing simulated water levels in the center of the peninsula and decreasing them near the coast were unsuccessful.

Differences between simulated and measured water levels for the Permeable interbeds (fig. 18*B*) were particularly large in an area immediately west of Liberty Bay. Thus, measured water levels attributed to the Permeable interbeds in this area may actually represent conditions in the Vashon aquifer. The mapped extents of the discontinuous Permeable interbeds were inherently less certain than the mapped extents of more continuous hydrogeologic units, and these uncertainties may explain the larger RMSE of the unit (table 12). Differences between simulated and measured water levels in the Sea-level and Deep aquifers (fig. 18*C* and 18*D*), however, were relatively small. These deeper units are of primary interest in this study, and their relatively small RMSEs indicate that the model may be used to make ground-water flow predictions for these units.

Ground-Water Discharge to Streams, Springs, and Seeps

In addition to comparing simulated and measured water levels, simulated and estimated baseflows were compared for 13 drainage basins for which data were available (table 13 and fig. 20). Specifically, sums of simulated ground-water discharge to streams, springs, and seeps were compared to baseflows estimated from one or more discharges measured during WY95, on the assumptions that (1) all spring and seep discharge in a drainage basin flows into streams and thus becomes part of baseflow, and (2) estimated baseflows for WY95 are representative of long-term average baseflows. However, as previously discussed, the estimated baseflows for WY95 probably represent upper limits of long-term average baseflows, because precipitation estimates for the study area exceeded the long-term average (1953-95) by about 30-35 percent during that time.

Most simulated predevelopment baseflows were less than estimated baseflows (table 13). Simulated baseflows for Johnson and Dogfish Creeks were larger than but close to estimated baseflows. The fact that simulated discharge was about 38 percent higher than estimated for Stream #129 was not significant, because the estimated baseflow was small (0.28 ft^3/s). Overall, simulated baseflows were probably less than estimated baseflows because, as explained previously, the simulated water levels in the Vashon aquifer, which is the main contributor to baseflow, represent average water levels for the aquifer. In the interior of the peninsula, ground-water discharge from perched water-bearing units higher in the aquifer were not simulated although they do contribute to estimated baseflow. The lower simulated streamflow, spring, and ground-water-seep discharge meant that a larger fraction of simulated long-term average recharge reached the deeper ground-water flow system. The simulated net ground-water discharge to all simulated streams, springs, and ground-water seeps equaled about 60 percent of long-term average recharge. About 45 percent of this was contributed by springs and ground-water seeps and the remainder by direct ground-water discharge to streams.

Ground-Water Discharge to Puget Sound

Off-shore discharge of ground water to Puget Sound is another important flux because it represents a significant part of the overall water budget of the ground-water flow system. This flux is difficult to measure, however, and no known measurements exist. Instead, off-shore discharge commonly is estimated using ground-water flow models. Using the model in steady-state mode, a predevelopment off-shore discharge of about 42 percent of long-term average recharge (about 6,900 gal/min) was calculated for Dyes Inlet, Liberty Bay/Port Orchard, and Hood Canal (table 14). The predevelopment off-shore discharge from the Sea-level aquifer to Hood Canal was simulated to be 2.4 percent of long-term average recharge (about 400 gal/min).

Table 13. Estimated and simulated baseflows in streams that drain selected drainage basins, SUBASE Bangor and vicinity, Kitsap County, Washington

[Drainage basins are presented in order of decreasing estimated baseflow. Locations of streamflow measurement sites are shown in figure 20. ft^3/s, cubic feet per second]

Drainage basin	Measuring point (row, column)	Estimated baseflow (ft^3/s)	Simulated baseflow (as percentage of estimated baseflow)								
			Predevelopment			July 1, 1979			April 15, 1995		
			Ground-water discharge to:								
			Stream	Springs and seeps	Total	Stream	Springs and seeps	Total	Stream	Springs and seeps	Total
Drainage basins entirely inside area where model nodes are active											
Clear Creek	150, 77	4.64	72.1	7.5	79.6	68.3	7.3	75.6	82.3	8.0	90.3
Barker Creek	165, 91	3.33	16.5	2.6	19.1	14.2	2.0	16.2	20.9	4.0	24.9
Devil's Hole Creek	107, 22	[1]3.00	2.6	49.9	52.5	0.4	35.6	36.0	1.8	46.2	48.0
Strawberry Creek	165, 76	1.70	59.3	0.1	59.4	54.6	0.0	54.6	70.1	0.5	70.6
Scandia Creek	121, 78	0.72	1.7	17.0	18.7	1.2	15.7	16.9	4.4	23.6	28.0
Johnson Creek	70, 70	[1]0.70	83.4	27.4	110.8	80.6	26.3	106.9	95.8	33.5	129.3
Farms Road Creek	148, 44	0.60	8.3	0.0	8.3	6.2	0.0	6.2	16.0	0.0	16.0
Jumpoff Joe Creek	20, 49	0.57	16.4	0.0	16.4	15.2	0.0	15.2	21.9	0.0	21.9
Stream #129	141, 42	0.28	0.0	138.3	138.3	0.0	135.5	135.5	0.0	149.0	149.0
Drainage basins partially inside area where model nodes are active											
Dogfish Creek	53, 74	[2]2.03	99.2	7.2	106.4	90.6	6.8	97.4	120.4	10.2	130.6
Anderson Creek	165, 45	[2]1.72	10.4	17.4	27.8	9.8	16.6	26.4	13.4	21.4	34.8
Steele Creek	150, 105	[2]1.52	79.2	0.0	79.2	71.8	0.0	71.8	118.8	0.0	118.8
Four Corners Creek	7, 55	[2]0.82	6.2	5.4	11.6	4.4	5.2	9.6	15.2	6.6	21.8

[1]Baseflow for water year 1995 as determined from continuous record by Bidlake and Payne (2001); all other baseflows from miscellaneous measurements in May 1995.

[2]Value is one-half of the estimated baseflow.

In steady-state mode, the model should calculate a flux from saltwater bodies equal to zero for predevelopment conditions. The fluxes that were calculated for predevelopment (table 14) provide a measure of the limitation of approximating the boundary between Puget Sound and the freshwater flow system with general-head-boundary cells. This limitation introduces estimated errors of about 5 percent of long-term average recharge to simulated fluxes.

Transient Conditions

Transient ground-water flow conditions were simulated from January 17, 1977 until April 15, 1995 using the simulated, steady-state predevelopment water levels as initial values. Comparisons of simulated and measured water levels were most meaningful if their changes over time were compared to their respective initial values, because transient simulated water levels are a function of initial values. For this reason, simulated and measured drawdowns since predevelopment were compared in addition to water levels.

Table 14. Simulated fluxes between the ground-water flow system and Puget Sound, SUBASE Bangor and vicinity, Kitsap County, Washington, predevelopment, July 1, 1979 and April 15, 1995

[**Hydrogeologic unit**: Qvt, Vashon till confining unit; Qvr, Shallow aquifer; Qva,Vashon aquifer; QCl, Upper confining unit; QA1, Sea-level aquifer; and QC2, Lower confining unit. Hydrogeologic designations are from Kahle (1998). **Flux**: Long-term average recharge for the simulated flow system is 16,440 gallons per minute (36.6 cubic feet per second). P, predevelopment; J, July 1, 1979; A, April 15, 1995]

Model layer No.	Hydro-geologic unit	Saltwater body	Flux (as percentage of long-term average recharge): From the ground-water flow system into Puget Sound			From Puget Sound into the ground-water flow system			Net (positive values indicate a net flux into Puget Sound)		
			P	J	A	P	J	A	P	J	A
1	Qvt/Qvr	Dyes Inlet	1.7	1.6	1.9	0.0	0.0	0.0	1.7	1.6	1.9
		Liberty Bay/Port Orchard	7.8	6.8	9.1	0.2	0.2	0.2	7.6	6.6	8.9
		Hood Canal	8.5	7.5	9.3	0.9	1.1	1.0	7.6	6.4	8.3
2	Qva	Dyes Inlet	1.1	1.1	1.1	0.0	0.0	0.0	1.1	1.1	1.1
		Liberty Bay/Port Orchard	0.8	0.7	0.8	0.0	0.0	0.0	0.8	0.7	0.8
		Hood Canal	0.3	0.3	0.3	0.0	0.0	0.0	0.3	0.3	0.3
3	QC1	Dyes Inlet	1.6	1.5	0.9	0.0	0.0	0.0	1.6	1.5	0.9
		Liberty Bay/Port Orchard	3.9	2.4	3.0	0.0	0.8	0.1	3.9	1.6	2.9
		Hood Canal	9.8	8.7	10.7	0.8	0.9	0.8	9.0	7.8	9.9
6, 7, 8	QA1	Hood Canal	2.4	1.5	2.0	0.1	0.4	0.1	2.3	1.1	1.9
9	QC2	Hood Canal	3.9	1.8	2.6	0.0	0.9	0.0	3.9	0.9	2.6
All	All	Total for Dyes Inlet[1]	4.4	4.1	3.9	0.0	0.0	0.0	4.4	4.1	3.9
All	All	Total for Liberty Bay/Port Orchard[1]	12.4	9.9	12.9	0.2	1.0	0.3	12.2	8.9	12.6
All	All	Total for Hood Canal[1]	24.9	19.8	24.8	1.8	3.4	1.9	23.1	16.4	22.9
All	All	Total for Dyes Inlet, Liberty Bay/Port Orchard, and Hood Canal[1]	41.7	33.9	41.6	1.9	4.3	2.2	39.8	29.6	39.4

[1]Total may not add to sum of subtotals due to rounding.

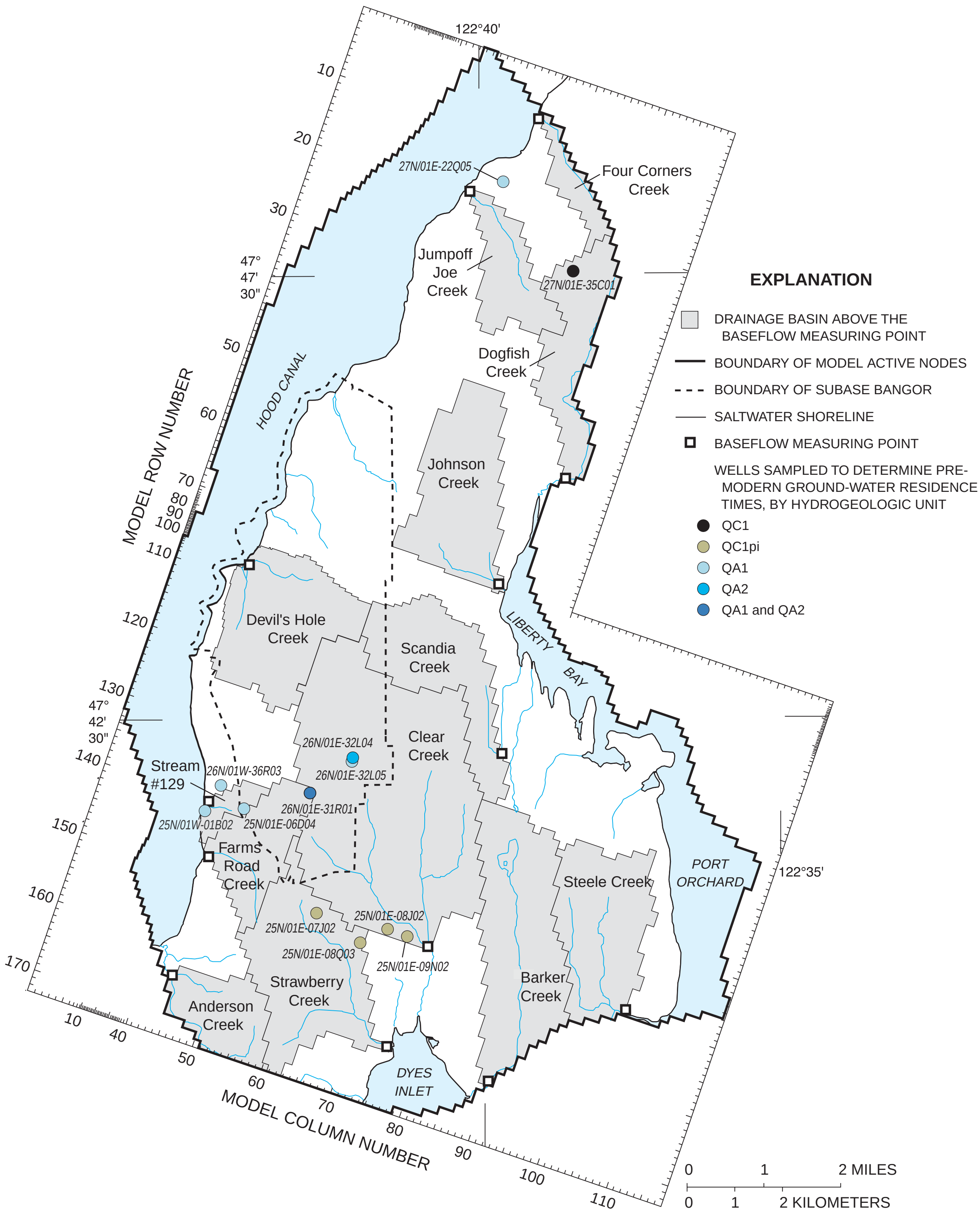


Figure 20. Locations of stream baseflow measuring points, drainage basins above the measuring points, and wells sampled to determine pre-modern ground-water residence times, SUBASE Bangor and vicinity, Kitsap County, Washington.

Historical water-level data since predevelopment were available for a number of wells on SUBASE Bangor and one off-base well (fig. 21). These data were graphed as drawdowns since predevelopment and compared with simulated drawdowns (sample hydrographs are shown in figure 22 and the remainder in Appendix 3). Except for several wells open to the Sea-level aquifer near Delta Pier, simulated and measured drawdowns matched reasonably closely. For some of the wells near Delta Pier, simulated drawdowns during the first few years after the initiation of water-level decreases were larger than measured drawdowns (for example, wells B-1, 401D, B-5, and B-4), while simulated drawdowns of nearby wells that are open to the same aquifer were similar to measured drawdowns (for example, wells B-7, B-2, and B-3). These more or less random matches and mismatches between simulated and measured drawdowns within a small area indicate that small-scale heterogeneity that is difficult to simulate may be responsible for the differences. Higher simulated storativities could decrease the simulated drawdowns in some wells, but may decrease them too much in others. On a regional scale, however, simulated drawdowns match measured drawdowns reasonably well.

Water Levels, Water-level Drawdowns, and Ground-Water Fluxes on July 1, 1979

Water levels of a sufficient number of wells were measured around July 1, 1979, to construct water-level and drawdown contour maps of the Sea-level aquifer near Delta Pier and compare simulated and measured values (figs. 23 and 24*A*). Simulated and measured water-level contours and lines of equal drawdown were similar, but as explained previously, the similarities in lines of equal drawdown were more significant. Simulated and measured drawdowns also were compared at individual points in the Sea-level and Deep aquifers (fig. 24) and all hydrogeologic units (table 15 and Appendix 4). The RMSE of drawdowns is smallest for deeper units and equals 9.3 ft for all units. The RMSE of water levels also was smallest for deeper units and equals 13.7 ft for all units (table 16). The relatively small differences between simulated and measured drawdowns for the Sea-level and Deep aquifers demonstrate that the flow model adequately represents these aquifers in areas where measurements were available.

Simulated baseflows for July 1, 1979 were smaller than simulated predevelopment baseflows of all streams listed in table 13, because simulated water levels in the Vashon aquifer, which provides most of the baseflows, were lower. They were lower because ground-water recharge in the stress period immediately preceding July 1, 1979 (stress period 12), was about 70 percent of long-term average recharge (fig. 17). This decrease in water levels represents a seasonal effect. Water-level decreases in the Vashon aquifer near Delta Pier, however, were in excess of seasonal decreases in response to the large ground-water pumping from the Sea-level aquifer. The resulting decrease in baseflows to Devil's Hole Creek since predevelopment is about 30 percent (table 13), which is larger than the decrease in baseflows to the other streams in table 13.

Ground-water pumping on and off SUBASE Bangor and lower than long-term average recharge rates during stress period 12 also affected fluxes to and from the saltwater bodies (table 14). On July 1, 1979, simulated ground-water discharge to Liberty Bay/Port Orchard and Dyes Inlet was about 410 and 50 gal/min less than the simulated ground-water discharge during predevelopment. Flow from Liberty Bay/Port Orchard into the ground-water system was larger by about 130 gal/min and remained zero from Dyes Inlet to the ground-water system. These changes were mostly attributed to ground-water pumping by off-base public-supply systems (fig. 8), because the ground-water levels near Liberty Bay/Port Orchard and Dyes Inlet were not affected by pumping near Delta Pier. The simulated decrease in ground-water discharge to Hood Canal and the corresponding increase in flow from the saltwater body to the ground-water system, however, were mostly attributed to pumping near Delta Pier. On July 1, 1979, ground-water discharge to Hood Canal was about 840 gal/min less than during predevelopment, while the flow from Hood Canal into the ground-water flow system was larger by about 260 gal/min.

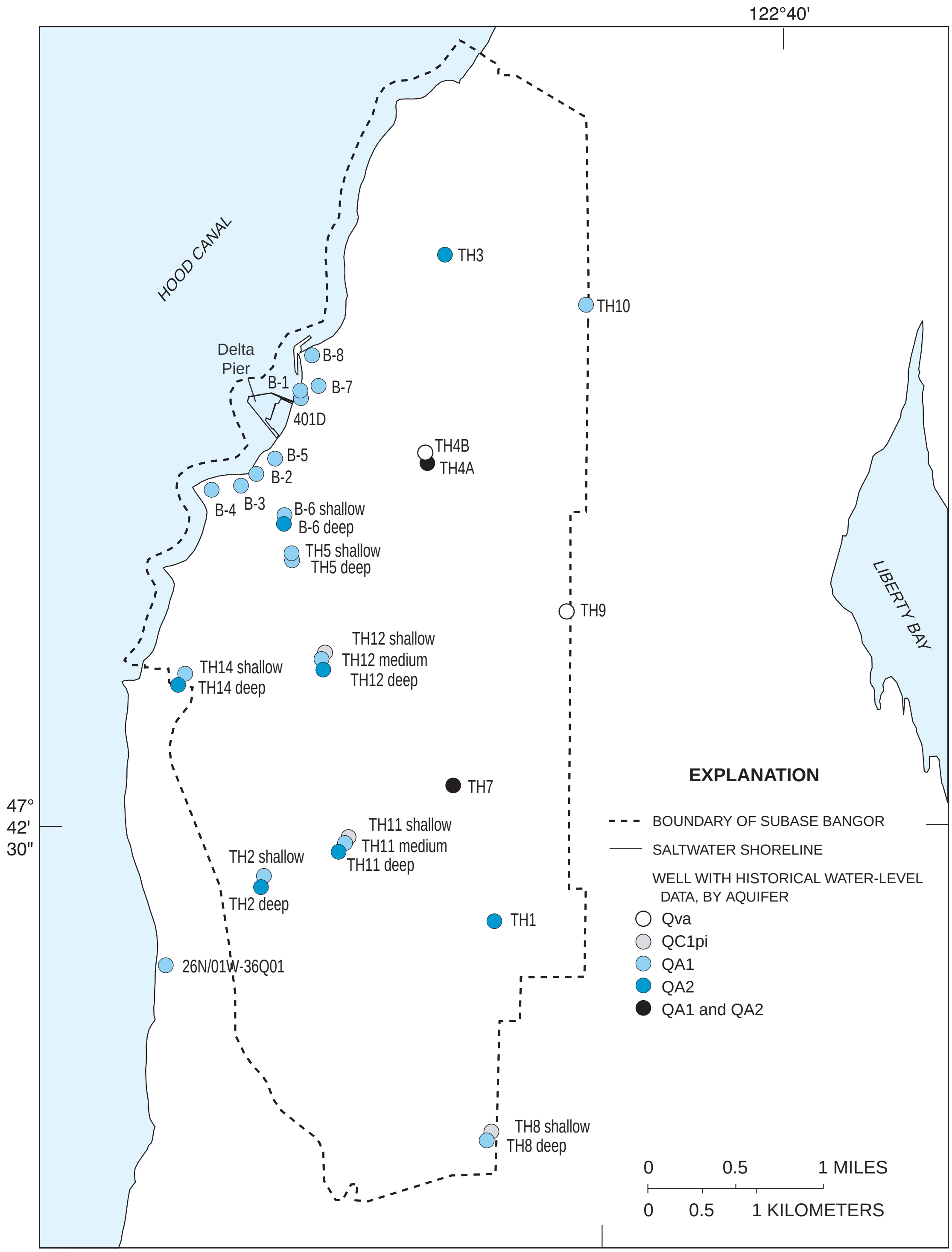


Figure 21. Locations of on- and off-base wells with historical water-level data since predevelopment, SUBASE Bangor and vicinity, Kitsap County, Washington.

Hydrographs are shown in e 22 and ndix 3.

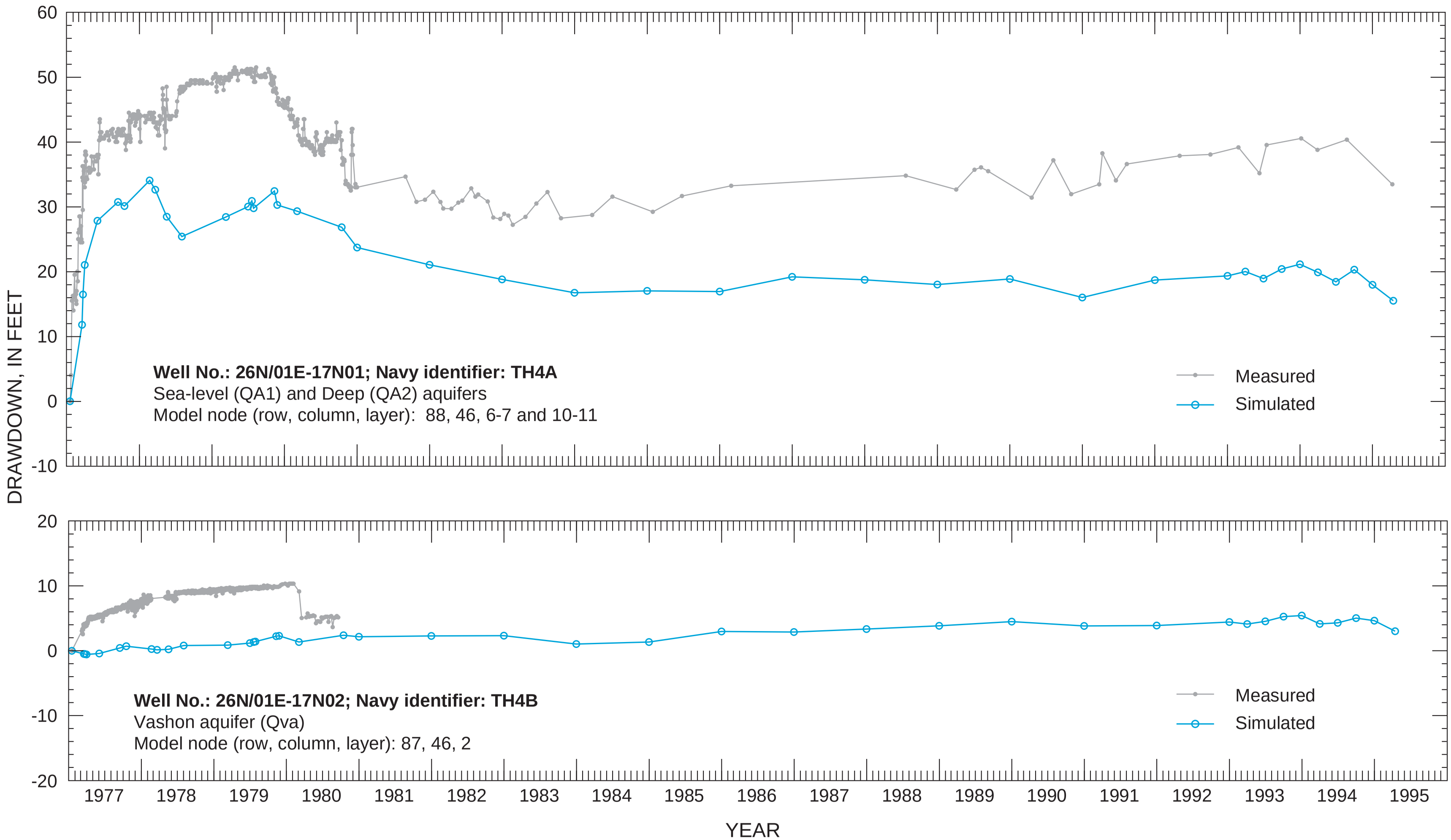


Figure 22. Simulated and measured drawdowns since predevelopment in wells open to selected aquifers, SUBASE Bangor and vicinity, Kitsap County, Washington.

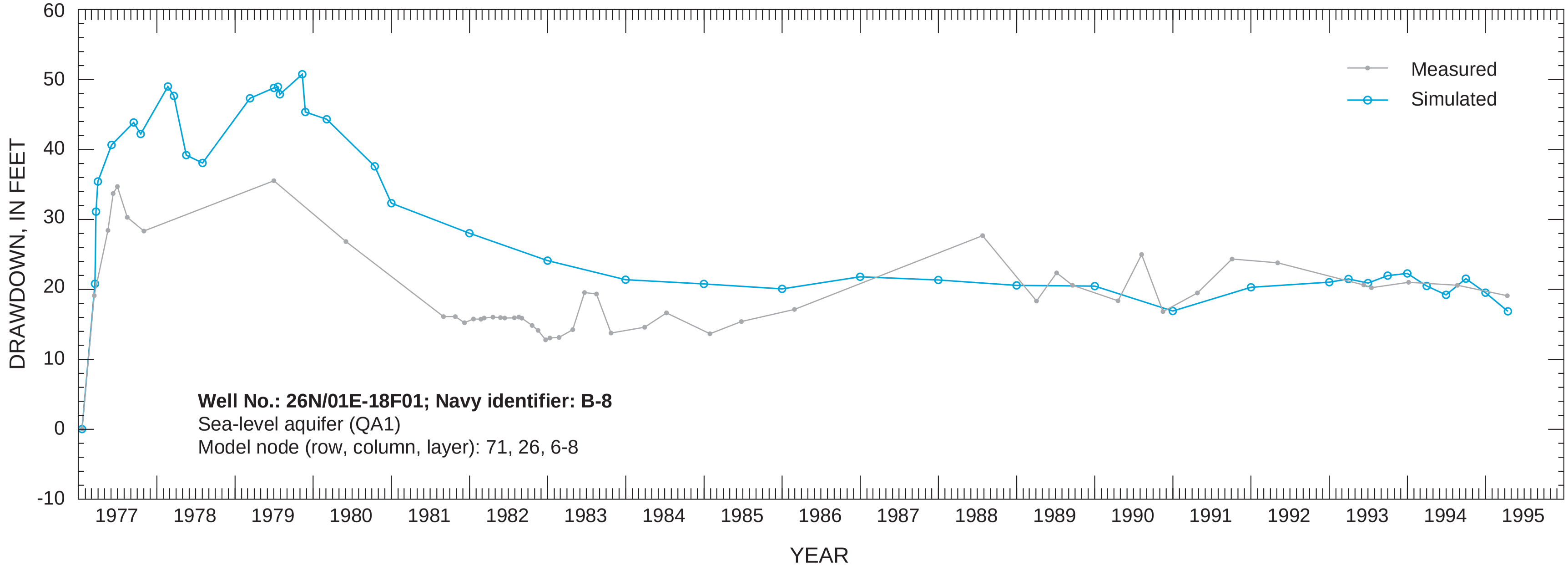


Figure 22.—*Continued.*

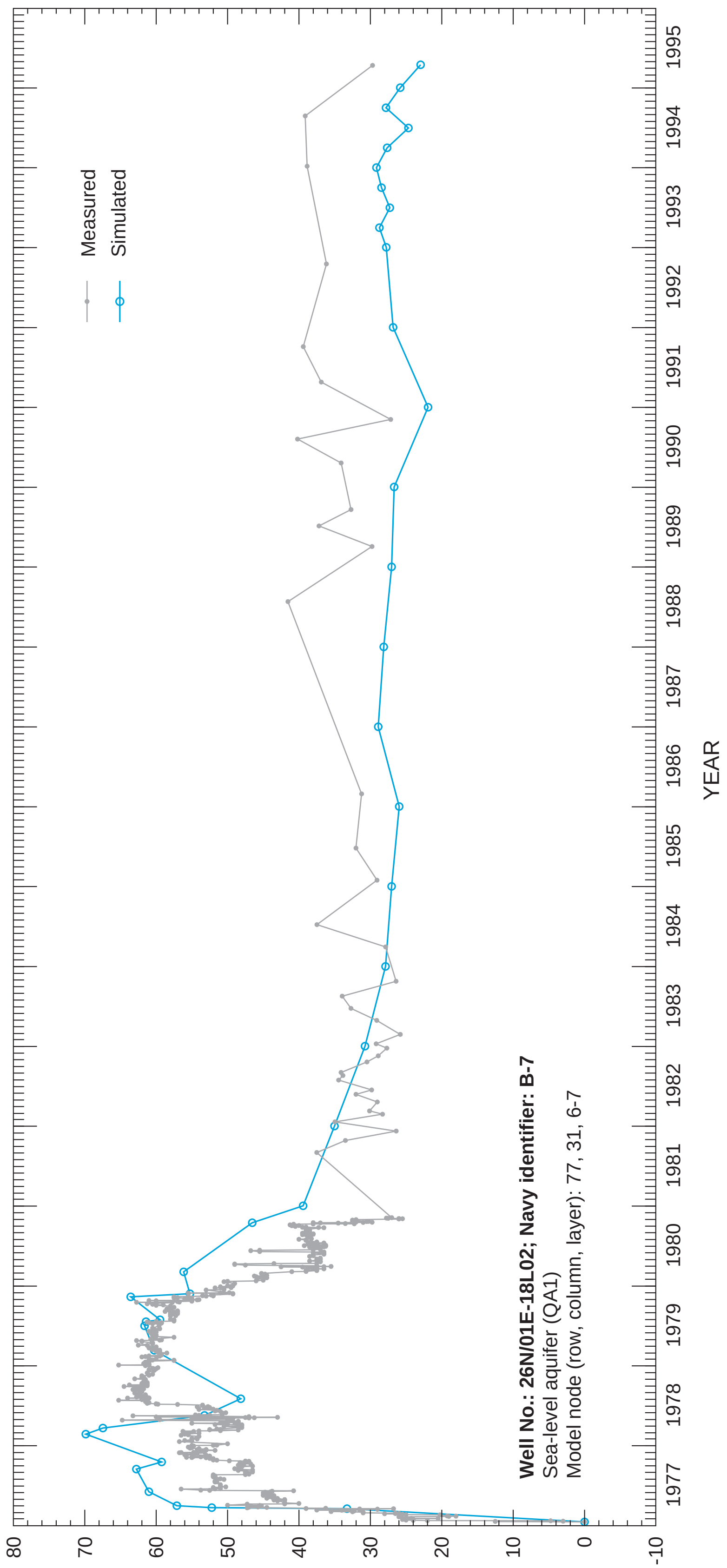
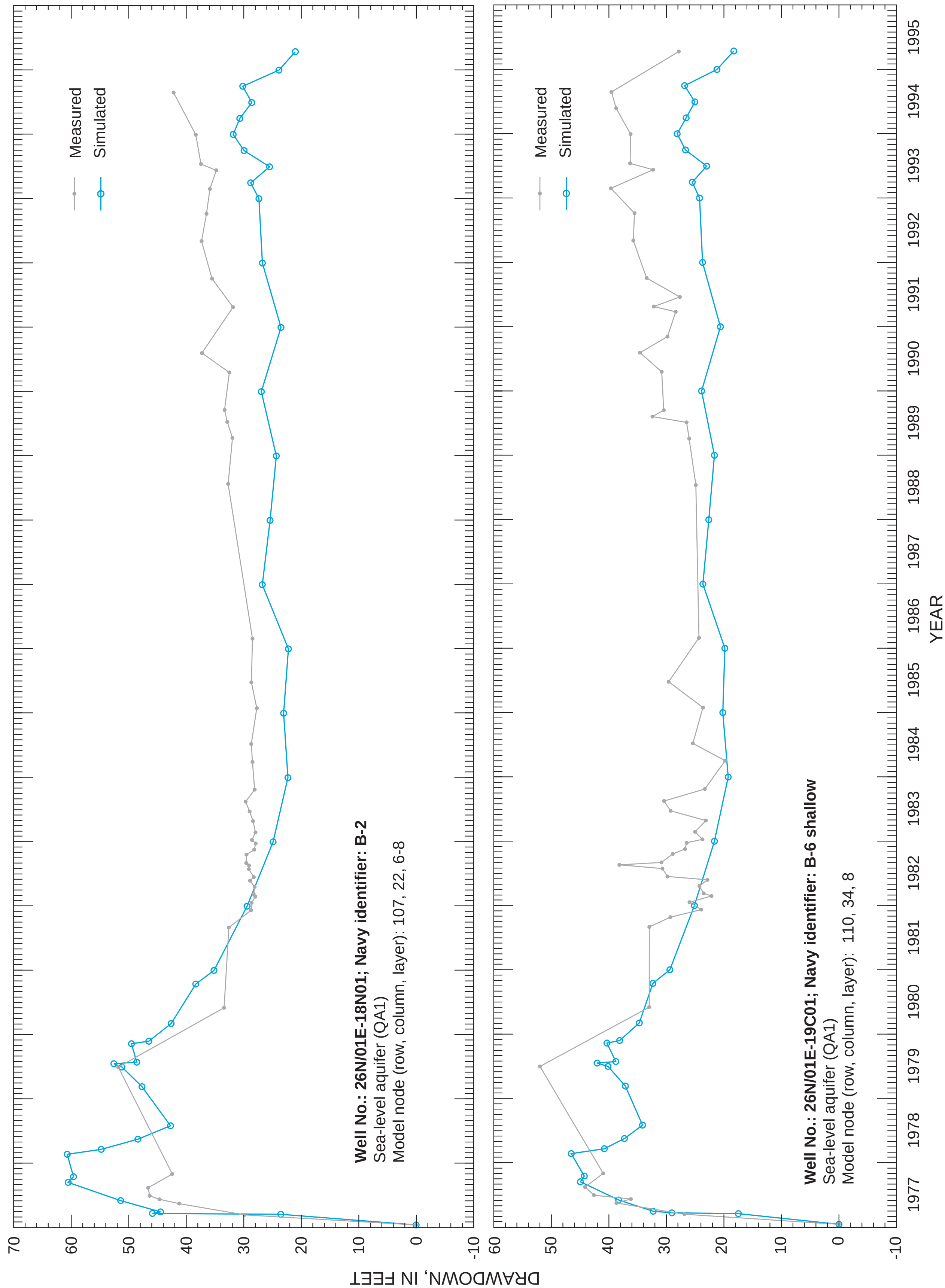


Figure 22.—*Continued.*



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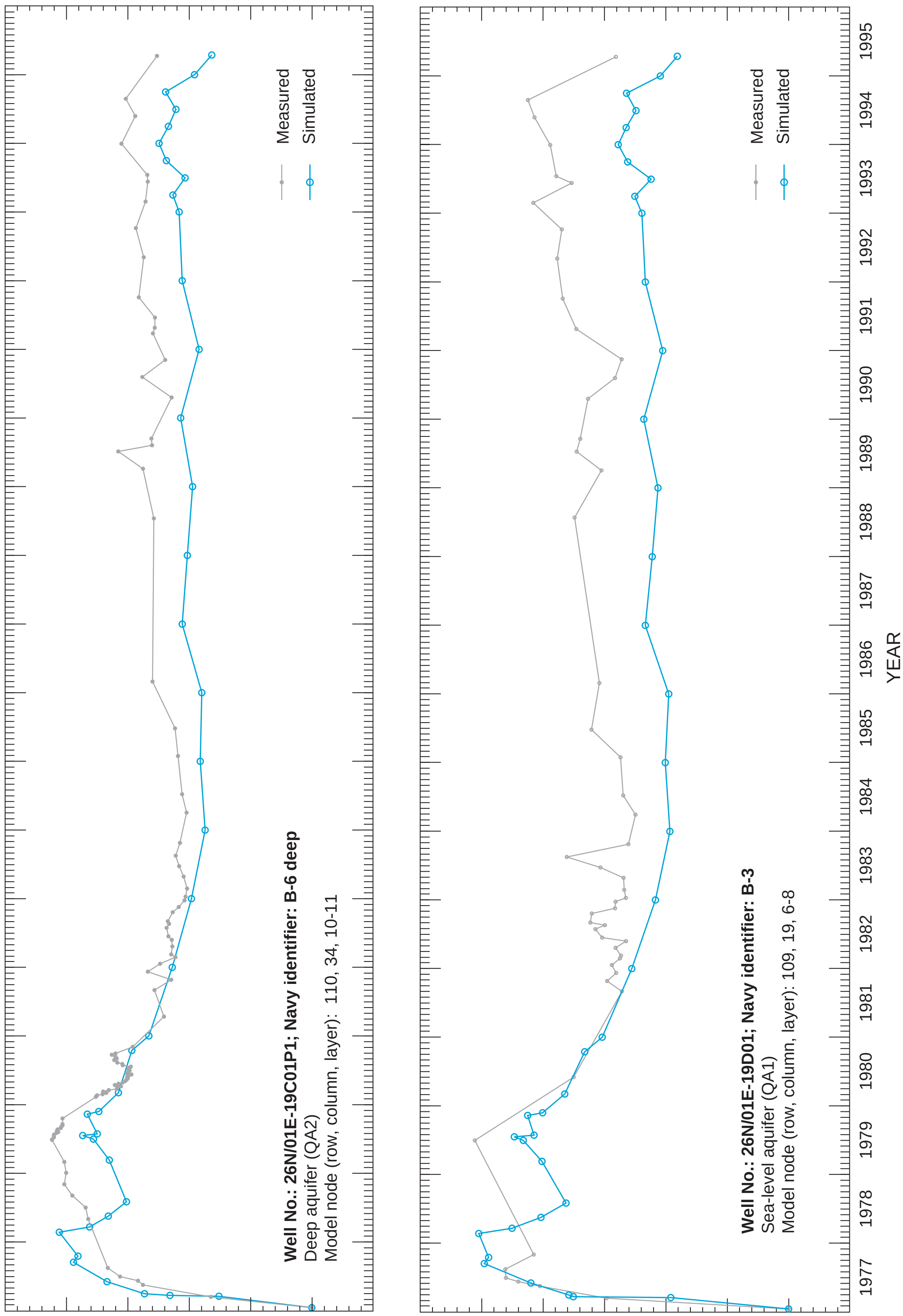
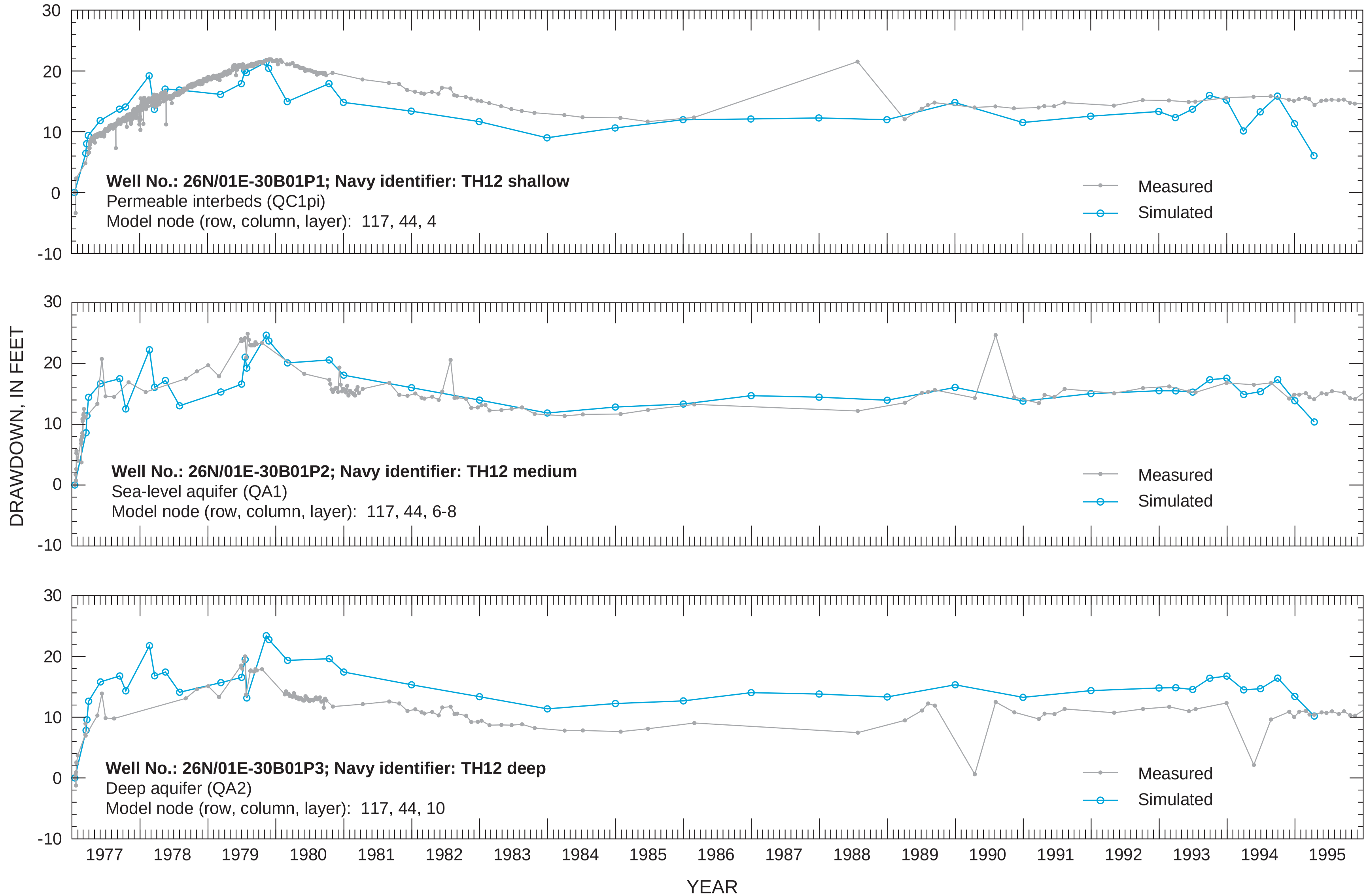


Figure 22.—*Continued.*



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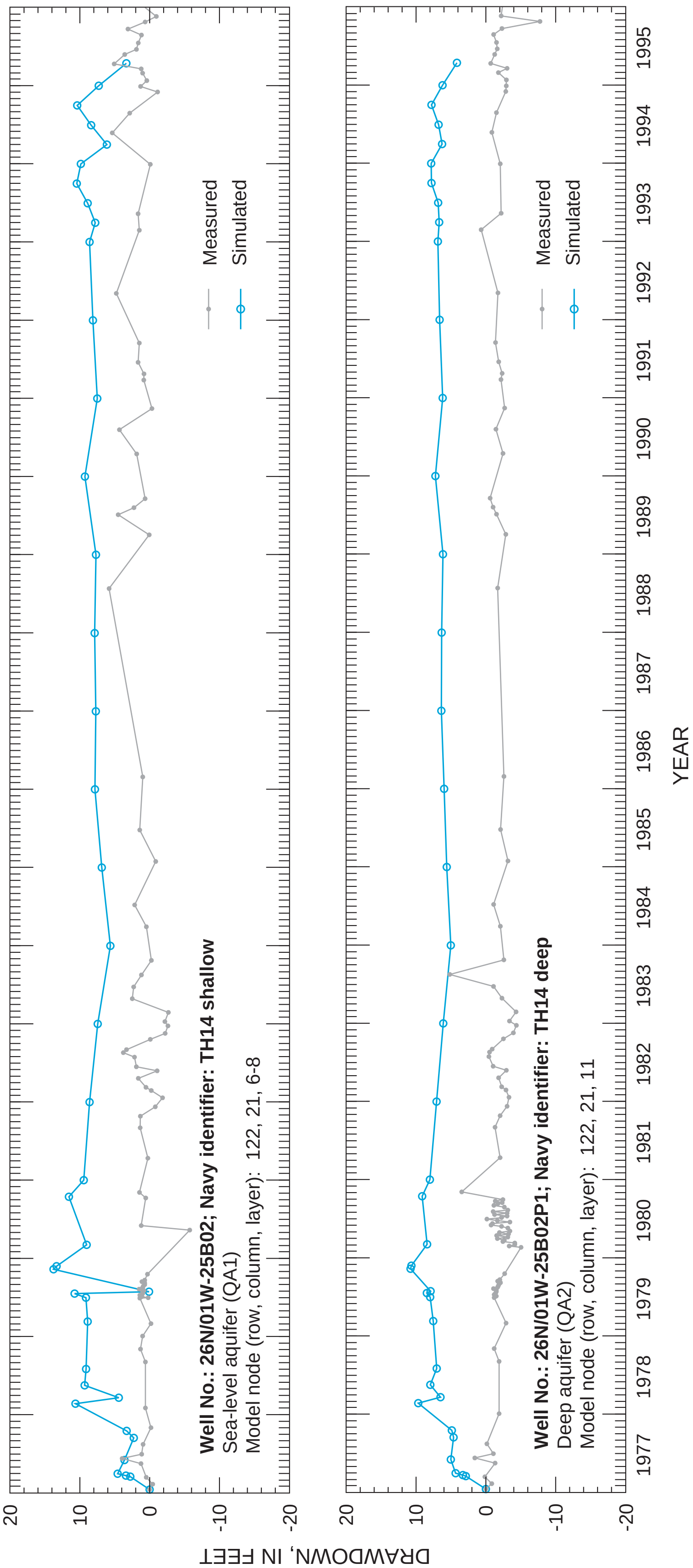


Figure 22.—*Continued.*

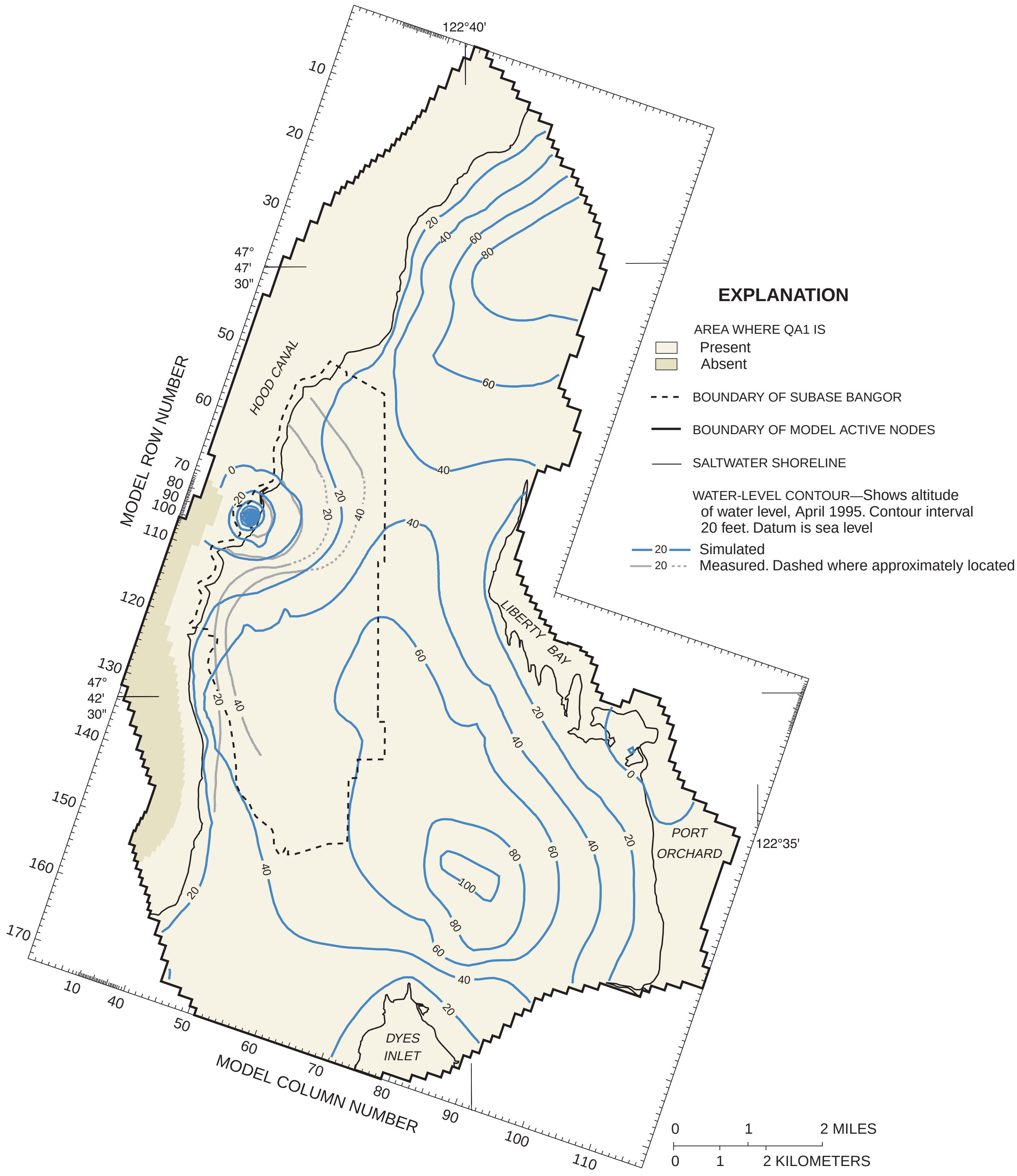
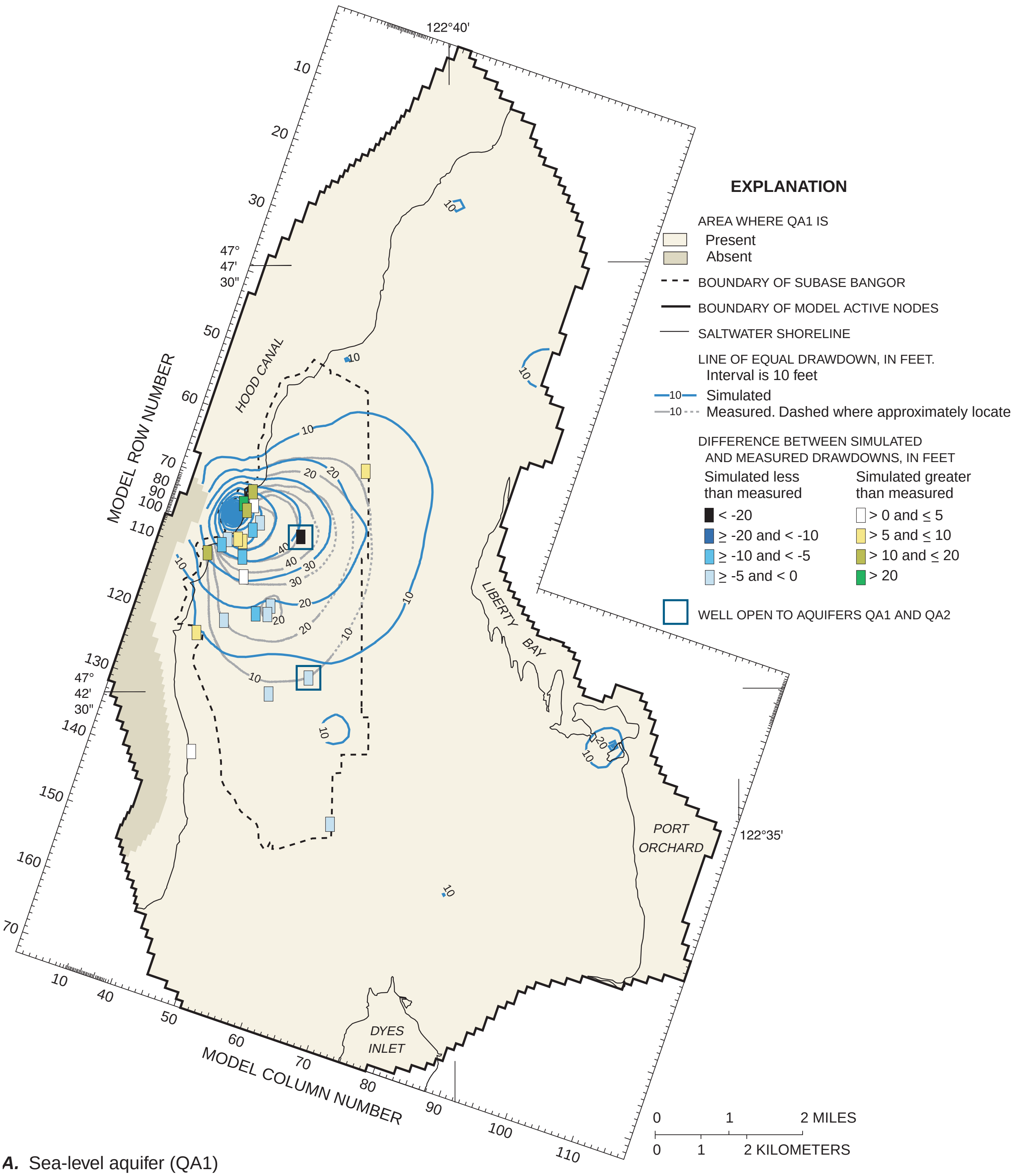
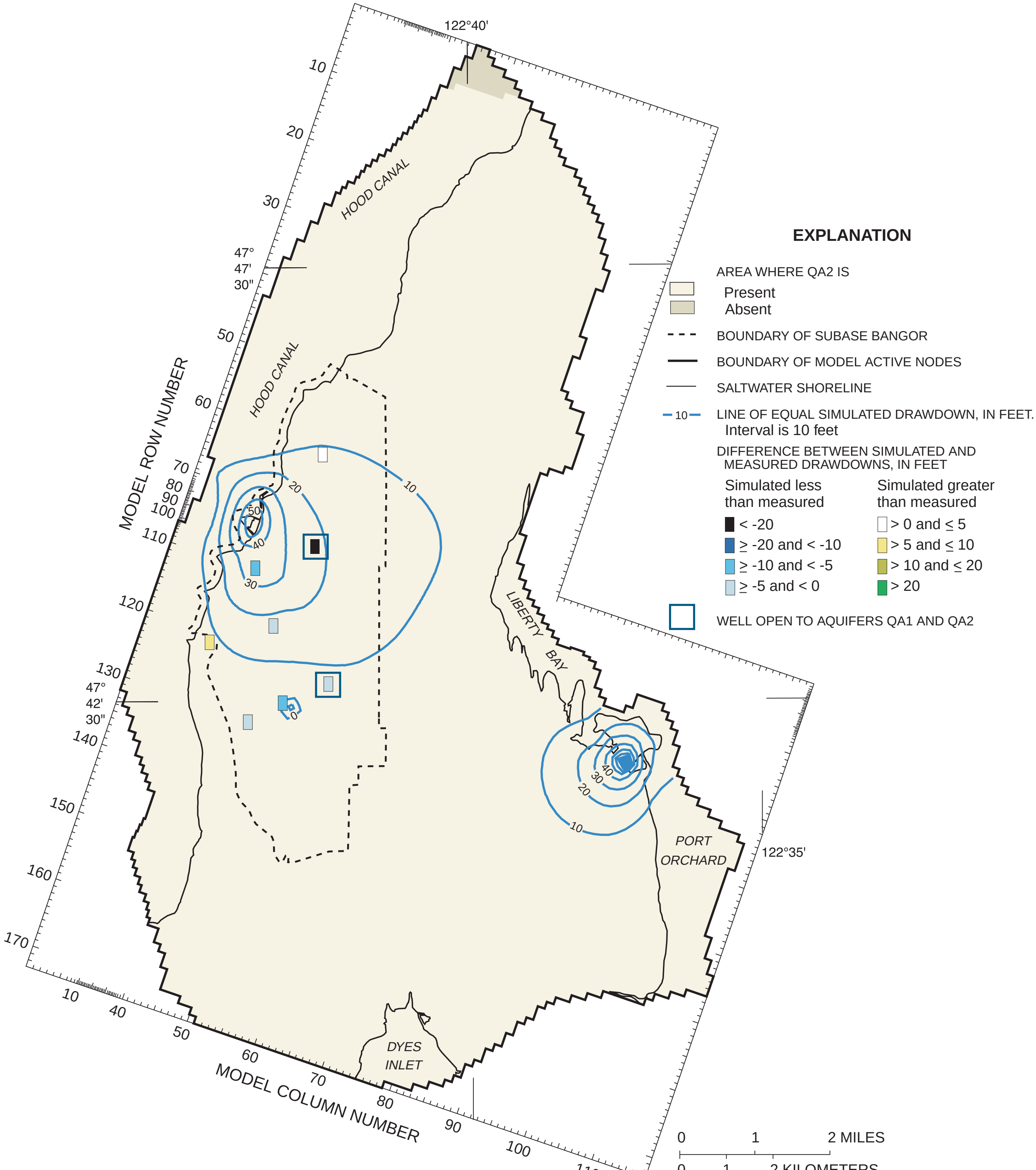


Figure 23. Simulated and measured water-level altitudes in the Sea-level aquifer (QA1), SUBASE Bangor and vicinity, Kitsap County, Washington, July 1, 1979.



A. Sea-level aquifer (QA1)

Figure 24. Simulated and measured drawdowns and the differences between simulated and measured drawdowns from predevelopment until July 1, 1979 in the Sea-level aquifer (QA1) and Deep aquifer (QA2), SUBASE Bangor and vicinity, Kitsap County, Washington.



B. Deep Aquifer (QA2)

Figure 24.—*Continued.*

Table 15. Statistics for differences between simulated and measured drawdowns since predevelopment, SUBASE Bangor and vicinity, Kitsap County, Washington, July 1, 1979 and April 15, 1995

[**Hydrogeologic unit**: Qva, Vashon aquifer; QClpi, Permeable interbeds; QA1, Sea-level aquifer; and QA2, Deep aquifer. Hydrogeologic designations are from Kahle (1998). **Difference between simulated and measured drawdown**: A positive difference means the simulated drawdown is greater than the measured drawdown. A negative difference means the opposite. **Root-mean-square error (RMSE)** = $\sqrt{(\text{Mean})^2 + (\text{Standard deviation})^2}$. –, statistic not computed because the number of values is small]

Hydrogeologic unit	Difference between simulated and measured drawdown (feet)						Number of values
	RMSE	Median	Mean	Standard deviation	Minimum	Maximum	
July 1, 1979							
Qva	–	–	–	–	-8.6	-4.3	2
QC1pi	9.9	6.8	5.7	8.1	-2.9	13.1	3
QA1	9.7	-0.6	2.5	9.4	-11.7	27.0	23
QA2	6.1	-1.6	-0.7	6.1	-6.7	9.3	6
QA1 and QA2	–	–	–	–	-20.5	-2.1	2
All units	9.3	-1.9	0.9	9.2	-20.5	27.0	36
April 15, 1995							
Qva[1]	28.0	6.5	14.8	23.8	-10.6	64.7	8
QC1pi[1]	14.0	5.9	5.3	13.0	-8.4	28.3	8
QA1[1]	10.0	-2.2	-2.3	9.8	-33.5	21.0	26
QA2	6.8	-0.2	1.6	6.6	-8.9	10.1	7
QA1 and QA2	–	–	–	–	-17.9	-1.9	2
All units[2]	14.1	-0.6	1.7	14.0	-33.5	64.7	53

[1]Includes measured drawdown for which the actual drawdown may have been smaller.

[2]Includes one observation each in Qvt /Qvr (Vashon till confining unit/Shallow aquifer) and QC1 (Upper confining unit) (not shown in this table).

Table 16. Statistics for differences between simulated and measured water levels, SUBASE Bangor and vicinity, Kitsap County, Washington, July 1, 1979 and April 15, 1995

[**Hydrogeologic unit**: Qvt, Vashon till confining unit; Qvr, Shallow aquifer; Qva, Vashon aquifer; QC1, Upper confining unit; QClpi, Permeable interbeds; QA1, Sea-level aquifer; and QA2, Deep aquifer. Hydrogeologic designations are from Kahle (1998). **Difference between simulated and measured water level**: A positive difference means the simulated water level is greater than the measured water level. A negative difference means the opposite. **Root-mean-square error (RMSE)** = $\sqrt{(\text{Mean})^2+(\text{Standard deviation})^2}$. –, statistic not computed because the number of values is small]

Hydrogeologic unit	Difference between simulated and measured water level (feet)						Number of values
	RMSE	Median	Mean	Standard deviation	Minimum	Maximum	
July 1, 1979							
Qva	–	–	–	–	-21.6	2.5	2
QC1pi	24.4	15.9	12.4	20.9	-10.0	31.5	3
QA1	13.4	-4.1	-5.8	12.1	-40.3	27.1	32
QA2	12.5	-0.1	-2.7	12.2	-16.9	10.6	6
QA1 and QA2	11.4	2.4	0.3	11.4	-11.9	10.6	3
All units	13.7	-3.6	-4.0	13.1	-40.3	31.5	46
April 15, 1995							
Qvt/Qvr	51.0	-21.4	-32.3	39.4	-113.9	12.9	12
Qva	48.6	-14.5	-22.0	43.3	-218.8	78.1	96
QC1	65.1	-29.5	-32.0	56.8	-132.3	66.4	28
QC1pi	52.5	5.4	-7.7	51.9	-140.0	60.7	43
QA1	21.8	0.0	0.0	21.8	-59.4	49.7	62
QA2	25.0	-11.2	-12.3	21.8	-52.1	22.0	12
QA1 and QA2	10.4	2.4	-0.6	10.4	-12.1	8.0	3
All units	45.2	-7.1	-15.1	42.6	-218.8	78.1	256

Water Levels, Water-Level Drawdowns, and Ground-Water Fluxes on April 15, 1995

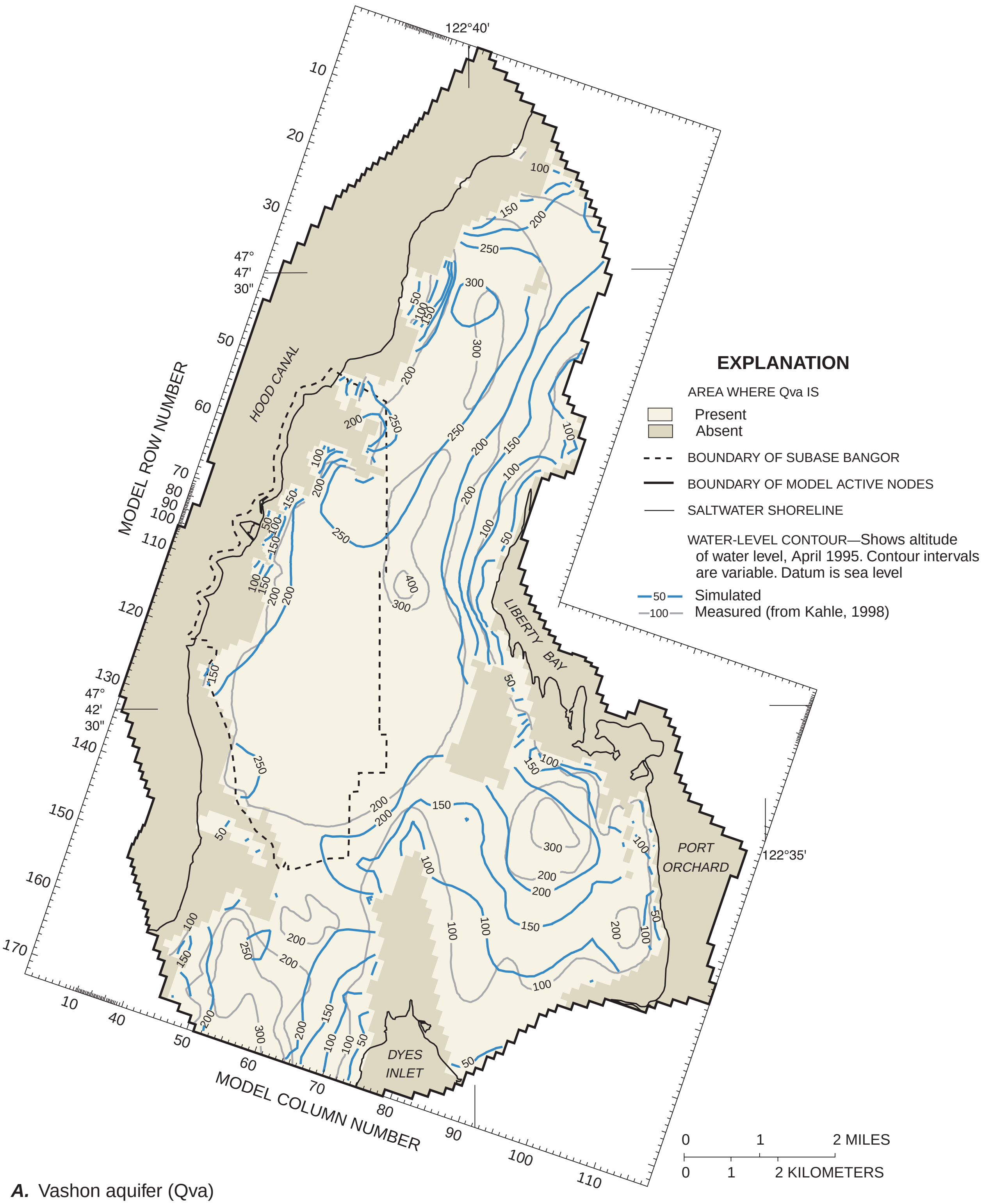
Kahle (1998) published water-level contours for the Vashon aquifer (Qva), the Permeable interbeds (QC1pi), and the Sea-level aquifer (QA1) that represent ground-water flow conditions in April 1995 (fig. 25). Simulated and measured water-level contours agree reasonably well for the Vashon and Sea-level aquifers (fig. 25*A* and 25*C*), but not the Permeable interbeds (fig. 25*B*). Because only a limited number of measurements were available for the Deep aquifer, contours of measured water levels could not be drawn (fig. 25*D*). The model simulates a cone of depression in the Sea-level aquifer near the Bucklin Ridge well not seen in Kahle's contours (fig. 8 and 25*C*). Kahle (1998) used an estimated static water level that was larger than 100 ft to draw water-level contours near the Bucklin Ridge well because the predevelopment water level was 131 ft and an April 1995 static water level was not available. The recovering water level measured in April 1995 was 51 ft, after the well was not pumped for an unknown period of time (probably less than 1 day). The recovering water level was 71 ft for August 1994, after the well was not pumped for about 20 hours. Water levels measured in April 1995 were recontoured in this study near the Bucklin Ridge well to reflect the lower water level that resulted from pumping the well (fig. 26).

A sufficient number of data points were available for the Sea-level aquifer to construct lines of equal drawdown since predevelopment (fig. 27*A*), and lines of equal drawdown for simulated and measured data matched reasonably well. Simulated and measured drawdowns also were compared at individual points in the Sea-level and Deep aquifers (fig. 27) and all hydrogeologic units (table 15 and Appendix 5). The RMSE of drawdowns is smallest for deeper units and equals 14.1 ft for all units. The RMSE of water levels (table 16) does not show a similar trend of decreasing errors for deeper units, although the RMSE was smaller for the Sea-level (QA1) and Deep aquifers (QA2) than the Vashon aquifer (Qva). The RMSE of water levels for all units equals 45.2 ft. Overall, the calibrated model has a negative bias: the median simulated water level for all units is about 7 ft less than measured water levels; however, the median error is 0 for the Sea-level aquifer.

On April 15, 1995, simulated water levels in the Vashon aquifer remained lower near Delta Pier, although less so than in July 1979. As a result, the simulated baseflow discharge of Devil's Hole Creek remained less than simulated for predevelopment but greater than that for July 1, 1979 (table 13). Simulated baseflow discharges for April 15, 1995 of the other streams in table 13 exceeded simulated predevelopment and July 1, 1979 values. The higher discharges for these streams are the result of higher seasonal water levels in the Vashon aquifer caused by ground-water recharge during stress period 40 that is greater than long-term average recharge.

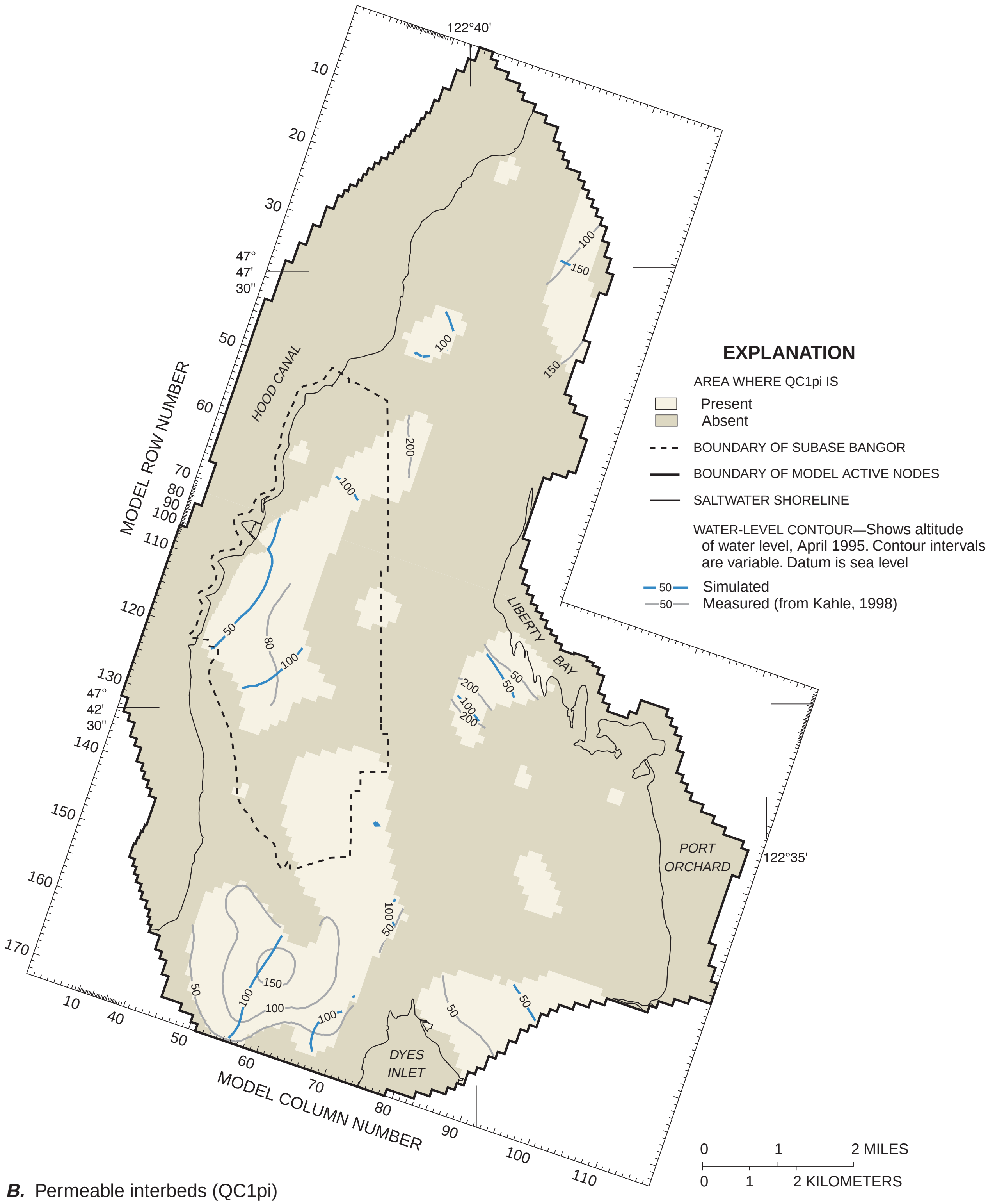
The possible effects of seasonal changes in recharge were simulated using shorter stress periods from January 1, 1993 until April 15, 1995 (stress periods 32 through 40). The absence of recharge and increase in ground-water pumping during the summer resulted in simulated water-level decreases and also decreases in ground-water discharges to saltwater bodies and streams, springs, and seeps (fig. 28). Similarly, higher than long-term average recharge and less ground-water pumpage from January 1 until April 15, 1995 increased water levels and fluxes to surface-water bodies.

Ground-water pumping on and off SUBASE Bangor and higher than long-term average recharge rates during stress period 40 also affected fluxes to and from the saltwater bodies, but only by small overall amounts (table 14). Total simulated ground-water discharge to Hood Canal, Liberty Bay/Port Orchard, and Dyes Inlet for April 15, 1995 was about 20 gal/min less than the predevelopment discharge. This total includes an increase in discharge to Liberty Bay/Port Orchard of about 80 gal/min, and decreases in discharge of about 80 and 20 gal/min to Dyes Inlet and Hood Canal, respectively. At the same time, total discharge from the saltwater bodies to the ground-water system increased about 50 gal/min, of which equal parts came from Hood Canal and Liberty Bay/Port Orchard. Saltwater encroachment for April 15, 1995 was insignificant.



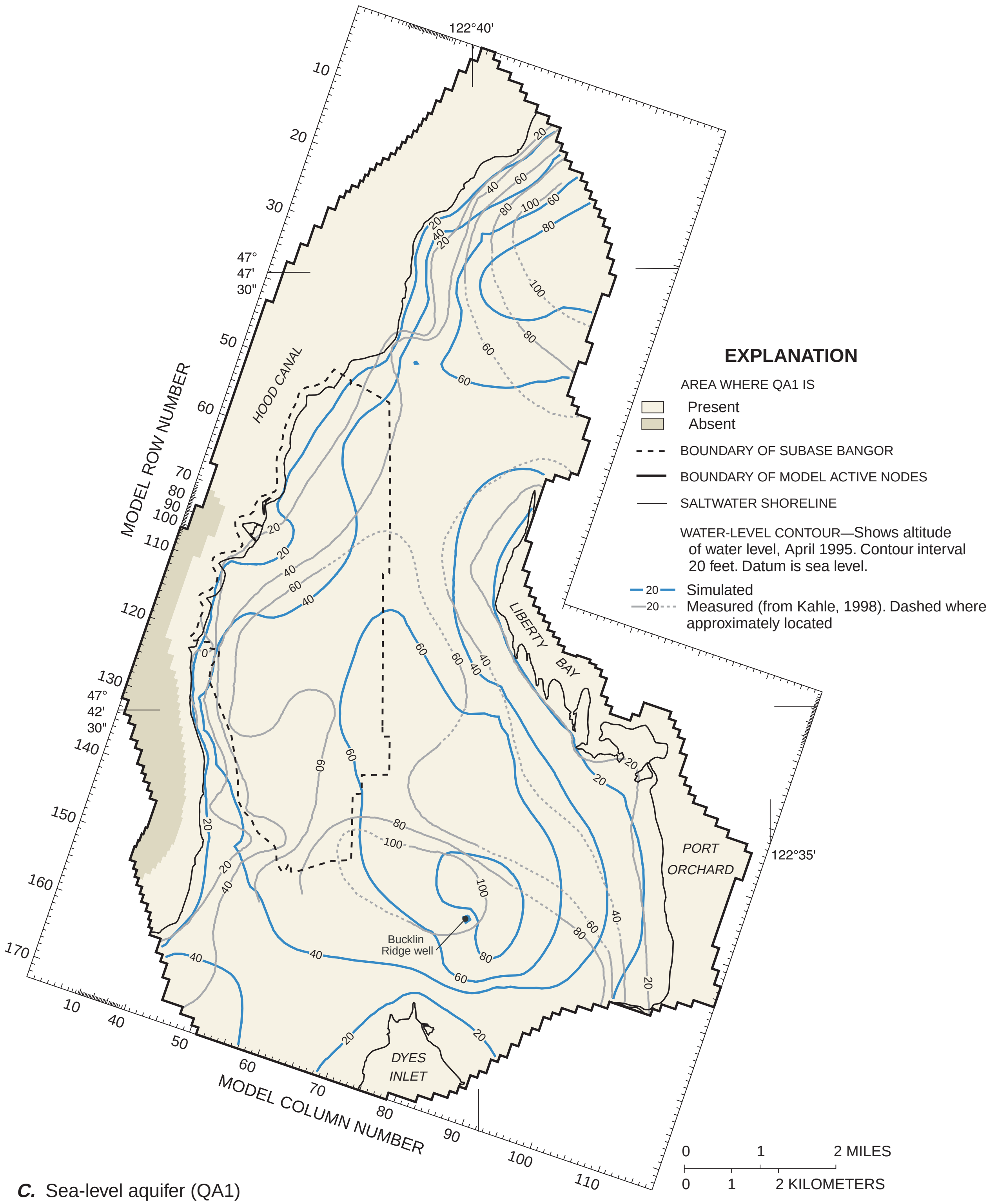
A. Vashon aquifer (Qva)

Figure 25. Simulated and measured water-level altitudes for the Vashon aquifer (Qva), Permeable interbeds (QC1pi), Sea-level aquifer (QA1), and Deep aquifer (QA2), SUBASE Bangor and vicinity, Kitsap County, Washington, April 15, 1995.



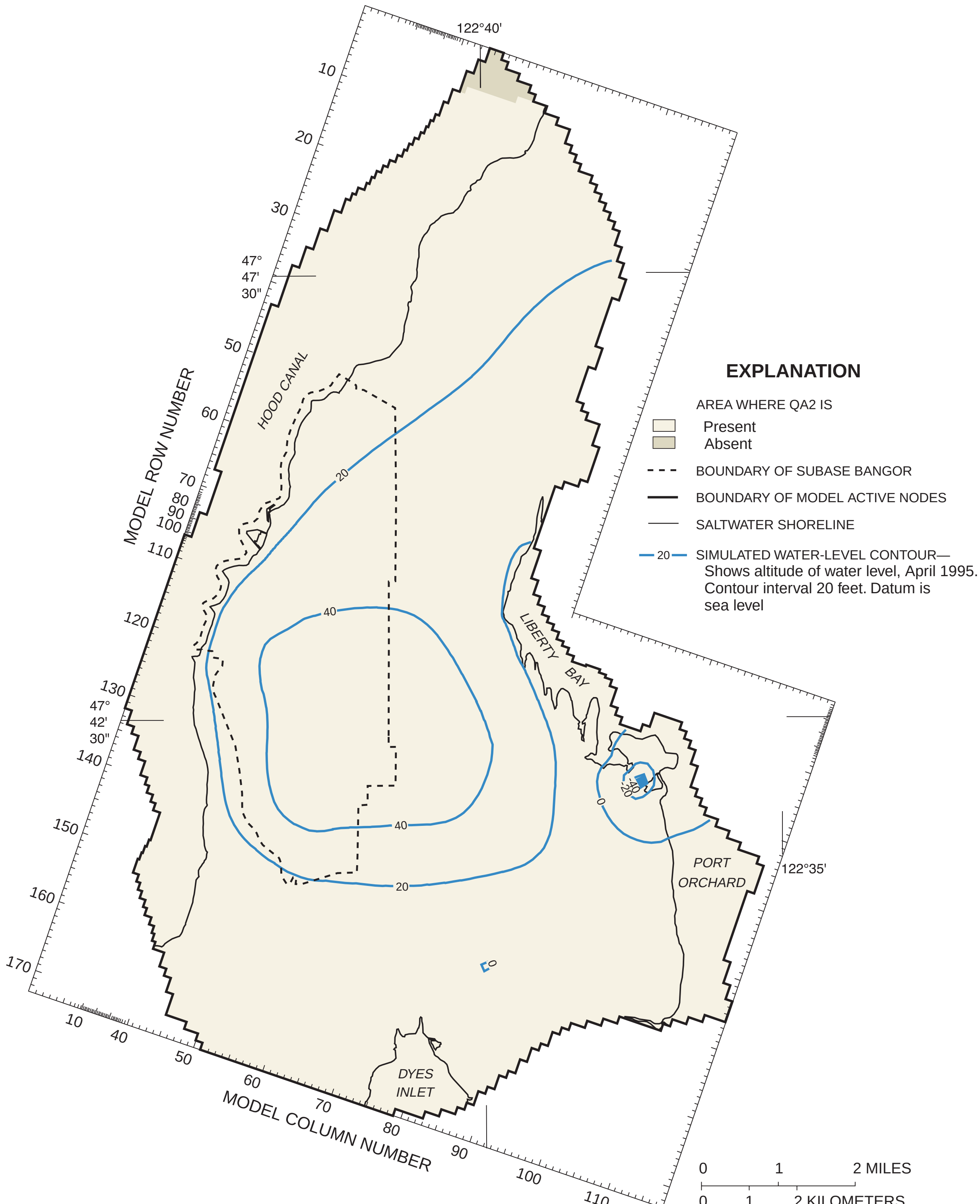
B. Permeable interbeds (QC1pi)

Figure 25.—*Continued.*



C. Sea-level aquifer (QA1)

Figure 25.—*Continued.*



D. Deep aquifer (QA2)

Figure 25.—*Continued.*

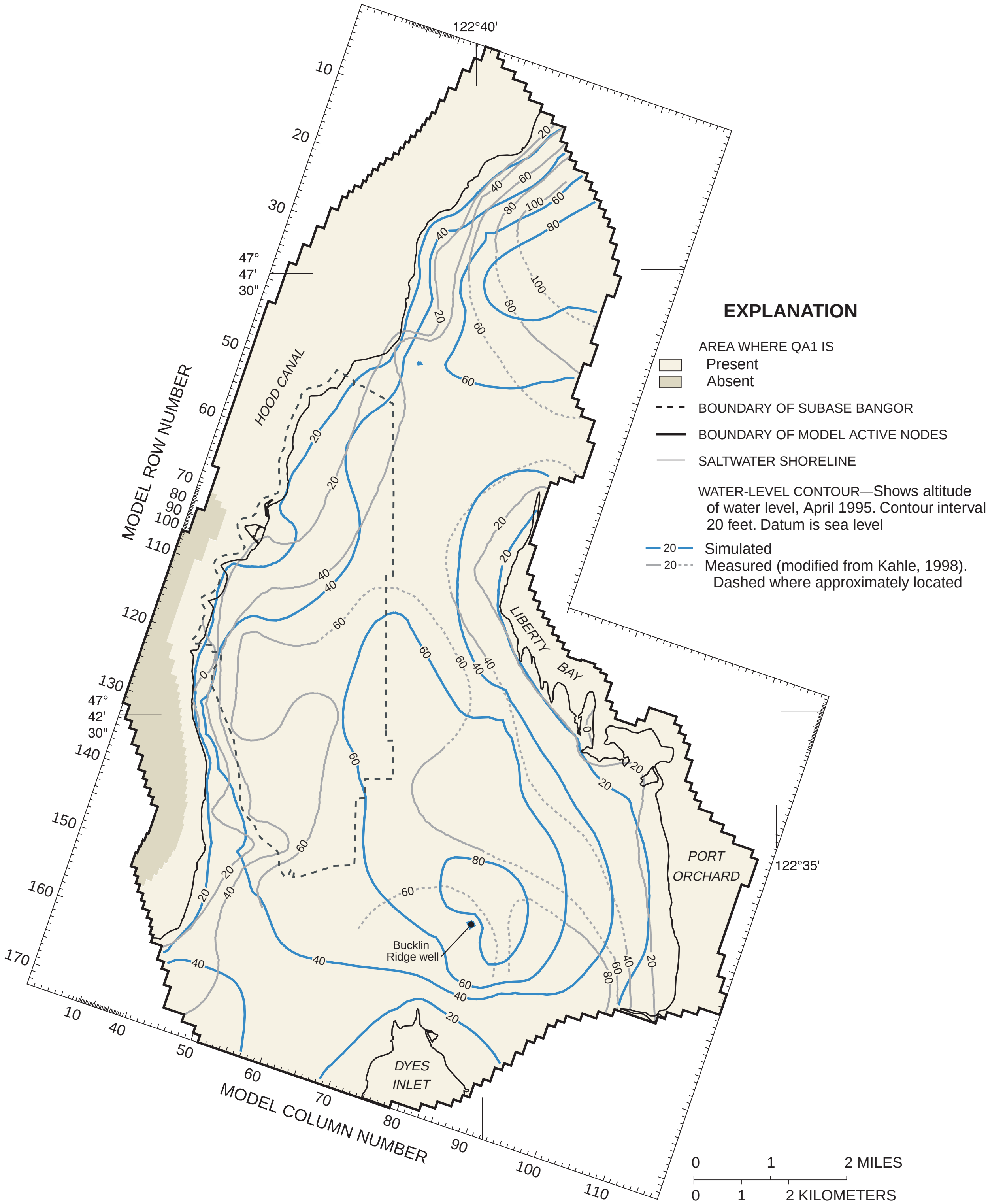
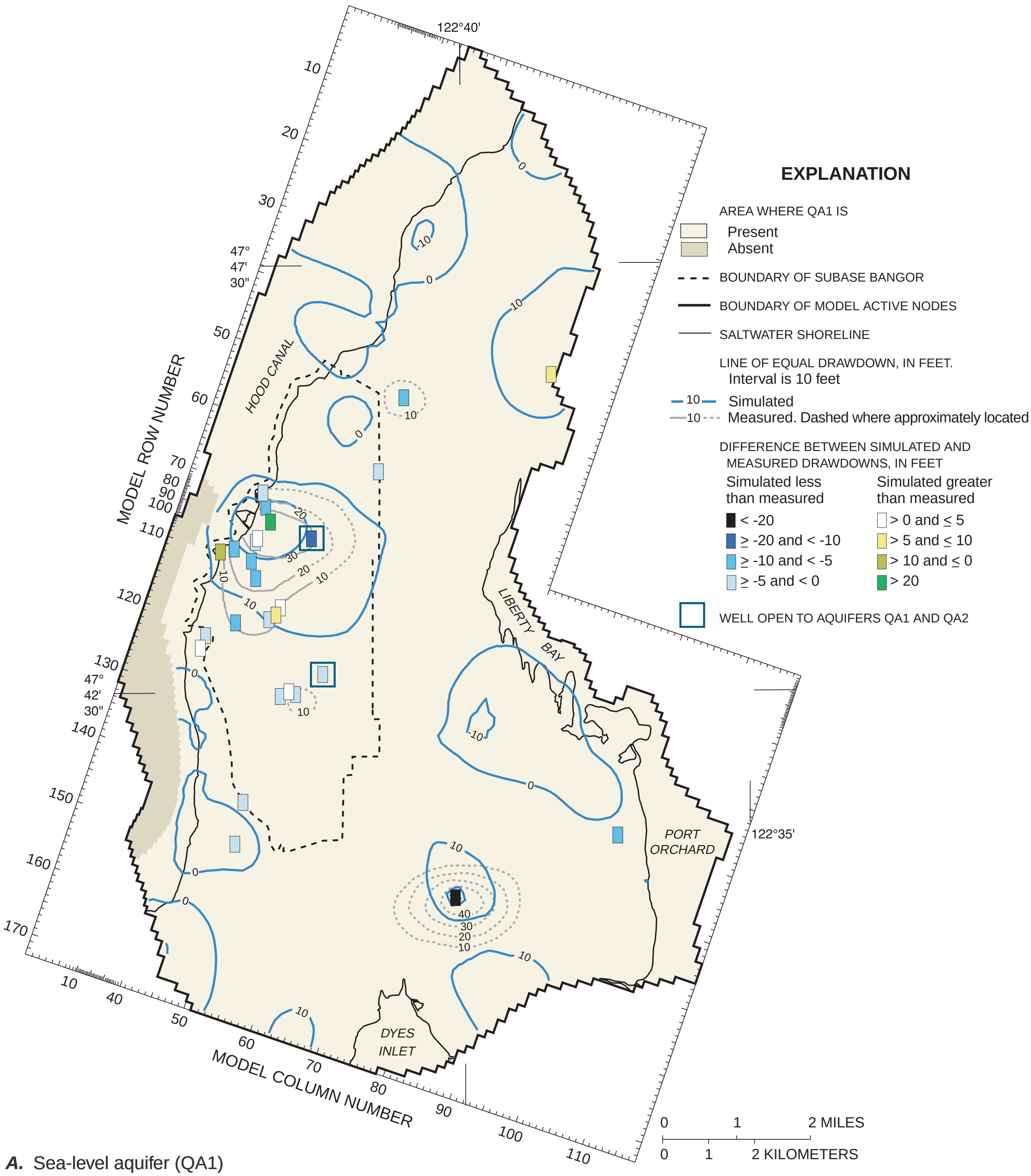


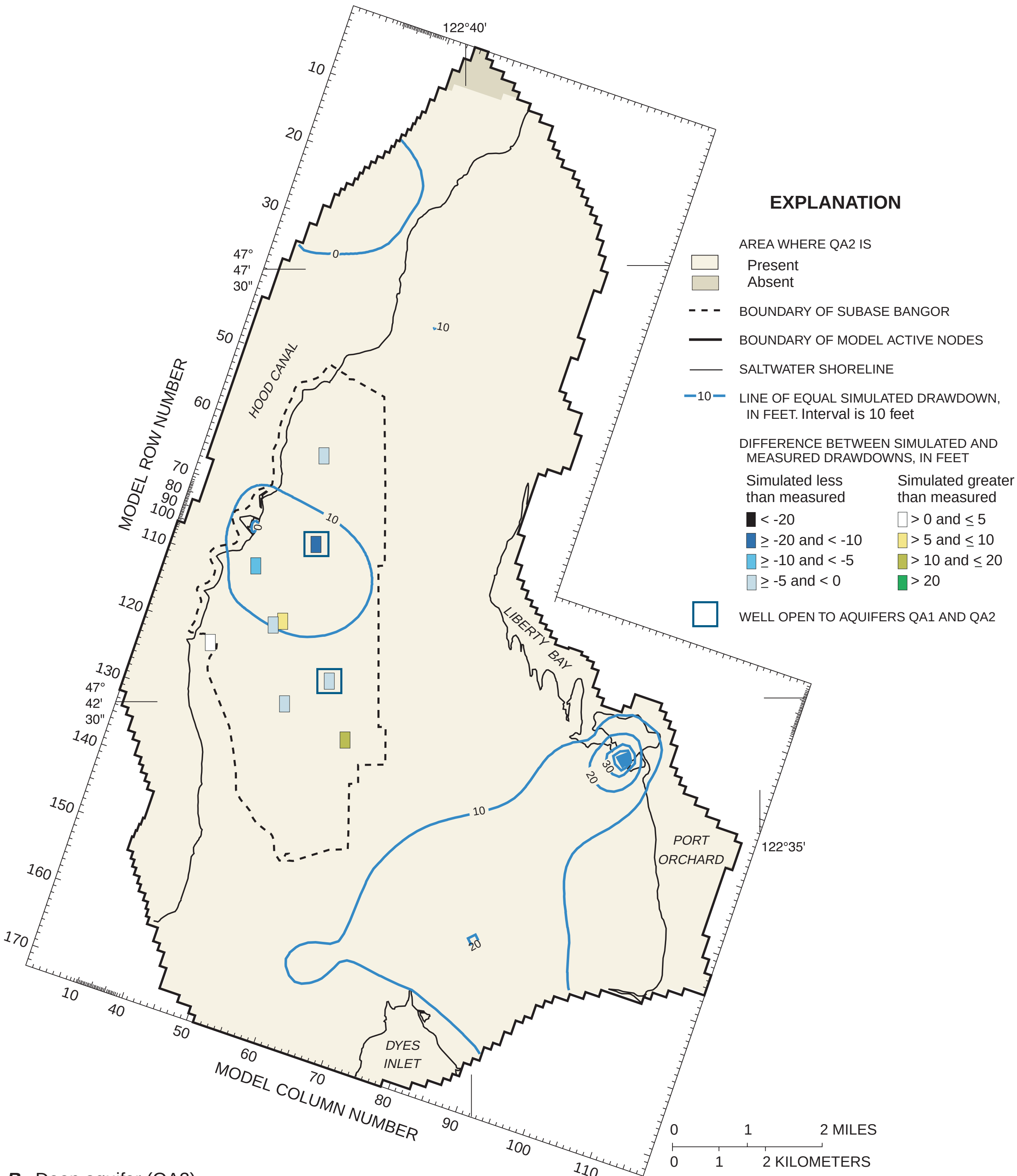
Figure 26. Simulated and measured water-level altitudes in the Sea-level aquifer (QA1), SUBASE Bangor and vicinity, Kitsap County, Washington, April 15, 1995.

Measured water-level altitudes were modified from Kahle (1998).



A. Sea-level aquifer (QA1)

Figure 27. Simulated and measured drawdowns and the differences between simulated and measured drawdowns from predevelopment until April 15, 1995 in the Sea-level aquifer (QA1) and Deep aquifer (QA2), SUBASE Bangor and vicinity, Kitsap County, Washington.



B. Deep aquifer (QA2)

Figure 27.—*Continued.*

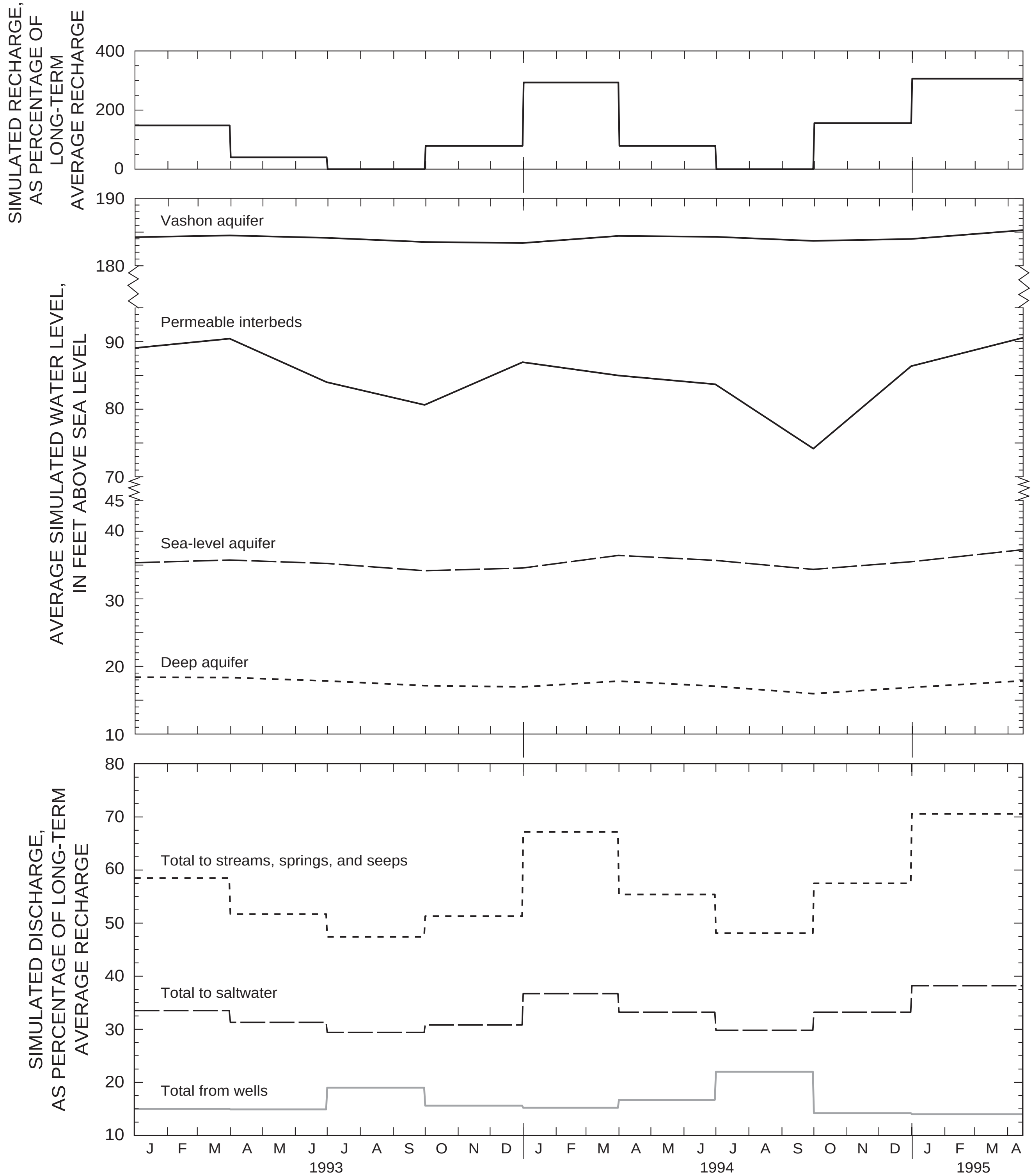


Figure 28. Simulated fluxes and water levels, SUBASE Bangor and vicinity, Kitsap County, Washington, January 1993 through April 15, 1995.

However, extrapolating the findings at the end of stress period 40 over the entire period from predevelopment until April 15, 1995, would be misleading. The fluxes at the end of stress period 40 only represent a snapshot of conditions on April 15, 1995. The long-term average effects of April 15, 1995 ground-water pumping can be determined by simulating the flow system in steady-state mode.

Ground-Water Residence Times

As part of the USGS Bangor studies, water samples from 33 wells were analyzed for selected environmental tracers, including tritium, chlorofluorocarbons (CFCs), and carbon isotopes (Stephen E. Cox, U.S. Geological Survey, written commun., 2002). The purpose of the study was to estimate residence times of ground water in different parts of the flow system. Residence time is defined as the time water has spent in the ground-water flow system since it was first isolated from the atmosphere in the recharge zone.

All samples from the Vashon aquifer (Qva) contained modern environmental tracers with residence times generally between 10 and 30 years. Modern is defined as later than about 1950. In deeper parts of the ground-water flow system, samples contained a range of environmental tracers, indicating both modern and pre-modern residence times. Using carbon isotopic dating techniques, residence times were estimated for samples from 12 wells that only contained pre-modern tracers (fig. 20) (Stephen E. Cox, U.S. Geological Survey, written commun., 2002).

The sampled ground water had a carbon source of comparatively "old" carbon from organic materials deposited contemporaneously with the interglacial and glacial sediments, thus, the residence times of the ground water appeared to be greater than actual residence times. Geochemical mass-balance modeling was used to improve the estimates, but uncertainties in the estimated residence times of pre-modern ground water remain significant (Stephen E. Cox, U.S. Geological Survey, written commun., 2002).

Residence times were simulated using the calibrated model in transient mode and particle-tracking software MODPATH (Pollock, 1994) by backtracking imaginary particles to the recharge zone from cells that contained the 12 wells sampled by Stephen E. Cox (U.S. Geological Survey, written commun., 2002). To allow for variations in traveltimes among particle paths starting at different locations within a cell, 600 particles were evenly distributed over the faces of each cell and their median, minimum, and maximum residence times were simulated (table 17). Simulated residence times are positively correlated with simulated effective porosities of model layers. (Effective porosity is defined as the fraction of aquifer or confining-unit volume that consists of interconnected pore spaces.) Ground water moves more slowly if the effective porosity is higher, which results in a higher residence time. The effective porosities that were used (table 9) represent upper limits of what is reasonable and, as a result, the simulated residence times represent an upper limit of residence times that can be simulated with the calibrated model.

Despite simulating upper limits of residence times, 6 of the 12 simulated median residence times were shorter than the estimated minimum residence times (table 17), although one is shorter by only 4 years (well 26N/01E-31R01). All estimated minimum residence times longer than 900 years and one of 330 years were greater than the corresponding simulated maximum values.

Different explanations are possible for the discrepancies between simulated and estimated residence times. For example, water sampled by Stephen E. Cox (U.S. Geological Survey, written commun., 2002) may have spent time in near-stagnant or low-velocity parts of the flow system that are not adequately simulated by the model (see, for example, Bethke and Johnson, 2002) or errors in the estimated residence times may be larger than reported.

Table 17. Estimated and model-simulated residence times of ground water at locations of selected wells, SUBASE Bangor and vicinity, Kitsap County, Washington

[**Well No.**: Locations of wells are shown in figure 20. See figure 3 for explanation of well-numbering system. **Estimated residence time**: From S.E. Cox (U.S. Geological Survey, written commun., 2002). –, site not located on SUBASE Bangor]

Well No.	Navy identifier	Model node (row, column, layer)	Residence time (years Before Present)				
			Estimated range	Simulated			
				Median	Minimum	Maximum	Median inside estimated range
Wells open to the Upper confining unit (QC1)							
27N/01E-35C01	–	25, 66, 3	1,900 –3,080	104	41	168	no
Wells open to the Permeable interbeds (QC1pi)							
25N/01E-07J02	–	150, 61, 4	50–500	163	106	199	yes
25N/01E-08J02	–	149, 71, 4	50–1,600	219	175	361	yes
25N/01E-08Q03	–	152, 68, 4	920–4,550	235	175	407	no
25N/01E-09N02	–	149, 74, 4	2,130–4,500	237	190	359	no
Wells open to the Sea-level aquifer (QA1)							
25N/01E-06D04	TH17	140, 47, 6-7	330–2,480	103	32	212	no
25N/01W-01B02	–	142, 42, 6	2,840–4,420	101	54	160	no
26N/01E-32L05	1181	129, 59, 8	50–1,040	211	16	428	yes
26N/01W-36R03	–	138, 43, 6	50–550	97	71	392	yes
27N/01E-22Q05	–	16, 53, 6	340–1,600	399	242	2,359	yes
Wells open to the Deep aquifer (QA2)							
26N/01E-32L04	TH1	129, 59, 10-11	250–1,500	478	360	1,816	yes
Wells open to the Sea-level and Deep aquifers (QA1 and QA2)							
26N/01E-31R01	505 (TH18)	135, 55, 6-8 and 10	300–2,000	296	182	661	no

[1]Sampled water may include a small percentage of modern water (modern is defined as later than about 1950).

Model Sensitivity Analysis

"The purpose of a sensitivity analysis is to quantify the uncertainties in the calibrated model caused by uncertainty in the estimates of aquifer parameters, stresses, and boundary conditions" (Anderson and Woessner, 1992). Different methods are available to conduct such an analysis, but there is no one method to conclusively determine model sensitivity. In this study, a traditional approach was used by adjusting the most important parameters by selected percentages and documenting the resulting change in simulated water levels and ground-water fluxes in different parts of the modeled area.

Ground-water modeling results are affected by various model parameters and assumptions, including the (1) geometry of the hydrogeologic units, (2) vertical and horizontal spacing of the model grid, (3) types and locations of model boundaries, (4) magnitudes and areal distributions of stresses such as ground-water recharge and pumpage, (5) conductances of stream, drain, and general-head-boundary cells, and (6) horizontal and vertical hydraulic conductivities of aquifers and confining units. In addition, transient-mode modeling results also are affected by the length and number of stress periods and the storativities of aquifers and confining units. Ideally, a complete sensitivity analysis would determine model sensitivity to all these parameters and assumptions, but only model sensitivity to the most important parameters was determined.

The sensitivity of the model in steady-state mode was determined during predevelopment by adjusting calibrated values of aquifer transmissivities, vertical conductivities of confining units, recharge, and stream, drain, and general-head-boundary conductances. Effects of the adjustments on both simulated water levels and ground-water fluxes were calculated (table 18). Similarly, the sensitivity of the model in transient mode was determined for simulations representing July 1, 1979 and April 15, 1995 conditions by adjusting calibrated values of storativity (table 19). The magnitudes of parameter adjustments affect the magnitudes of changes in simulated water levels and ground-water fluxes. For this reason, an attempt was made to increase and decrease each parameter by the same factor to facilitate the interpretation of results. However, this approach was not always possible because some parameter changes prevented the model from converging on a numerical solution. For example, when recharge was decreased by 50 percent the model did not converge. As a result, a decrease of 25 percent was used instead. Similarly, when the storativity was decreased by a factor of 10 the model did not converge. To avoid this problem, the calibrated storativities were decreased by a factor of 2 instead.

Interpretation of a traditional sensitivity analysis as done here can only be qualitative. Without the more rigorous sensitivity analysis that can be done using parameter-estimation techniques (for example, Hill, 1998), the degree of correlation between model parameters and the relative contribution of parameters to model sensitivity cannot be quantitatively determined. The sensitivity analysis as done here is most useful if combined with findings of model sensitivity during the process of trial-and-error model calibration.

During model calibration, water levels and ground-water fluxes were determined to be relatively insensitive to the vertical anisotropy of aquifers but sensitive to vertical hydraulic conductivities of confining units. In particular, the vertical hydraulic conductivities of the two regional confining units (the Upper confining unit, QC1, and the Lower confining unit, QC2) were extremely important in determining water levels and discharges in aquifers of the study area. For example, if vertical hydraulic conductivities are too high in those units in parts of the model with downward ground-water flow, water levels in aquifers above them decrease and water levels in aquifers below them increase. Horizontal water-level gradients in aquifers are determined by horizontal hydraulic conductivities--large hydraulic conductivities generate low hydraulic gradients and vice versa.

As part of the sensitivity analysis, aquifer transmissivities were changed by changing the horizontal hydraulic conductivity and keeping the aquifer thickness constant (eq. 1). An increase in the aquifer horizontal hydraulic conductivity (and thus transmissivity) by a factor of 10 increased the median error in water levels from -6.3 to -60.1 ft (table 18). The corresponding RMSE increased from 41.9 to 102.2 ft.

Table 18. Results of sensitivity analysis of the model in steady-state mode at predevelopment, SUBASE Bangor and vicinity, Kitsap County, Washington

[**Difference between simulated and measured water levels**: Calibrated model in steady-state mode at predevelopment: median error = -6.3 feet, RMSE = 41.9 feet. A positive median means the simulated water levels are greater than the measured water levels. A negative median means the opposite. RMSE, root-mean-square error. **Changes in simulated net flux from the ground-water system**: Long-term average recharge for the simulated flow system is 16,440 gallons per minute (36.6 cubic feet per second)]

Model-input parameter	Difference between simulated and measured water levels (feet)		Changes in simulated net flux from the ground-water system (as percentage of long-term average recharge)			
	Median error	RMSE	To streams	To springs and seeps	Total to springs, seeps, and streams	To saltwater
Aquifer transmissivity						
Increase by factor of 10	-60.1	102.2	-3.6	-3.0	-6.6	+6.6
Decrease by factor of 10	139.1	223.0	+6.6	+3.3	+9.9	-9.9
Vertical conductivity of confining units						
Increase by factor of 10	-26.2	80.3	-11.9	-7.0	-18.9	+18.9
Decrease by factor of 10	5.4	62.8	+8.9	+5.8	+14.7	-14.7
Recharge						
100-percent increase	31.3	73.0	+46.7	+33.3	+80.0	+20.0
25-percent decrease	-17.3	53.9	-10.9	-8.1	-19.0	-6.0
Stream conductance						
Increase by factor of 10	-7.3	41.9	+0.2	-0.1	+0.1	-0.1
Decrease by factor of 10	-5.2	41.8	-1.1	+0.7	-0.4	+0.4
Drain conductance						
Increase by factor of 10	-9.1	42.4	-0.3	+0.7	+0.4	-0.4
Decrease by factor of 10	-4.1	41.3	+0.9	-1.9	-1.0	+1.0
General-head-boundary conductance						
Increase by factor of 10	-7.5	42.2	-0.7	-1.6	-2.3	+2.3
Decrease by factor of 10	-4.0	41.7	+1.3	+1.9	+3.2	-3.2

Table 19. Results of sensitivity analysis of the model in transient mode for July 1, 1979 and April 15, 1995 conditions, SUBASE Bangor and vicinity, Kitsap County, Washington

[**Difference between simulated and measured water-level drawdowns since predevelopment**: A positive median means the simulated drawdowns are greater than the measured drawdowns. A negative median means the opposite. RMSE, root-mean-square error. **Changes in simulated net flux from the ground-water system**: Long-term average recharge for the simulated flow system is 16,440 gallons per minute (36.6 cubic feet per second)]

Model-input parameter	Difference between simulated and measured water-level drawdowns since predevelopment (feet)		Changes in simulated net flux from the ground-water system (as percentage of long-term average recharge)			
	Median error	RMSE	To streams	To springs and seeps	Total to springs, seeps, and streams	To saltwater
July 1, 1979[1]						
Storativity of aquifers and confining units						
Increase by factor of 10	-11.6	15.4	+1.1	+2.4	+3.5	+5.3
Decrease by factor of 2	-7.3	11.6	+0.7	+1.5	+2.2	+3.7
April 15, 1995[2]						
Storativity of aquifers and confining units						
Increase by factor of 10	-0.1	11.5	-1.7	-2.2	-3.9	-2.0
Decrease by factor of 2	0.2	13.8	-1.7	-1.4	-3.1	-2.3

[1]Calibrated model in transient mode on July 1, 1979: median error = -1.9 feet, RMSE = 9.3 feet.

[2]Calibrated model in transient mode on April 15, 1995: median error = -0.6 foot, RMSE = 14.1 feet.

Similarly, a doubling of recharge increased the median error in water levels to 31.3 ft and the RMSE to 73.0 ft, and the model bias changed from negative to positive. Although separate increases in aquifer horizontal hydraulic conductivity and recharge resulted in greater model errors, simultaneous increases would not likely have the same effect because recharge and horizontal hydraulic conductivity are positively correlated in most ground-water flow models. This means that prior knowledge of one is required to conclusively determine the other.

In this study, ground-water recharge from precipitation was an independently determined parameter (Bidlake and Payne, 2001) that was not adjusted during the calibration process, even though it has uncertainties associated with it. Ground-water recharge was not adjusted, because it was estimated from actual measurements of components of the water budget and likely represents the best estimate of recharge available to date. Instead, horizontal hydraulic conductivities of aquifers and other parameters were adjusted to obtain model calibration. The resulting horizontal hydraulic conductivities generally were lower than those calculated from measurements. An argument could be made that the model could have been calibrated by increasing the recharge estimates, which would have resulted in larger calibrated values of horizontal hydraulic conductivities in aquifers. Thus, uncertainties in recharge values determined by Bidlake and Payne (2001) could have an important effect on the modeling results. However, the approach that was selected simulated more conservative ground-water fluxes.

During model calibration, the conductance of the off-shore general-head-boundary cells near the base was determined to be an important parameter that controls water levels in the Sea-level aquifer on SUBASE Bangor. These conductances were very small and are believed to represent a fine-grained, low-permeability unit draped over off-shore aquifers that protrude into Hood Canal. Conductance values for drains and streams were secondary in importance to those of the general-head-boundary cells in Hood Canal near SUBASE Bangor. The sensitivity analysis shows that overall, simulated water levels and ground-water fluxes were not very sensitive to global changes in stream, drain, and general-head-boundary conductances (table 18). A similar, but slightly better model calibration could have been obtained by decreasing the stream, drain, and general-head-boundary conductances.

The storativity of aquifers and confining units was not changed during model calibration. Instead, storativities were used that were calculated from specific storage and unit thickness (eq. 4). Storativity affects the rate at which water levels and ground-water fluxes change in response to stresses. The sensitivity analysis indicates that in transient mode, the model has low to moderate sensitivity to storativity (table 19). A smaller RMSE and thus better model calibration could have been obtained for April 15, 1995 conditions by increasing or decreasing the storativity by a factor of 10 and 2, respectively, although the same changes would have resulted in a larger RMSE and thus worse model calibration for July 1, 1979 conditions. Overall, the model calibration would have been worse if the storativity had been changed to the values used in the sensitivity analysis.

EFFECTS OF SIMULATED GROUND-WATER PUMPING ALTERNATIVES

To evaluate possible future conditions of the ground-water flow system on and near SUBASE Bangor, the calibrated ground-water flow model was used to simulate the effects of four hypothetical ground-water pumping alternatives. Ground-water recharge was assumed equal to the long-term average recharge used to simulate predevelopment conditions. Possible changes in the ground-water flow system were examined to determine the effects of different pumping alternatives on (1) locations of zones of recharge of public-supply wells throughout the study area and hypothetical wells southwest of SUBASE Bangor; (2) traveltimes from recharge source areas to discharging wells; (3) water levels in the Sea-level aquifer; and (4) the potential for saltwater encroachment. Each of the alternatives were simulated as steady-state, and therefore, the simulated results represent what would ultimately happen to the flow system provided sufficient time lapsed for the system to equilibrate to the imposed stresses; how much time this would take is unknown.

Description of Ground-Water Pumping Alternatives

Four hypothetical ground-water pumping alternatives were selected (table 20):

Alternative 1 — 1995 pumping rates, off-shore discharge from gravity-flow wells, and 1995 well locations (fig. 29).

Alternative 2 — Double 1995 pumping rates, off-shore discharge from gravity-flow wells assumed to be zero, and 1995 well locations.

Alternative 3 — Pumping rates projected for the year 2020, off-shore discharge from gravity-flow wells assumed to be zero, 1995 well locations, and one new well on SUBASE Bangor.

Alternative 4 — Pumping rates projected for the year 2020, off-shore discharge from gravity-flow wells assumed to be zero, 1995 well locations, and one new well on and two new wells off SUBASE Bangor (fig. 30).

Table 20. Assumed rates of ground-water discharge from wells on and off SUBASE Bangor for pumping alternatives 1, 2, 3, and 4, Kitsap County, Washington

[**Total discharge**: Rates are current (1995) rates for alternative 1 and projected 2020 rates for alternatives 3 and 4. **Abbreviations**: gal/min, gallons per minute]

Alternative No.	Discharge on SUBASE Bangor (gal/min)		Discharge off SUBASE Bangor (gal/min)	Total discharge (gal/min)
	On-shore supply wells	Off-shore gravity-flow wells		
1	822	85	1,814	2,721
2	1,645	0	3,629	5,274
3, 4	1,400	0	3,203	4,603

According to estimates by the U.S. Bureau of the Census (1992) and the Puget Sound Council of Governments (1988), population growth in the study area is expected to average 2.3 percent per year from 1990 to 2020. Assuming that this growth occurs off SUBASE Bangor and that the average rate of population growth corresponds to an identical increase in ground-water pumping, off-base pumpage would be 76.6 percent greater in 2020 than in 1995. Water use on-base would increase modestly to 1,327 gal/min in 2012 (Parametrix, Inc., 1994). Allowing for a small additional increase in water use from 2012 until 2020 and assuming that all water used on SUBASE Bangor is obtained from public-supply wells on-base, ground-water pumpage on SUBASE Bangor was projected to be 1,400 gal/min in 2020.

For alternative 3, the pumping rate for the new well on SUBASE Bangor was assumed to be 250 gal/min from the Sea-level aquifer (fig. 30). The remaining increase in ground-water pumpage over 1995 rates (328 gal/min) was equally distributed among public-supply wells 501, 502, 503, and 504 near Delta Pier (fig. 8). Pumping rates for all off-base wells pumping in 1995 were increased by 76.6 percent.

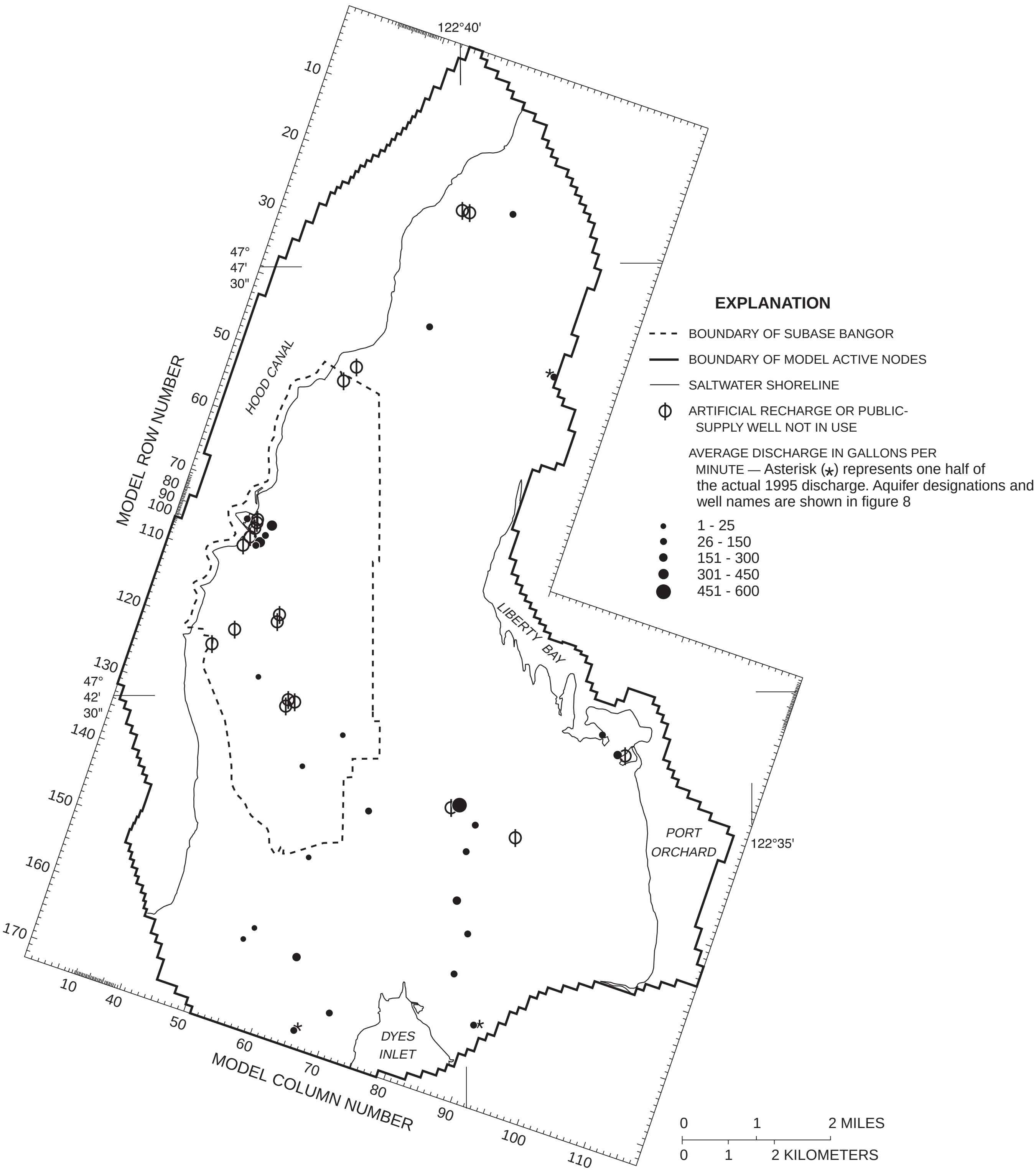


Figure 29. Areal distribution of ground-water discharge for ground-water pumping alternative 1 (1995 rates of discharge), SUBASE Bangor and vicinity, Kitsap County, Washington.

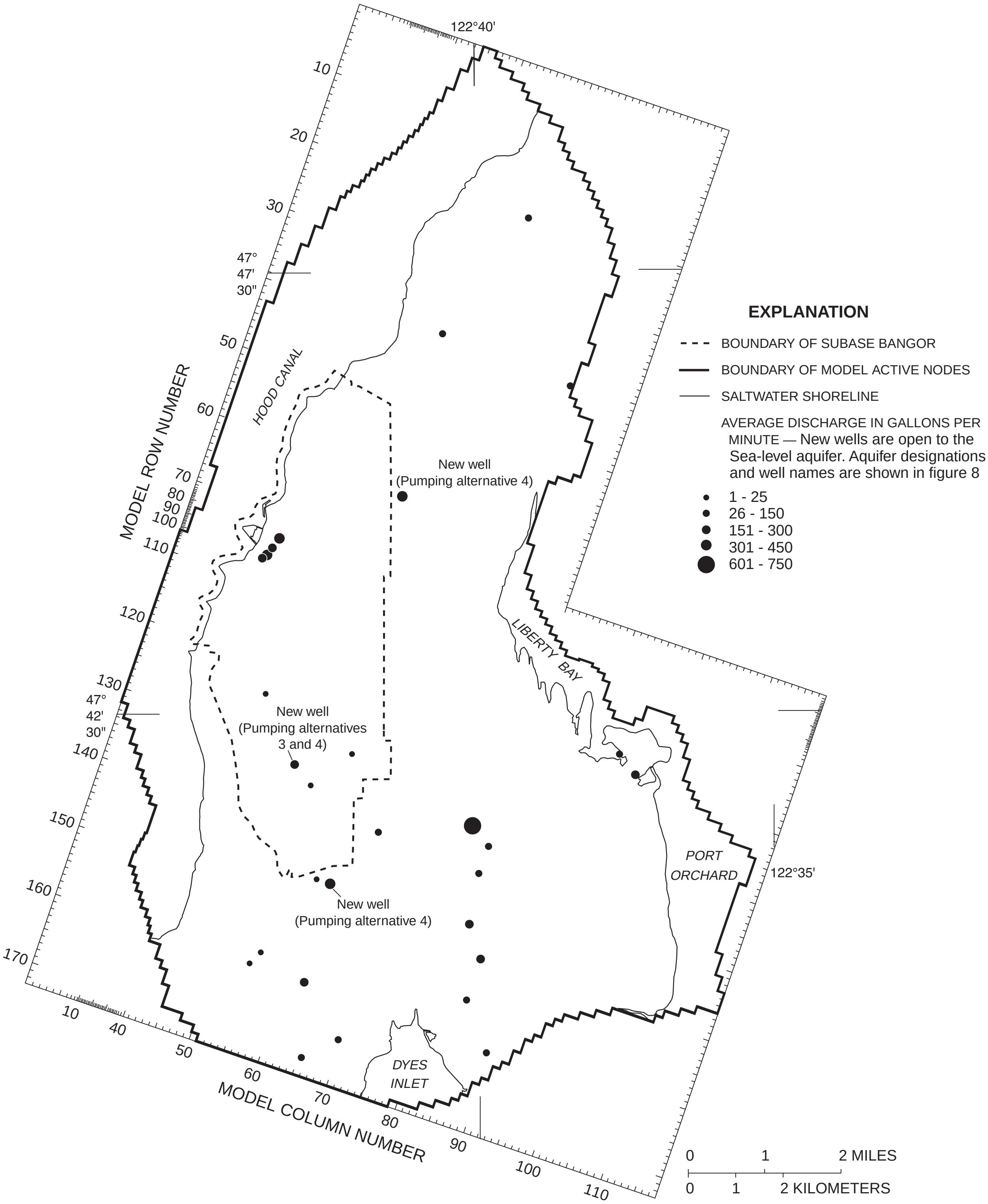


Figure 30. Areal distribution of ground-water discharge for ground-water pumping alternative 4 and locations of new wells used in pumping alternatives 3 and 4, SUBASE Bangor and vicinity, Kitsap County, Washington.

For alternative 4, the total amount of water pumped from the study area was identical to that of alternative 3 (table 20) and on-base rates and patterns of pumping were identical to those of alternative 3. The two new wells off-base, each pumping at rates of 400 gal/min from the Sea-level aquifer, were assumed to be located east and south of SUBASE Bangor (fig. 30). The remainder of the increase in off-base ground-water pumpage since 1995 was obtained by increasing the 1995 pumping rates of existing off-base wells by 32.5 percent.

Fluxes and Water-Level Drawdowns

All ground-water pumping alternatives resulted in changes in simulated ground-water discharge to springs and seeps, to streams, and to saltwater compared to predevelopment (table 21). For instance, simulated discharge to springs and seeps and streams during predevelopment was about 60 percent of long-term average recharge, but decreased to 52 percent for alternative 1, and decreased to about 47 percent for alternatives 3 and 4.

If 1995 rates of ground-water pumping were to continue (alternative 1), projected water-level drawdowns in the Vashon aquifer at an unknown time in the future would be less than 10 ft on SUBASE Bangor and more than 20 and 60 ft about 3 miles northeast and about 1.5 miles east of the base, respectively (fig. 31). Maximum drawdowns northeast and east of the base would be centered on the Edgewater No. 4 and Spirit Ridge No. 4 wells, respectively (fig. 8). However, for April 1995 conditions, the model simulated significantly lower water levels and larger drawdowns in the Vashon aquifer than measured near the Spirit Ridge No. 4 well and, as a result, the alternative 1 results suggest far worse conditions than are likely to occur. For alternative 1, pumping rates were assumed to be 79 gal/min for the Edgewater No. 4 well and 555 gal/min for the Spirit Ridge No. 4 well. Projected water-level drawdowns for the Sea-level aquifer would be less than 10 ft on and near SUBASE Bangor and more than 20 ft in two areas between Dyes Inlet and Liberty Bay (fig. 32*A*). Maximum projected drawdowns in the Sea-level aquifer would be in the general vicinity of well fields of the Silverdale Water District No. 16 and Island Lake water systems.

Table 21. Simulated fluxes between the ground-water flow system and Puget Sound during predevelopment and pumping alternatives 1, 2, 3, and 4, SUBASE Bangor and vicinity, Kitsap County, Washington

[**Simulated flux**: Long-term average recharge for the simulated flow system is 16,440 gallons per minute (36.6 cubic feet per second). **Pumping alternative No. 2**: Total does not add to 100 percent due to rounding]

Direction of ground-water flux	Simulated flux (as percentage of long-term average recharge)				
	Pre-development	Pumping alternative No.			
		1	2	3	4
From wells	0	16.6	32.1	28.0	28.0
To springs and seeps	26.8	23.9	21.3	22.3	22.2
To streams	35.5	30.0	25.1	26.1	27.2
From streams	–2.1	–1.9	–1.8	–1.9	–1.9
Net to springs, seeps, and streams	60.2	52.0	44.6	46.5	47.5
To saltwater	41.7	33.9	28.3	29.4	28.2
From saltwater	–1.9	–2.5	–4.9	–3.9	–3.7
Net to saltwater	39.8	31.4	23.4	25.5	24.5

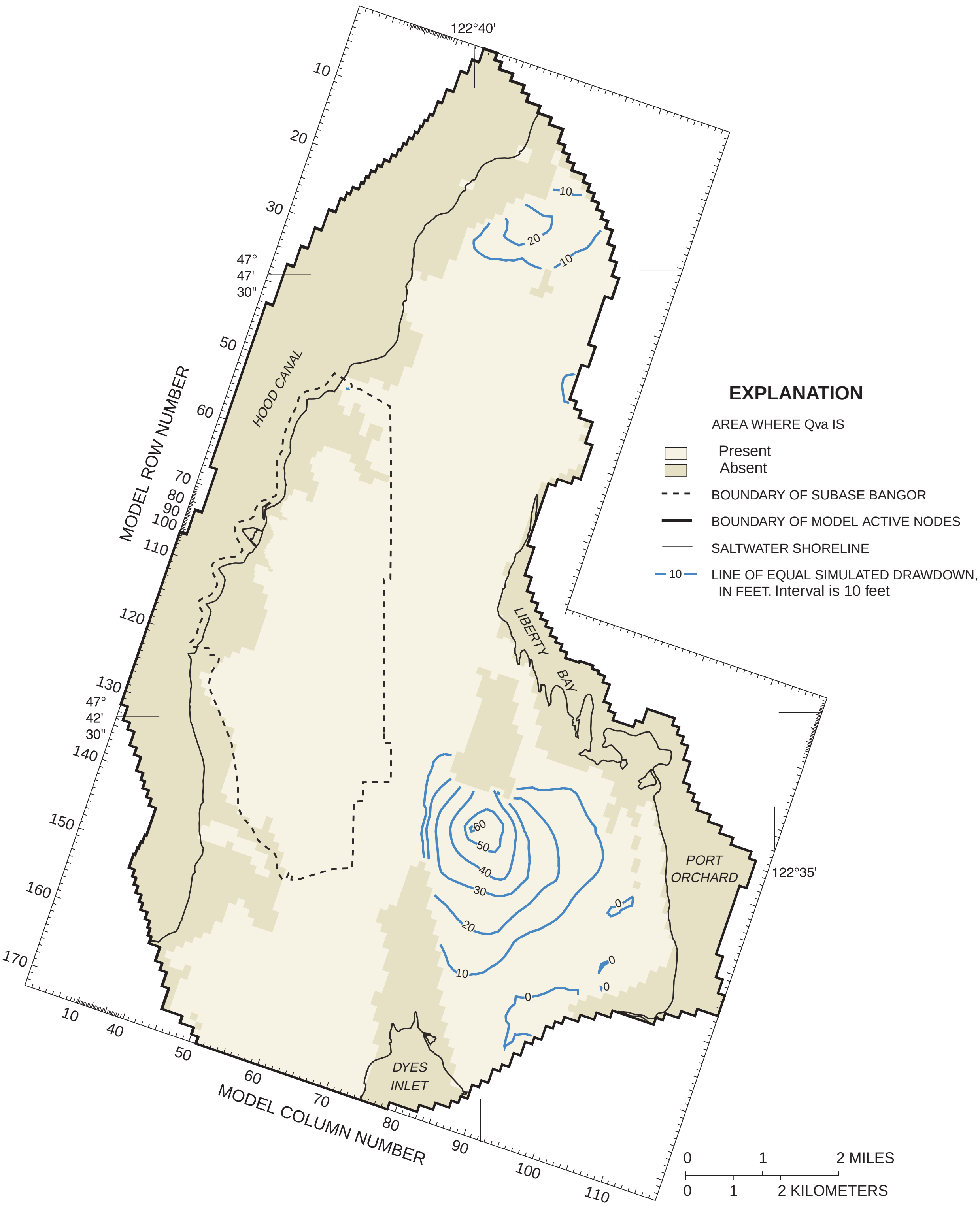
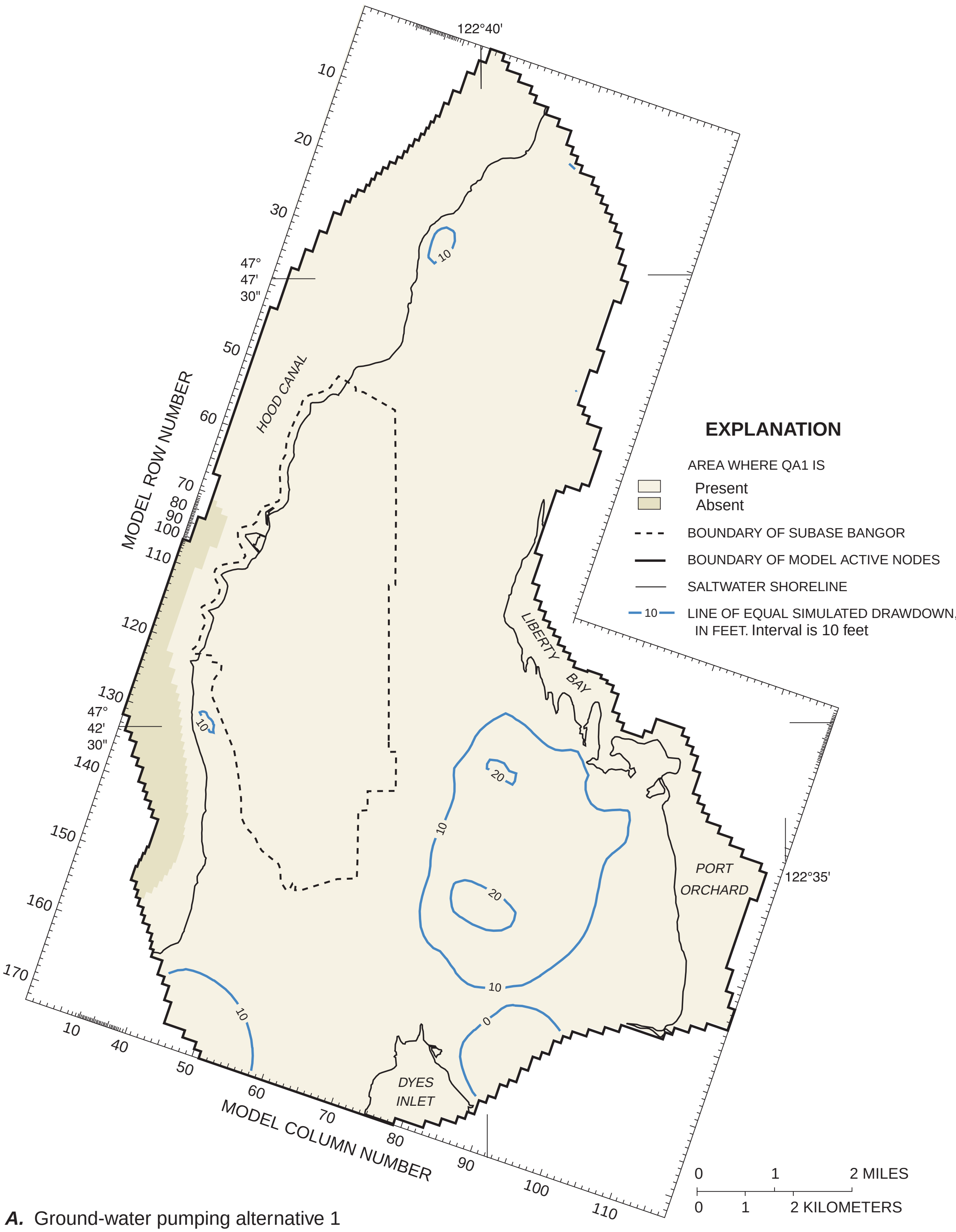
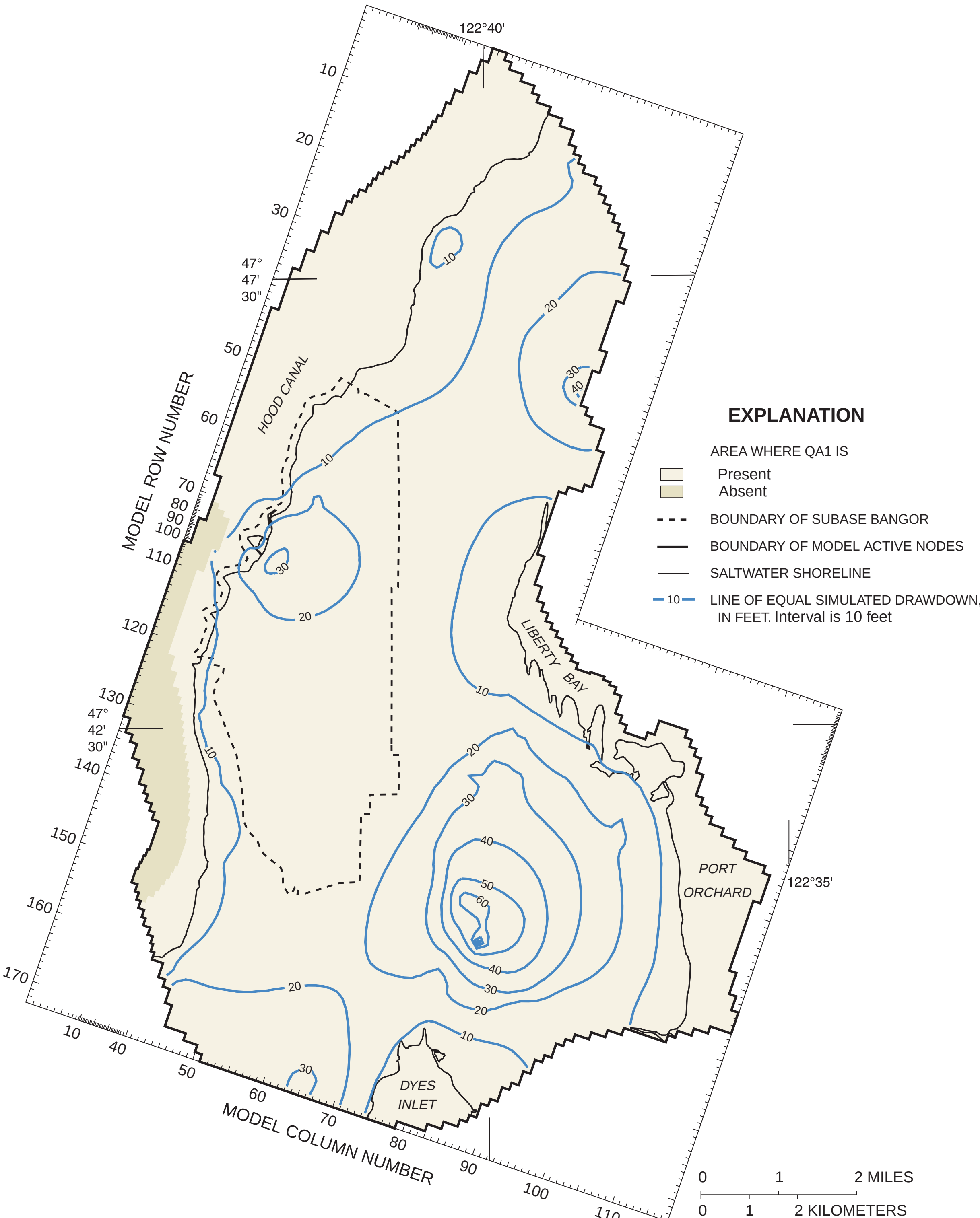


Figure 31. Simulated drawdowns in the Vashon aquifer (Qva) from April 15, 1995 until steady-state for ground-water pumping alternative 1, SUBASE Bangor and vicinity, Kitsap County, Washington.



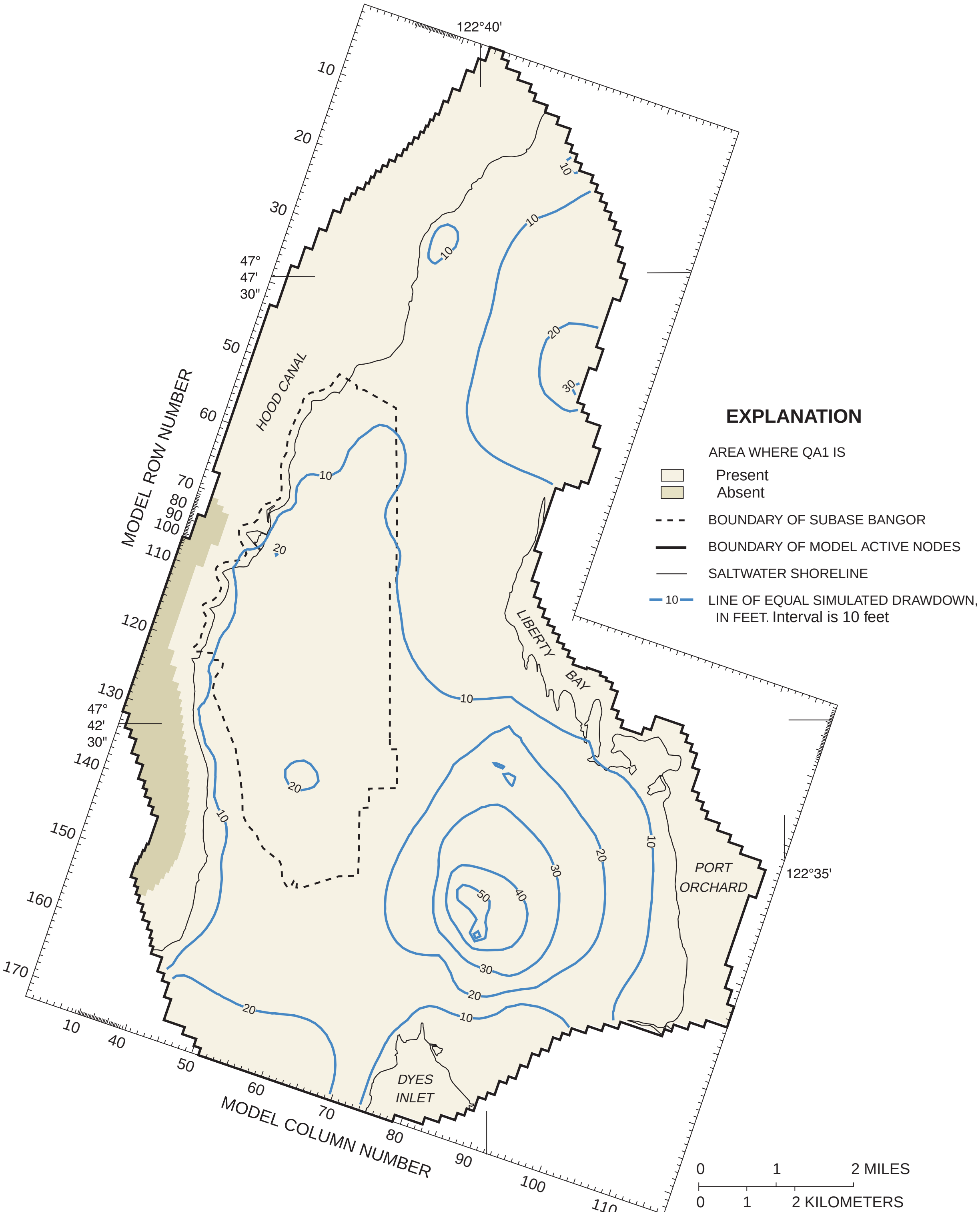
A. Ground-water pumping alternative 1

Figure 32. Simulated drawdowns in the Sea-level aquifer (QA1) from April 15, 1995 until steady-state for ground-water pumping alternatives 1-4, SUBASE Bangor and vicinity, Kitsap County, Washington.



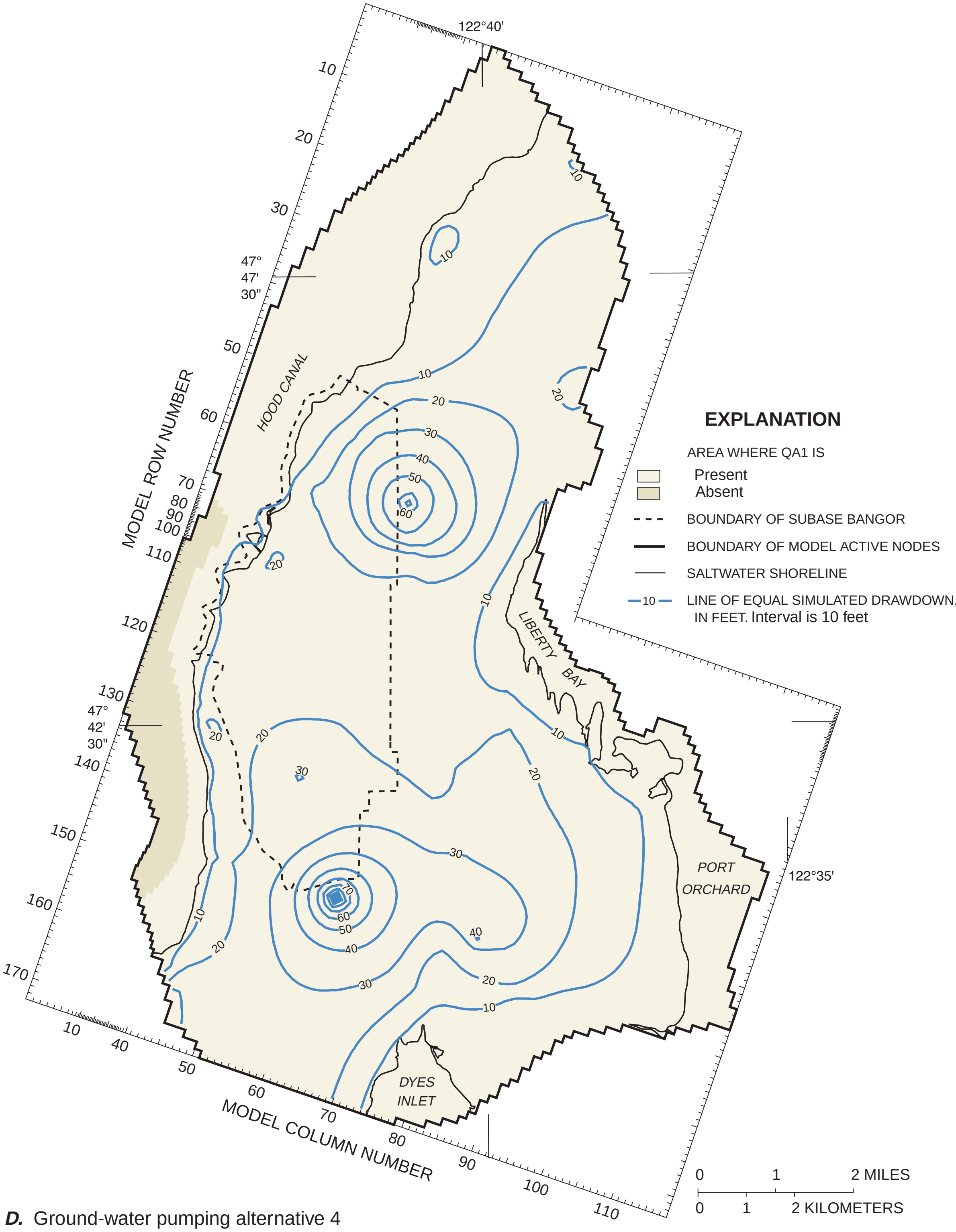
B. Ground-water pumping alternative 2

Figure 32.—*Continued.*



C. Ground-water pumping alternative 3

Figure 32.—*Continued.*



D. Ground-water pumping alternative 4

Figure 32.—*Continued.*

Compared to alternative 1, ground-water pumping alternatives 2, 3, and 4 would increase projected drawdowns throughout the study area. Similar to alternative 1, maximum projected water-level drawdowns in the Vashon aquifer would be centered on the Edgewater No. 4 and Spirit Ridge No. 4 wells, but projected drawdowns would be larger (not shown). Projected drawdowns in the Sea-level aquifer using alternative 2 would increase the sizes and depths of cones of depression that were simulated for April 15, 1995 conditions (fig. 26) near Delta Pier, between Dyes Inlet and Liberty Bay, and north of Liberty Bay near the part of the Poulsbo well field that is located inside the model active-node boundary (fig. 32*B*).

Projected drawdowns in the Sea-level aquifer using alternatives 3 and 4, which simulate identical pumping rates but with different distributions, would result in different patterns (fig. 32*C* and 32*D*). Projected water-level drawdowns on SUBASE Bangor using alternative 3 were centered on the new well (fig. 30), with a maximum projected drawdown in excess of 20 ft. Similar to alternative 2, the cones of depression that were simulated for April 15, 1995 conditions (fig. 26) would increase in size and depth. Projected water-level drawdowns using alternative 4 were centered on the new wells east and south of SUBASE Bangor (fig. 30). In addition, the projected drawdowns centered on the southern new well would coalesce with those between Dyes Inlet and Liberty Bay and projected drawdowns would also develop north of Liberty Bay in excess of 20 ft.

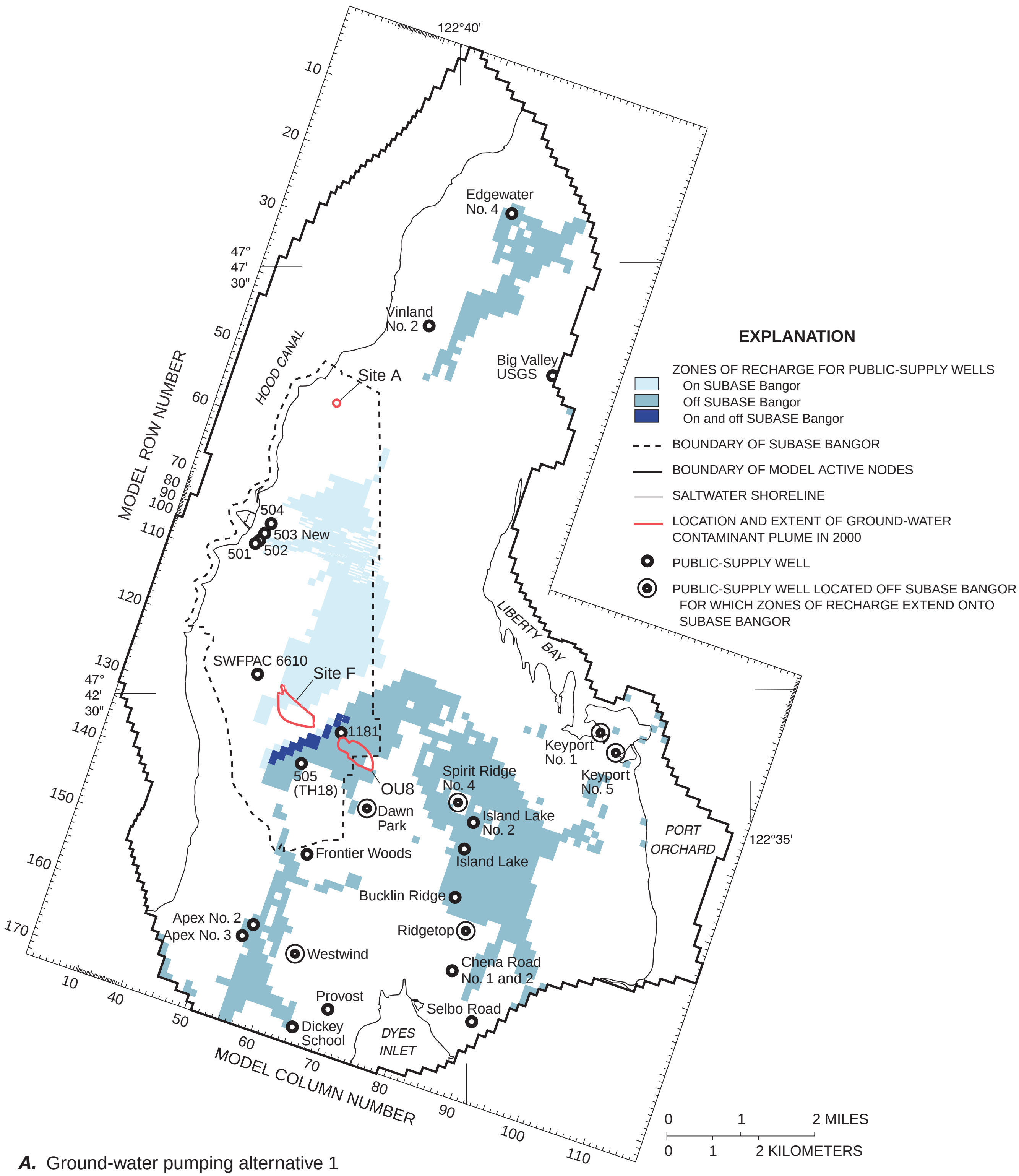
In 1998, KPUD drilled a test well open to the Sea-level aquifer in the general vicinity of the hypothetical new well located east of SUBASE Bangor for alternative 4. On the basis of aquifer-test results, KPUD recommended that this well be completed as a 300 gal/min production well and be used intermittently (Sebren, 1998). This recommended pumping rate is less than the 400 gal/min assumed for alternative 4.

Zones of Recharge and Traveltimes

Using the particle-tracking software MODPATH (Pollock, 1994), the contributing zones of recharge for wells can be determined by tracing imaginary particles to the top surface of the model from model cells that represent open intervals of pumping wells. As particles are backtracked to their source area, the time required to travel from the recharge zone to the open interval also is calculated. This procedure was applied to each of the four simulated pumping alternatives.

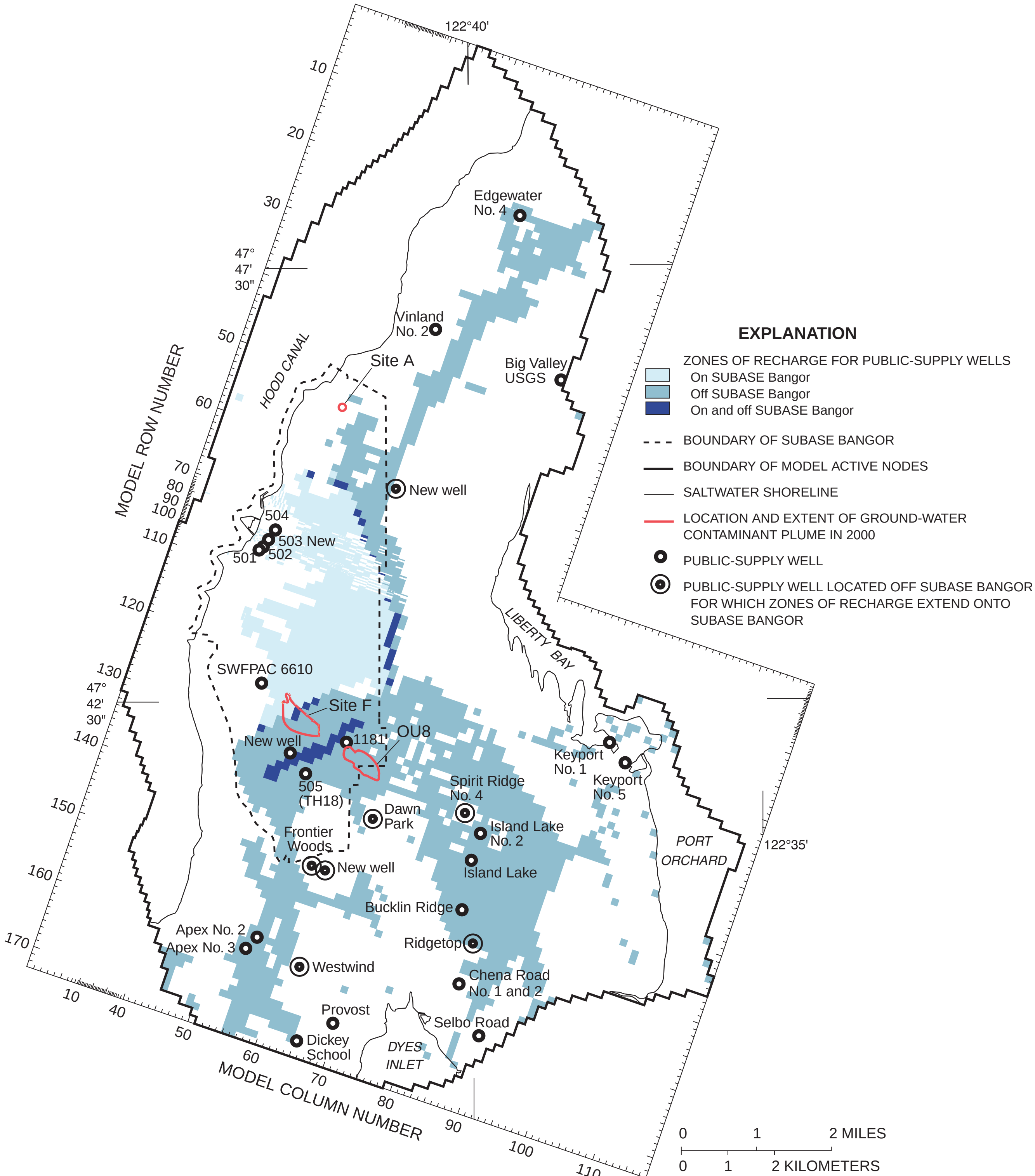
For all pumping alternatives, recharge for public-supply wells on SUBASE Bangor predominantly originates inside the boundaries of the base (fig. 33). Recharge for most off-base public-supply wells originates off-base, but some source water for some wells originates on-base. For example, for alternative 1, zones of recharge for the Dawn Park, Westwind, Ridgetop, Spirit Ridge No. 4, and Keyport No. 1 and No. 5 wells (fig. 33A) extend onto SUBASE Bangor. As noted previously, projected water levels in the Vashon aquifer near the Spirit Ridge No. 4 wells were likely too low and the fact that the zone of recharge of this well extends onto the base may be an artifact of this condition. For the Dawn Park well, almost the entire zone of recharge is on-base, while only a small fraction is on-base for the Keyport No. 5 well. The sizes of contributing zones of recharge generally increased as simulated pumping rates increased. In addition, contributing zones extend to greater distances from pumping wells if the wells are open to deeper parts of the flow system.

Traveltimes from zones of recharge to pumping wells were highly variable. Median traveltimes among all four alternatives for the public-supply wells on SUBASE Bangor ranged from 54 to 340 years (table 22). Median traveltimes among all four alternatives for the off-base wells ranged from 18 to 2,759 years.



A. Ground-water pumping alternative 1

Figure 33. Zones of recharge for public-supply wells for ground-water pumping alternatives 1 and 4, SUBASE Bangor and vicinity, Kitsap County, Washington.



B. Ground-water pumping alternative 4

Figure 33.—*Continued.*

Table 22. Model-simulated traveltimes from zones of recharge to selected discharge wells for pumping alternatives 1, 2, 3, and 4, SUBASE Bangor and vicinity, Kitsap County, Washington

[Discharge wells are included if their zones of recharge extend onto SUBASE Bangor. **Well No.**: See figure 3 for explanation of well-numbering system. **Navy identifier or common name**: Locations of wells are shown in figure 33. –, Navy identifier or common name not available]

Well No.	Navy identifier or common name	Model node (row, column, layer)	Traveltime from zone of recharge to well (years)		
			Median	Minimum	Maximum
Alternative 1					
On SUBASE Bangor					
26N/01E-18K01	504	87, 38, 7	189	33	1,802
26N/01E-18P03	501	104, 32, 6-7	170	16	350
26N/01E-18P04	502	101, 34, 6-8	200	7	2,328
26N/01E-18P06	503 New	95, 36, 6-7	163	69	1,561
26N/01E-30L01	SWFPAC 6610	125, 45, 4	55	46	70
26N/01E-31R01	505 (TH18)	135, 55, 6-8 and 10	295	183	658
26N/01E-32L05	1181	129, 59, 8	219	131	245
Off SUBASE Bangor					
25N/01E-03E01	Spirit Ridge No.4	133, 78, 2	18	0	5,304
25N/01E-05J01	Dawn Park	138, 66, 4	166	129	297
25N/01E-15D01	Ridgetop	150, 85, 10	2,005	1,182	58,003
25N/01E-18H01	Westwind	161, 63, 10-11	1,543	828	48,507
26N/01E-36M01	Keyport No.1	117, 94, 10-11	1,203	322	39,274
26N/01E-36P05	Keyport No.5	119, 97, 10-11	1,784	166	71,773
Alternative 2					
On SUBASE Bangor					
26N/01E-18K01	504	87, 38, 7	177	13	348,301
26N/01E-18P03	501	104, 32, 6-7	106	9	218
26N/01E-18P04	502	101, 34, 6-8	194	6	3,463
26N/01E-18P06	503 New	95, 36, 6-7	141	8	4,573
26N/01E-30L01	SWFPAC 6610	125, 45, 4	54	45	69
26N/01E-31R01	505 (TH18)	135, 55, 6-8 and 10	296	184	577
26N/01E-32L05	1181	129, 59, 8	218	132	245
Off SUBASE Bangor					
25N/01E-03E01	Spirit Ridge No.4	133, 78, 2	18	0	2,116
25N/01E-05J01	Dawn Park	138, 66, 4	152	93	345
25N/01E-07A01	Frontier Woods	147, 60, 4	84	33	199
25N/01E-15D01	Ridgetop	150, 85, 10	2,488	586	35,408
25N/01E-18H01	Westwind	161, 63, 10-11	1,376	663	37,863
26N/01E-04B01	Vinland No.2	40, 52, 10	1,694	418	18,973
26N/01E-36M01	Keyport No.1	117, 94, 10-11	789	149	21,500
26N/01E-36P05	Keyport No.5	119, 97, 10-11	1,897	147	41,872

Table 22. Model-simulated traveltimes from zones of recharge to selected discharge wells for pumping alternatives 1, 2, 3, and 4, SUBASE Bangor and vicinity, Kitsap County, Washington—*Continued*

Well No.	Navy identifier or common name	Model node (row, column, layer)	Traveltime from zone of recharge to well (years)		
			Median	Minimum	Maximum
		Alternative 3			
On SUBASE Bangor					
26N/01E-18K01	504	87, 38, 7	181	15	15,346
26N/01E-18P03	501	104, 32, 6-7	137	13	352
26N/01E-18P04	502	101, 34, 6-8	184	7	4,523
26N/01E-18P06	503 New	95, 36, 6-7	142	10	16,573
26N/01E-30L01	SWFPAC 6610	125, 45, 4	55	45	70
26N/01E-31R01	505 (TH18)	135, 55, 6-8 and 10	274	176	676
26N/01E-32L05	1181	129, 59, 8	140	122	230
New well	–	133, 52, 6-8	192	104	934
Off SUBASE Bangor					
25N/01E-03E01	Spirit Ridge No.4	133, 78, 2	18	0	3,850
25N/01E-05J01	Dawn Park	138, 66, 4	149	102	330
25N/01E-07A01	Frontier Woods	147, 60, 4	84	35	199
25N/01E-15D01	Ridgetop	150, 85, 10	2,493	642	121,548
25N/01E-18H01	Westwind	161, 63, 10-11	1,537	722	17,206
26N/01E-04B01	Vinland No.2	40, 52, 10	1,705	540	12,796
26N/01E-36M01	Keyport No.1	117, 94, 10-11	1,139	162	27,677
26N/01E-36P05	Keyport No.5	119, 97, 10-11	1,884	149	39,627
		Alternative 4			
On SUBASE Bangor					
26N/01E-18K01	504	87, 38, 7	165	15	503,918
26N/01E-18P03	501	104, 32, 6-7	122	10	260
26N/01E-18P04	502	101, 34, 6-8	192	7	3,351
26N/01E-18P06	503 New	95, 36, 6-7	151	9	2,594
26N/01E-30L01	SWFPAC 6610	125, 45, 4	55	45	69
26N/01E-31R01	505 (TH18)	135, 55, 6-8 and 10	340	180	603
26N/01E-32L05	1181	129, 59, 8	129	116	219
New well	–	133, 52, 6-8	179	112	1,095
Off SUBASE Bangor					
25N/01E-03E01	Spirit Ridge No.4	133, 78, 2	19	0	11,359
25N/01E-05J01	Dawn Park	138, 66, 4	144	112	287
25N/01E-07A01	Frontier Woods	147, 60, 4	74	33	135
25N/01E-15D01	Ridgetop	150, 85, 10	2,759	916	21,143
25N/01E-18H01	Westwind	161, 63, 10-11	1,912	830	37,789
New well	–	63, 54, 6-8	501	79	14,963
New well	–	147, 62, 6-8	333	109	5,584

For alternative 1, median traveltimes of imaginary particles that originate on SUBASE Bangor and discharge from the Westwind, Ridgetop, and Keyport No. 1 and No. 5 wells were 1,348, 1,542, 1,968, and 2,448 years, respectively. Median traveltimes for the Dawn Park and Spirit Ridge No. 4 wells were 164 and 79 years, respectively (table 23). The long time required to travel from contributing zones of recharge to the Westwind, Ridgetop, and Keyport No. 1 and No. 5 wells indicates that if any possible contamination were to migrate off SUBASE Bangor and not naturally attenuate to harmless substances, it would take a long time to reach those public-supply wells. The possible contamination also would be greatly diluted as it blended with recharge from other areas. Significant blending also would occur for the Spirit Ridge No. 4 well, but not the Dawn Park well, because most of its zone of recharge is located on-base.

For alternative 1, the zone of recharge of the Dawn Park well included a small area that is part of the OU8 contaminant plume (fig. 33*A*). This plume was stable or decreasing in size in 2000 as a result of naturally occurring biodegradation (EA Engineering, Science, and Technology, 2000). In 10 years, concentrations of the plume contaminants, benzene and 1,2-dichloroethane (DCA), are expected to be less than the 5 µg/L drinking water Maximum Contaminant Limit (U.S. Environmental Protection Agency, 2002) in the off-base part of the Vashon aquifer (EA Engineering, Science, and Technology, 2000). Contaminants continue to be monitored to verify that natural attenuation is progressing. Assuming ground-water transport of contaminants by advection with no dispersion and no retardation (dispersion speeds up transport and retardation slows it down), any plume contaminants that were to be captured by the Dawn Park well would take a minimum of about 130 years to reach the well (table 23). Thus, natural attenuation during that time would most likely degrade any contaminants to harmless compounds and, therefore, the risk is minimal that contaminants originating on SUBASE Bangor would ever reach the Dawn Park well.

Homeowners southwest of SUBASE Bangor have expressed concern over the possibility that contaminants on-base could reach their supply wells. Zones of recharge were determined to check this possibility by backtracking imaginary particles from an array of hypothetical wells open to the Sea-level aquifer to the water table (fig. 34). Pumping rates for these wells were assumed to be negligible and were set equal to zero. Particle tracking for each of the four simulated pumping alternatives demonstrates that the recharge zones for the hypothetical wells extend onto SUBASE Bangor. However, contributing recharge originates in an area of known contamination only for alternative 1, which generates the most extensive recharge zone on-base. Contributing recharge originates south and west of areas with known contamination for alternatives 2, 3, and 4.

Table 23. Model-simulated traveltimes for imaginary particles that recharge on SUBASE Bangor and discharge in off-base public-supply wells for pumping alternative 1, Kitsap County, Washington

[**Well No**: See figure 3 for explanation of well-numbering system. **Common name**: Locations of wells are shown in figure 33]

Well No.	Common name	Model node (row, column, layer)	Traveltime from zone of recharge to well (years)			Percentage of imaginary particles that recharges on SUBASE Bangor
			Median	Minimum	Maximum	
25N/01E-03E01	Spirit Ridge No. 4	133, 78, 2	79	52	4,936	5
25N/01E-05J01	Dawn Park	138, 66, 4	164	129	297	89
25N/01E-15D01	Ridgetop	150, 85, 10	1,542	1,182	12,984	35
25N/01E-18H01	Westwind	161, 63, 10–11	1,348	828	11,698	68
26N/01E-36M01	Keyport No.1	117, 94, 10–11	1,968	1,790	3,684	9
26N/01E-36P05	Keyport No.5	119, 97, 10–11	2,448	1,904	28,181	4

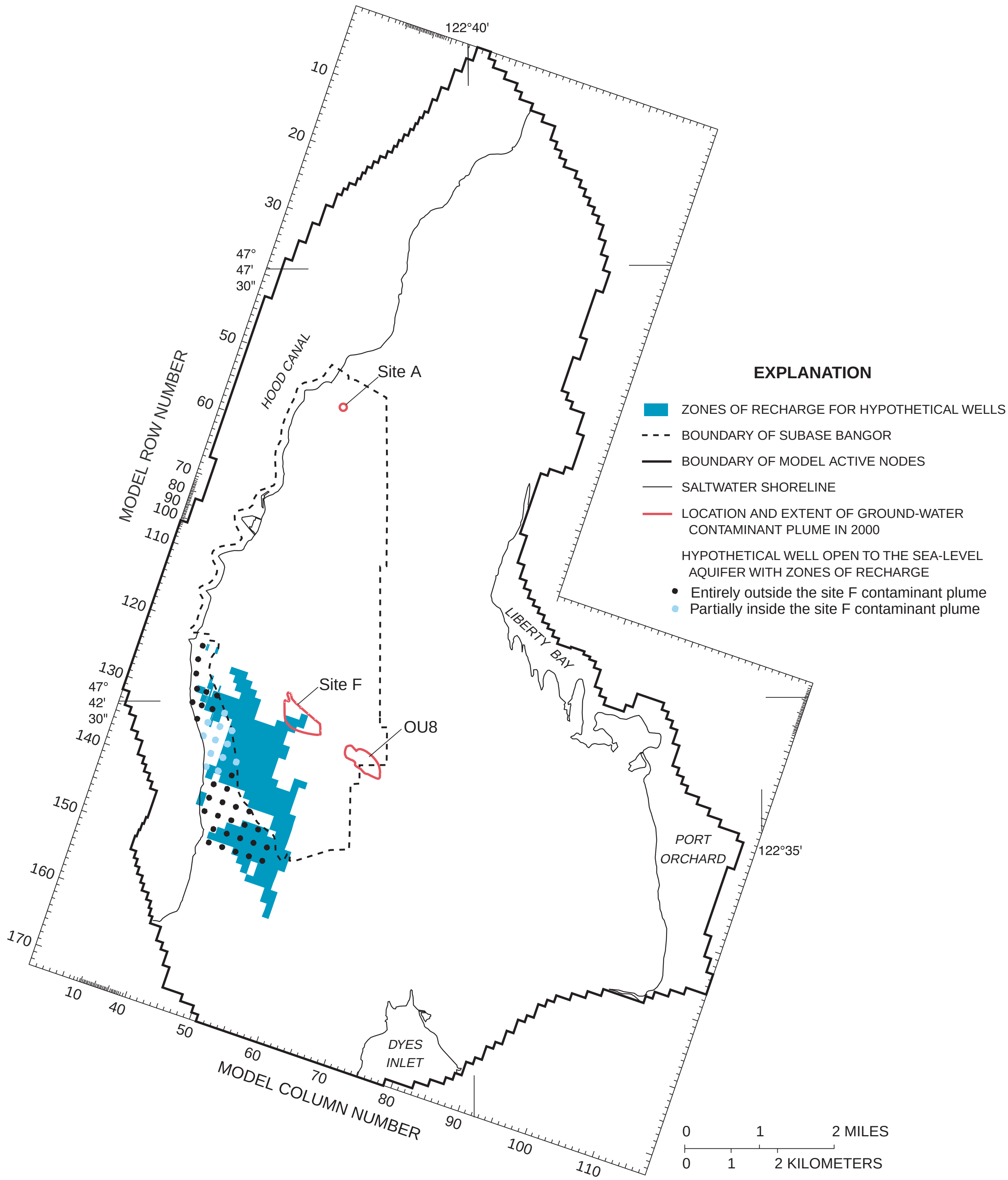


Figure 34. Zones of recharge for hypothetical wells southwest of SUBASE Bangor for ground-water pumping alternative 1, SUBASE Bangor and vicinity, Kitsap County, Washington.

For alternative 1, particles for 12 out of 44 hypothetical wells recharge within the boundaries of the area of the Site F contaminant plume (fig. 34). Primary contaminants of concern in this plume include hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX), 2,4,6-trinitrotoluene (TNT), and 2,6-dinitrotoluene (DNT) (Hart Crowser, Inc., 2002). If the 12 hypothetical wells were to pump water from the entire thickness of the Sea-level aquifer, about 3 to 11 percent of all imaginary particles pumped by each well would originate from the area presently occupied by the contaminant plume. The simulated traveltimes for these particles ranged from 243 to 433 years, with a median of 385 years. Thus, if contaminants migrated by advection with no dispersion and no retardation, a minimum of about 240 years would be required for contaminants in the Site F plume to reach the well.

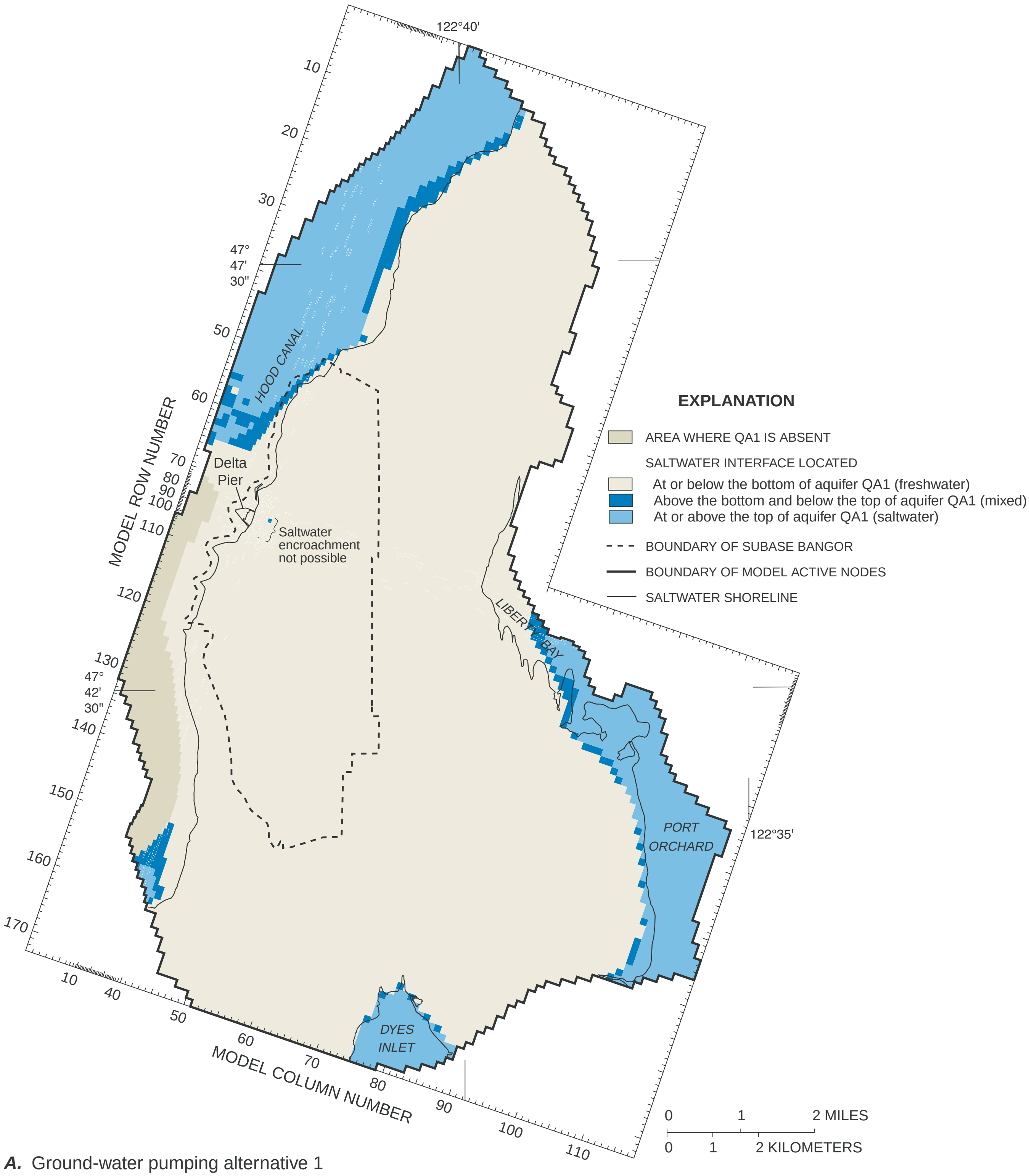
The earliest ground-water contamination at Site F may have occurred around 1960. Remediation of the contaminant plume, which is confined to the Vashon aquifer, started in 1994 and by 2000, the plume had been contained by a combination of extraction and reintroduction wells (Hart Crowser, Inc., 2000). Based on trends in TNT concentrations in the site F plume since 1994, clean-up of the plume is estimated to take about 150 years (Hart Crowser, Inc., 2000).

Alternative 1 does not include a simulation of the extraction and reintroduction wells that contain the Site F contaminant plume. Therefore, estimates of possible contaminant migration to supply wells southwest of SUBASE Bangor represent a worst-case scenario that assumes the contaminant plume is not contained. Even if this worst-case scenario were to occur, risks to supply wells located southwest of SUBASE Bangor would be further minimized because contaminant concentrations would be substantially decreased as a result of significant dilution and natural attenuation processes during the long period of travel to the supply wells.

Potential for Saltwater Encroachment

The potential for saltwater encroachment in the long term was estimated by computing steady-state potential saltwater interface positions for hypothetical pumping alternatives 1, 2, 3, and 4. The positions were calculated for each model cell on the basis of simulated steady-state water levels and the Ghyben-Herzberg principle (for example, Bear, 1979, p. 385). This principle states that under static conditions, the pressure exerted by a column of saltwater can be represented by an equivalent pressure exerted by a column of freshwater and was previously summarized in equation 3. Using the saltwater specific weights that prevail in the study area (previously provided in section "Boundary Conditions"), the depth to the saltwater interface decreases by 43.5 ft for every 1 ft of freshwater head decrease. The calculated interface position was compared with the estimated altitude of the top and bottom of the hydrogeologic unit to determine whether the interface is above, below, or inside the unit (fig. 35). Because the Ghyben-Herzberg principle assumes steady-state conditions, the calculated interface positions represent estimates of conditions that could occur eventually for the simulated pumping alternatives. The amount of time that would lapse before potential interfaces would reach their final positions is unknown.

The calculated altitudes of potential interface positions were highly sensitive to the simulated freshwater head. Each 1 ft of error in the simulated water level results in an error of 43.5 ft in the calculated saltwater-interface position. If the simulated water level is too low, the calculated saltwater-interface position will be too high and thus the possibility of saltwater encroachment may be indicated even though it would not occur. Conversely, if the simulated water level is too high, the calculated saltwater interface position will be too low and the possibility of saltwater encroachment may be missed.

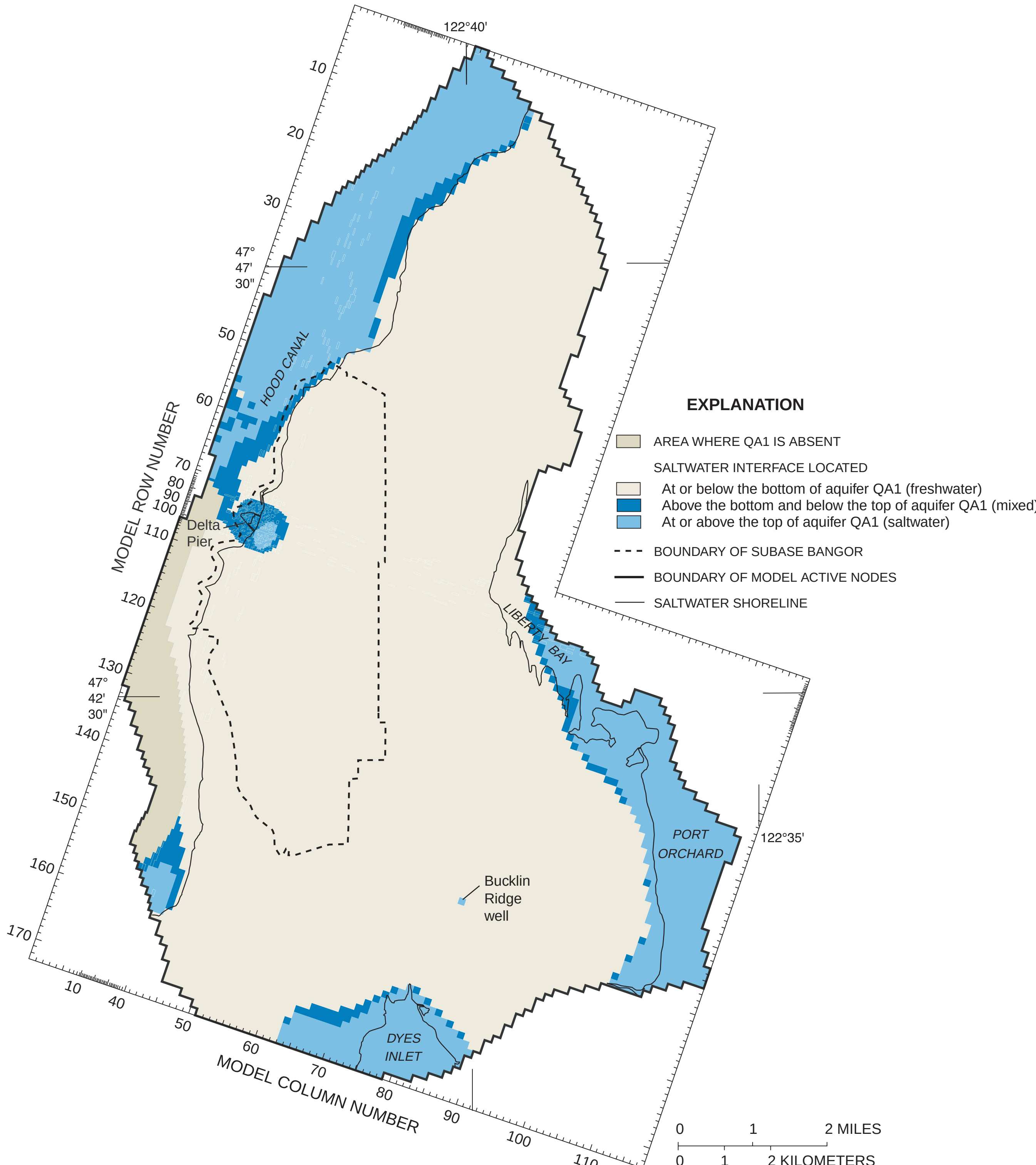


A. Ground-water pumping alternative 1

Figure 35. Potential steady-state positions of the saltwater-freshwater interface in the Sea-level aquifer (QA1) for ground-water pumping alternatives 1-4, SUBASE Bangor and vicinity, Kitsap County, Washington.

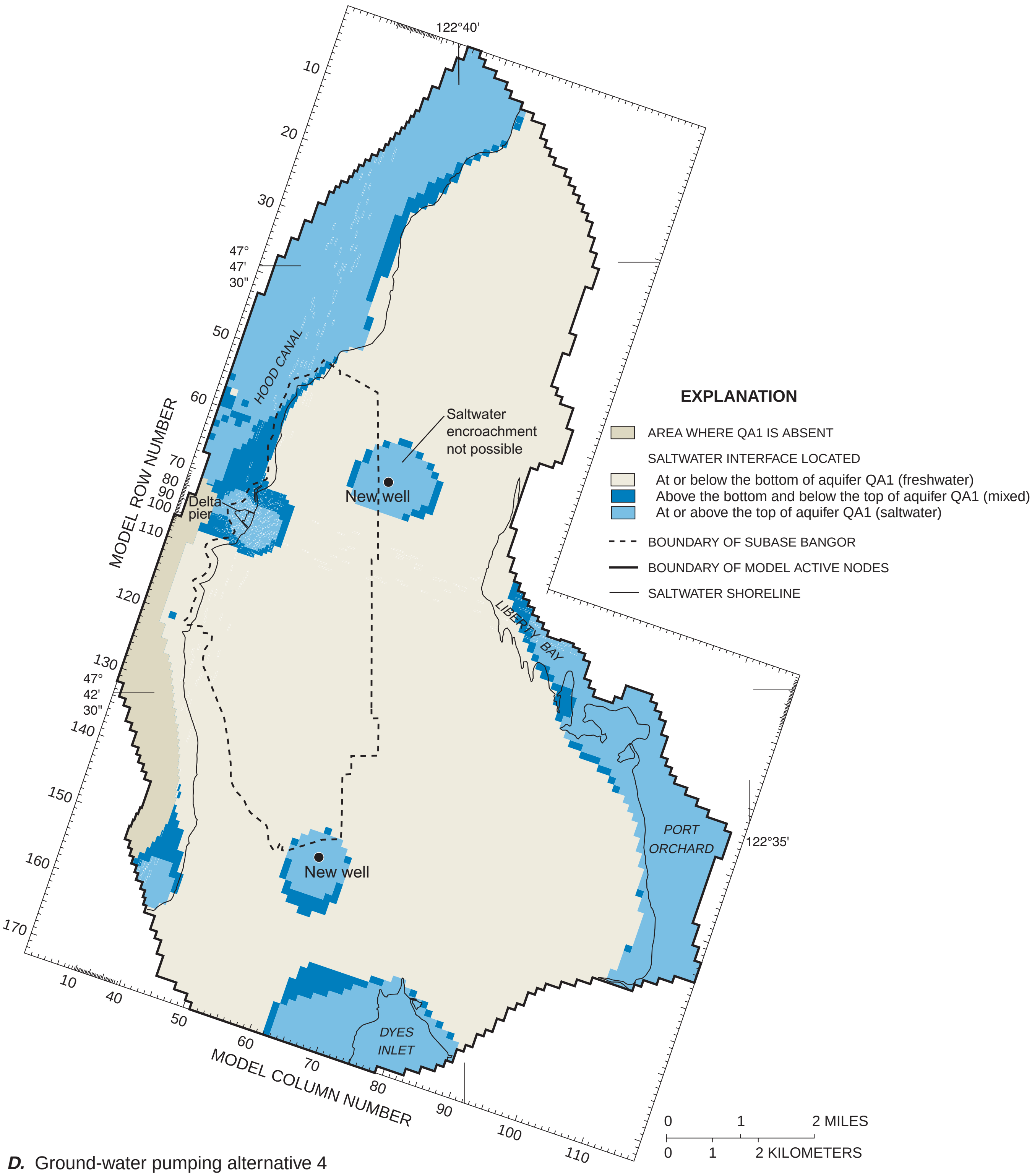
B. Ground-water pumping alternative 2

Figure 35.—*Continued.*



C. Ground-water pumping alternative 3

Figure 35.—*Continued.*



D. Ground-water pumping alternative 4

Figure 35..—*Continued.*

How well the simulated water levels for the pumping alternatives represent the future ground-water flow system is unknown. This would vary with the accuracy of the simulated starting water levels and the ability of the model to accurately simulate the hydrologic stresses applied to the ground-water flow system. What is known, for example, is that the simulated starting water levels in the Sea-level aquifer on April 15, 1995 (fig. 25*C*) were higher than measured water levels in some areas and lower in other areas. The mean and median errors in simulated water levels at 62 measurement points in the Sea-level aquifer were 0 ft and the RMSE was 21.8 ft (table 16). Errors in the starting water levels may be compounded or offset during the simulation of the pumping alternatives, depending on how well the model simulates drawdowns in different parts of the study area. From the model calibration, it is known that median drawdowns in the Sea-level and Deep aquifers simulated from predevelopment until April 15, 1995 were smaller than measured drawdowns (table 15) and there is areal variability in the errors of simulated drawdowns (fig. 27). The uncertainty associated with the accuracy of simulated long-term water levels for the pumping alternatives indicates that the potential saltwater encroachment patterns presented here should be interpreted with caution.

The technique for estimating a potential saltwater interface position as outlined above does not consider whether a saltwater source is available to the area of the aquifer where a potential interface was calculated inside or above the unit. However, saltwater encroachment can only occur if the affected area is in direct contact with saltwater sources around, beneath, or above the affected area. Such sources may include Puget Sound and hydrogeologic units immediately above or below in which saltwater has encroached. This means, for example, that for alternative 1, saltwater encroachment is not a risk in the Sea-level aquifer near Delta Pier (fig. 35*A*), even though in the areas immediately surrounding the public-supply wells near Delta Pier an interface is calculated inside the aquifer. Because these small areas were not in contact with a saltwater source, saltwater encroachment is not expected in the Sea-level aquifer. In contrast, for alternative 2, the affected area near Delta Pier is in contact with saltwater and therefore saltwater encroachment appears possible for this alternative (fig. 35*B*).

Pumping alternatives 3 and 4 generate different potential saltwater encroachment patterns in the Sea-level aquifer near Delta Pier (fig. 35*C* and 35*D*), even though the total amount of water pumped from the flow system was identical for both. For both alternatives, the potential for saltwater encroachment is indicated near Delta Pier. The risk of saltwater encroachment in the Sea-level aquifer near Delta Pier was greater for alternative 4 than 3, which is primarily due to the effects of ground-water pumping by the hypothetical new well along the eastern boundary of SUBASE Bangor. The differences in saltwater encroachment patterns for alternatives 3 and 4 illustrate that the locations of pumping wells in addition to the amount of water pumped are important when evaluating the potential for saltwater encroachment. Lowered water levels in the Sea-level aquifer near the hypothetical new wells off-base result in simulated potential interface positions inside and above the unit near the wells (fig. 35*D*). However, saltwater encroachment only appears possible in the area along the southern boundary of SUBASE Bangor, through upconing of saltwater that may have encroached in deeper units. The area along the eastern boundary is entirely surrounded by freshwater and therefore, saltwater encroachment is not a risk at this site.

Because water-level and hydrogeologic data for the Sea-level and Deep aquifers southeast and south of SUBASE Bangor were sparse, the model performance could not be verified and simulated water levels for the different pumping alternatives may not be correct in those areas. Near parts of Liberty Bay and Port Orchard, the Sea-level aquifer and deeper units were not mapped by Kahle (1998) due to insufficient data and instead, the geometry of the units in those areas was projected for the purpose of this study. The combination of uncertainty in the geometry of deeper hydrogeologic units and lack of calibration data means that the simulated potential saltwater encroachment patterns for the Sea-level aquifer along Dyes Inlet, Liberty Bay, and Port Orchard (all alternatives) and near the Bucklin Ridge well (alternatives 2 and 3) should be viewed with caution. Simulated saltwater encroachment patterns for the Deep aquifer (not shown) indicate large-scale saltwater encroachment potential southeast and south of SUBASE Bangor for all alternatives, with encroaching saltwater originating in Hood Canal, Dyes Inlet, Liberty Bay, and Port Orchard. Smaller-scale saltwater encroachment potential exists north of and on SUBASE Bangor, with encroaching saltwater originating in Hood Canal. As already explained, however, the accuracy of these projected potential saltwater encroachment patterns is limited by the uncertainties and errors in the simulation of the freshwater flow system, which are further magnified due to the large contrast in saltwater and freshwater densities.

LIMITATIONS AND ASSUMPTIONS

The ground-water flow model documented in this report was designed to gain insight into ground-water flow on a regional scale. Attempts to use the model for applications other than its intended purpose could lead to erroneous results. A ground-water flow model is a numerical representation of an actual ground-water flow system and this representation has a degree of error associated with it. To create a model, various assumptions and generalizations are made about the actual flow system, each of which may affect how well the model represents the system. The representation also is affected by the numerical approach on which the model is based.

For example, MODFLOW, the model used in this study, uses a finite-difference approach to calculate a numerical solution of the ground-water flow equation (McDonald and Harbaugh, 1988). In this approach, the actual flow system is represented by a mesh of rectangular cells that each represent averaged hydrologic conditions; the sizes of the cells determine the resolution of the simulated results. Cell sizes were selected to be compatible with the resolution of available data and the resolution required to simulate predevelopment conditions, development of the resource until April 15, 1995 and possible future conditions of the regional ground-water flow system. Each hydrogeologic unit was represented by one layer of cells, except for the Sea-level and Deep aquifers, which were represented by three and two layers, respectively. Vertical water-level gradients cannot be simulated within hydrogeologic units represented by one layer and thus, for example, such gradients cannot be simulated in the Vashon aquifer. The modeling approach also requires the specification of model boundary conditions. The choice of boundary types and locations is important, because they can affect simulated results. In this study, natural hydrologic boundaries were selected where possible and other boundaries were selected sufficiently far from SUBASE Bangor to minimize errors in simulated results on and near the base. Because the southern and northeastern boundaries of the model do not represent natural hydrologic boundaries, simulated results are less reliable near Dyes Inlet and north of Liberty Bay, respectively.

All hydrogeologic units were simulated as if they were confined. In reality, the Vashon till confining unit/Shallow aquifer (model layer 1) is unconfined and the Vashon aquifer (model layer 2) is unconfined over much of its areal extent. By assuming confined conditions and not permitting previously confined aquifers to convert to unconfined conditions during the simulations, the transmissivities and storativities of the model layers remained constant for the entire simulation and, as a result, the numerical stability of the model was greatly improved. To mitigate possible effects of this simplifying assumption, saturated thicknesses were used to calculate transmissivities and storativities of the model layers. The saturated thickness of model layer 2 was calculated from interpolated water-level measurements and bottom altitudes of the Vashon aquifer, but it was largely estimated for model layer 1.

Model performance should not be affected adversely if simulated water levels in model layers 1 and 2 generated simulated saturated thicknesses similar to those that were assumed. On average, simulated saturated thicknesses were similar to assumed values for model layer 2, but not for model layer 1. For example, median differences between simulated and measured water levels indicate that the simulated saturated thickness of layer 2 was about 15 and 21 percent less than assumed for predevelopment and April 1995 conditions, respectively. These differences result in small enough differences in transmissivities and storativities so that modeling results should not be significantly affected. However, median differences between simulated and measured water levels in the parts of model layer 1 that were assumed to be saturated indicate that simulated saturated thicknesses were about 74 and 63 percent less than assumed for predevelopment and April 1995 conditions, respectively. In addition, simulated water levels were below the bottom of layer 1 in a significant number of model cells, a condition that is ignored in the simulations. Based on the differences between simulated and assumed conditions in layer 1, simulated results for layer 1 are not considered reliable. However, because the parts of layer 1 that were assumed to be saturated only occupy limited parts of the study area (fig. 14*A*), simulated errors in model layer 1 are not expected to result in significant errors for deeper model layers.

The ground-water flow model was calibrated in steady-state and transient modes using a process of trial-and-error parameter adjustments to minimize differences between simulated and measured or estimated variables. Because of non-linearity, ground-water flow models do not have unique numerical solutions — multiple combinations of calibrated parameter values are possible that could each produce similar minimized differences between simulated and measured or estimated variables. For example, if ground-water recharge were assumed to be larger than ground-water recharge estimates by Bidlake and Payne (2001), calibrated horizontal hydraulic conductivities would have been larger and closer to estimated hydraulic conductivities. Measurements of local hydraulic properties, however, may not be representative of values on a regional scale. The fact that flow models do not have unique solutions indicates that calibrated hydraulic parameters may not accurately reflect the actual hydraulic parameters of the simulated system. Calibrated solutions are considered plausible if simulated results match measurements or estimates reasonably well and calibrated parameters appear reasonable based on the hydrogeology of the study area. Errors in the calibrated model were significant. The poor agreement between simulated and measured values could be improved by making many local changes to hydraulic parameters but these changes were not supported by other data. Errors in the calibrated model may have resulted in errors in the simulated effects of different alternatives of ground-water pumping, including water levels, water-level drawdowns, traveltimes of imaginary particles from zones of recharge to discharging wells, locations of zones of recharge, and patterns of potential saltwater encroachment.

Particle paths calculated for imaginary particles show that some of the water pumped by off-base public-supply wells and hypothetical wells located southwest of SUBASE Bangor originates on-base. The accuracy of the calculated flowpaths, zones of recharge, and traveltimes depends on how well the model represents the actual system and assumptions inherent to MODPATH, the particle-tracking software that was used (Pollock, 1994). Even though the calculation of particle paths has errors associated with it, the results can be used as an indication that advective transport from the Site F contaminant plume to hypothetical wells southwest of SUBASE Bangor is possible and that it would take a long time for contaminants to reach the wells (a minimum of about 240 years). Assuming no containment of the contaminant plume and no dispersion and no retardation of migrating contaminants, any contamination originating in the Site F plume would be greatly diluted by the time it reached the hypothetical wells due to blending with uncontaminated ground water. The results also can be used as an indication that only one of the simulated off-base public-supply wells (Dawn Park) captures a significant part of its recharge on-base and a relatively short time is needed for this recharge to reach the well. For example, if 1995 ground-water pumping rates were to continue in the future, the median traveltime for water pumped from the Dawn Park well that originates on-base would be 164 years (table 23).

An important limitation of this study is the use of the uniform-density ground-water flow model MODFLOW to represent a freshwater ground-water system that is in contact with saltwater. Because MODFLOW is not a variable-density model, simulated flow of saltwater from Puget Sound into the model is treated as freshwater once it enters through the model boundary. During steady-state predevelopment conditions, the model should calculate a flux from saltwater bodies equal to zero but it calculated a flux of about 2 percent of long-term average recharge. This error provides a measure of the limitation of approximating the boundary between Puget Sound and the freshwater flow system with general-head-boundary cells.

Potential saltwater encroachment patterns were simulated that could ultimately occur for four different alternatives of ground-water pumping. Water levels simulated with the calibrated flow model were combined with information about the top and bottom altitudes of hydrogeologic units to estimate if the altitude of the saltwater interface calculated according to the Ghyben-Herzberg principle indicates the possibility of future saltwater encroachment. This approach has several sources of error. For example, small errors in the simulated water levels result in large errors in the calculated altitude of the saltwater interface. If the simulated water level is estimated 1 ft too high, the altitude of the calculated saltwater interface will be 43.5 ft too low. Any error in the calculated altitude of the saltwater interface is compounded by assigning the interface to a relative position within a hydrogeologic unit, because there are uncertainties in the altitudes of tops and bottoms of these units. For example, near parts of Liberty Bay and Port Orchard, the Sea-level aquifer and deeper units were not mapped by Kahle (1998) due to insufficient data and, for modeling purposes, the geometry of the units was projected. As a result, simulated potential saltwater encroachment patterns are less certain in those areas.

SUMMARY AND CONCLUSIONS

A three-dimensional uniform-density ground-water flow model was constructed of Naval Submarine Base Bangor (SUBASE Bangor) and surrounding areas as a tool to evaluate how ground-water flow on-base interacts with the regional flow system and how possible future ground-water pumping may affect the system. SUBASE Bangor is a U.S. Navy installation of about 11 square miles that has been in operation since 1944. Past activities on-base resulted in soil and shallow ground-water contamination. By 2000, all sites were in remediation and remaining ground-water contamination consisted of three well-characterized plumes. An off-shore drydock, Delta Pier, was constructed on SUBASE Bangor from 1977 through 1980. This effort required the reduction of artesian water levels in the Sea-level aquifer. Large amounts of ground water were pumped, resulting in water-level decreases over about one-half of the base and a maximum water-level decrease off-shore in excess of 110 feet (ft). Detailed records of ground-water pumpage, artificial recharge, and water levels collected during the construction of Delta Pier were used to help calibrate the ground-water flow model.

The ground-water flow system was conceptualized as 11 model layers of aquifers and confining units. The simulated layers form the upper part of a sequence of glacial and interglacial sediments that were deposited on top of bedrock. The source of almost all ground-water recharge is precipitation, some of which leaves the flow system as discharge to wells, streams, springs, and seepage faces, and some flows deeper into the system to recharge deeper aquifers. Ground water may discharge to Puget Sound from aquifers located at or below sea level.

The ground-water flow system was simulated as a freshwater system that is in contact with saltwater where aquifers and confining units crop out in Puget Sound. Simulated ground-water recharge ranged from 8 to 10 inches per year over most of the simulated area. Streams, springs, and ground-water seeps are represented by the model. The freshwater flow-system boundary with saltwater was simulated by general-head-boundary model cells that were assigned heads that are representative of the height of the saltwater column above the cells. Simulated flow of saltwater from Puget Sound into the model was treated as freshwater once it entered the model. Model calibration was achieved by trial-and-error adjustments of estimated initial hydraulic parameters to minimize differences between simulated and measured water levels from prior to January 17, 1977 (termed "predevelopment"), water-level drawdowns since predevelopment until April 15, 1995, ground-water discharge to streams in water year 1995, and estimated residence times of ground water in different parts of the flow system.

Errors in the calibrated model were significant. The poor agreement between simulated and measured values could be improved by making many local changes to hydraulic parameters but these changes were not supported by other data. Overall, the model has negative bias: simulated water levels were less than measured water levels for predevelopment, July 1, 1979 and April 15, 1995 conditions with median errors for all hydrogeologic units of -6.3, -3.6, and -7.1 ft, respectively. The root-mean-square error (RMSE) of water levels during predevelopment conditions equals 41.9 ft, which is 9.3 percent of the range of measured water levels in the flow system. The RMSE of simulated water-level drawdowns for all units equals 9.3 ft for drawdowns from predevelopment until July 1, 1979 and 14.1 ft for drawdowns from predevelopment until April 15, 1995. Simulated ground-water discharge to streams generally is less than what was estimated for water year 1995 and simulated median ground-water residence times are shorter than the estimated minimum residence times for 6 out of 12 wells.

Calibrated values of horizontal hydraulic conductivities range from 0.003 foot per day (ft/d) for confining units to 25 ft/d for aquifers. Vertical hydraulic conductivities range from 0.0003 to 0.25 ft/d. Specific storage was estimated to be 3.5×10^{-6} per foot for confined aquifers and 3.1×10^{-5} per foot for fully saturated confining units. A sensitivity analysis showed that simulated water levels and fluxes are sensitive to vertical hydraulic conductivities of confining units, and in particular the Upper and Lower confining units, which are regional in extent. Other parameters to which simulated results are sensitive include ground-water recharge and the conductances of off-shore general-head-boundary cells near SUBASE Bangor.

During predevelopment, about 60 percent of long-term average recharge discharged from the ground-water flow system to streams, springs, and ground-water seeps, and the remainder entered deeper units and eventually discharged off-shore to Puget Sound. During Delta Pier construction, water-level decreases led to a decrease in off-shore discharge to Hood Canal. Water levels largely recovered after the completion of the drydock in 1980, although April 1995 water levels in the Sea-level aquifer near Delta Pier continued to be more than 30 ft below those of predevelopment. Southeast of SUBASE Bangor, the model simulated a cone of depression that developed between predevelopment and April 1995 in the Sea-level aquifer near the Bucklin Ridge well (25N/01E-10N01). This well is part of the Silverdale Water District No. 16 public-supply system.

Ground-water pumping by most public-supply systems inside the active-node model boundaries had been relatively constant between 1980 and 1995, with some systems showing overall increases or decreases. The exception is Silverdale Water District No. 16, for which ground-water pumpage steadily increased between 1984 and 1995 due to an expansion of the service area and the addition of wells. Excluding the gravity flow from off-shore pressure reduction wells on SUBASE Bangor and one-half of the pumpage from three wells located close to model boundaries, ground-water pumpage in 1995 averaged about 800 gal/min on-base and 1,800 gal/min off-base. On the basis of population-growth estimates of 2.3 percent per year, off-base ground-water pumpage was estimated to increase to about 3,200 gal/min by 2020. During the same time period, ground-water pumpage was estimated to increase to 1,400 gal/min on SUBASE Bangor.

To evaluate how future ground-water pumping may affect the ground-water flow system on and near SUBASE Bangor, four pumping alternatives were simulated ranging from no change in 1995 rates of pumping (alternative 1), to doubling the rates (alternative 2), and to using rates of pumping projected for 2020 (alternatives 3 and 4). For alternative 3, it was assumed that one new well would be installed on SUBASE Bangor and for alternative 4, it was assumed that two additional wells would be added off-base. Ground-water recharge was assumed equal to the long-term average recharge used to simulate predevelopment conditions. For each alternative, the flow-system conditions were simulated that would ultimately occur provided sufficient time lapsed for the system to equilibrate to the imposed stresses; how much time this would take is unknown.

Compared to predevelopment conditions, all simulated alternatives resulted in reduced ground-water discharge to Puget Sound and to springs, seeps, and streams. In addition, all alternatives also resulted in water-level decreases compared to 1995. For example, if 1995 rates of ground-water pumping were to continue in the future (alternative 1), projected water-level drawdowns on SUBASE Bangor would be less than 10 ft in the Vashon and Sea-level aquifers compared to April 1995 conditions. Off-base, however, projected drawdowns in excess of 20 and 60 ft were simulated in the Vashon aquifer about 3 miles northeast and about 1.5 miles east of the base, respectively. In the Sea-level aquifer between Dyes Inlet and Liberty Bay, projected drawdowns in excess of 20 ft were simulated in the general vicinity of well fields of the Silverdale Water District No. 16 and Island Lake water systems. Alternatives 2, 3, and 4 generated larger projected drawdowns than alternative 1 throughout the study area.

An evaluation of the zones of recharge of public-supply wells for the different alternatives showed that source waters for wells located on SUBASE Bangor predominantly originate on-base for all alternatives. Source waters for most off-base public-supply wells originate off-base, but some source waters of selected off-base public-supply wells originate on-base. The relative contributions and traveltimes of these on-base source waters were evaluated in more detail for alternative 1, to determine if on-base ground-water contamination poses a risk to off-base public water-supply systems. Based on the evaluation, this risk is very small. For example, on-base source waters for all but two of the six off-base public-supply wells for which zones of recharge extend onto SUBASE Bangor would take more than 1,300 years to reach the wells. The long traveltime means that if any possible contamination were to escape SUBASE Bangor and not naturally attenuate to harmless substances, it would take a long time to reach the off-base public-supply wells. In addition, the possible contamination would be greatly diluted as it blended with recharge from other areas. On-base source waters for the two other public-supply wells, Dawn Park and Spirit Ridge No. 4, have median traveltimes from the source to the wells of 164 and 79 years, respectively. However, only the Dawn Park well receives a significant portion of its source water from inside the base boundaries and the on-base zone of recharge of the Spirit Ridge No. 4 well may be an artifact of the model simulation. Even if the simulated zone of recharge is correct, however, the risk of contamination to the Spirit Ridge No. 4 well is very small.

The zone of recharge of the Dawn Park well includes a small area that is part of the OU8 contaminant plume that crosses the southeastern boundary of SUBASE Bangor. Recent information shows that this plume was stable or decreasing in size in 2000 as a result of naturally occurring biodegradation and the plume continues to be monitored to verify that natural attenuation is progressing. As long as containment and remediation of the OU8 contaminant plume continues, the risk is minimal that contaminants originating on SUBASE Bangor would ever reach the Dawn Park well. If contamination were to escape the OU8 contaminant plume, the simulation indicates it would take more than 120 years to reach the well. During that time, contaminant concentrations would be reduced by natural attenuation.

The potential for advective transport of on-base ground-water contamination to off-base wells also was evaluated for an array of 44 hypothetical wells open to the Sea-level aquifer and located southwest of SUBASE Bangor. For all alternatives, zones of recharge for the hypothetical wells extend onto SUBASE Bangor, but only for alternative 1 does source water originate in an area of known ground-water contamination, the Site F contaminant plume. Remediation of the plume started in 1994 and by 2000, it had been contained by a combination of extraction and reintroduction wells. Calculations show that if contaminants were to escape the plume and migrate by advection with no dispersion and no retardation, it would require a minimum of about 240 years for contaminants in the Site F plume to reach 12 out of the 44 hypothetical wells. Significant dilution and natural attenuation processes during the long period of travel would substantially reduce contaminant concentrations before source water reached the hypothetical wells.

The potential for saltwater encroachment that could ultimately occur was estimated for each alternative by computing the altitudes of saltwater interfaces from simulated water levels and the Ghyben-Herzberg principle. The altitudes of the interfaces were compared to top and bottom altitudes of the Sea-level and Deep aquifers to determine if the aquifers would contain freshwater, saltwater, or a mixture of both at an unknown time in the future. This approach for determining the potential for saltwater encroachment has considerable uncertainty associated with it and results should be interpreted with caution.

If 1995 rates of ground-water pumping continue in the future (alternative 1), saltwater encroachment is not expected to occur in the Sea-level aquifer near Delta Pier. However, if 1995 rates are doubled (alternative 2), encroachment may occur. Two different distributions of estimated 2020 ground-water pumpage (alternatives 3 and 4) result in different potential saltwater encroachment patterns. Both alternatives show the potential for saltwater encroachment in the Sea-level aquifer near Delta Pier, but the potential is greater for alternative 4 than 3. Alternative 4 indicates the possibility of saltwater encroachment in the vicinity of a hypothetical new well south of SUBASE Bangor, through upconing of saltwater from the Deep aquifer below. Additional potential for saltwater encroachment in the Sea-level aquifer is indicated in parts of the study area where less is known about the geometry of hydrogeologic units and consequently results are less certain in those areas. It includes areas along Dyes Inlet, Liberty Bay, and Port Orchard for all alternatives, and near the Bucklin Ridge well for alternatives 2 and 3. All alternatives indicated the potential for large-scale saltwater encroachment in the Deep aquifer southeast and south of SUBASE Bangor and smaller-scale encroachment north of and on SUBASE Bangor.

The ground-water flow model documented in this report was designed to gain insight into ground-water flow on a regional scale and it should only be used for this purpose. The model is a representation of the actual flow system and this representation has errors associated with it. Errors in the calibrated model were significant, which may have resulted in errors in the simulated effects of alternatives of future ground-water pumping, including water levels, water-level drawdowns, times of travel from zones of recharge to discharging wells, locations of zones of recharge, and patterns of potential saltwater encroachment.

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Appendix 1. Physical and hydrologic data for wells used in this study that were not used in the hydrogeology study by Kahle (1998), SUBASE Bangor and vicinity, Kitsap County, Washington

[**Well No.**: See figure 3 for explanation of well-numbering system. Latitudes and longitudes of the wells are on file with the U.S. Geological Survey. **Hydrogeologic unit**: Qva, Vashon aquifer; QC1pi, Permeable interbeds; QA1, Sea-level aquifer. Hydrogeologic designations are from Kahle (1998). **Primary use of water**: P, public supply; D, dewater; H, domestic. **Type of log available**: D, driller's. **Abbreviations**: gal/min, gallons per minute; ft/d, feet per day; –, not reported]

Well No.	Navy identifier	Hydro-geologic unit	Altitude of land surface (feet)	Depth of well (feet)	Discharge (gal/min)
25N/01E-03P01	([1])	Qva	280	270	–
25N/01E-03R01	([1])	Qva	345	238	24
25N/01E-16R01	([1])	QC1pi	200	216	–
25N/01E-18E01	([1])	QC1pi	505	366	20
25N/01W-01A03	([1])	QA1	220	213	10
26N/01E-18N03	WRP-5	QA1	10	184.5	1,000
26N/01W-36Q01	([1])	QA1	130	144	7

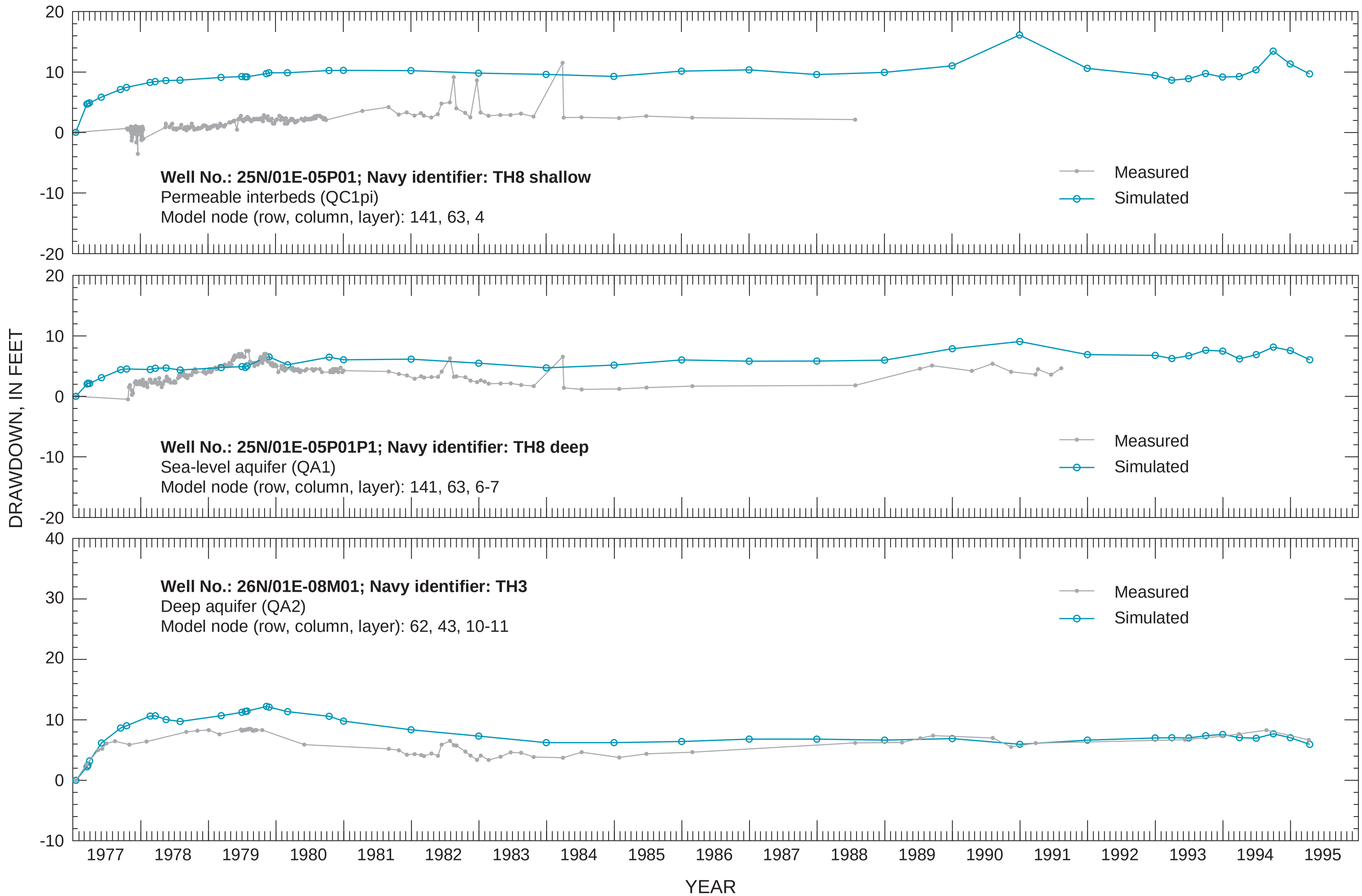
Well No.	Drawdown (feet)	Time of drawdown reading since start of pumping (hours)	Estimated horizontal hydraulic conductivity (ft/d)	Primary use of water	Type of log available
25N/01E-03P01	–	–	–	P	D
25N/01E-03R01	10	3	61	P	D
25N/01E-16R01	–	–	–	P	D
25N/01E-18E01	0.3	1	1,200	P	D
25N/01W-01A03	1	2	560	H	D
26N/01E-18N03	20	6	200	D	D
26N/01W-36Q01	20	4	16	H	D

[1]Site not located on SUBASE Bangor.

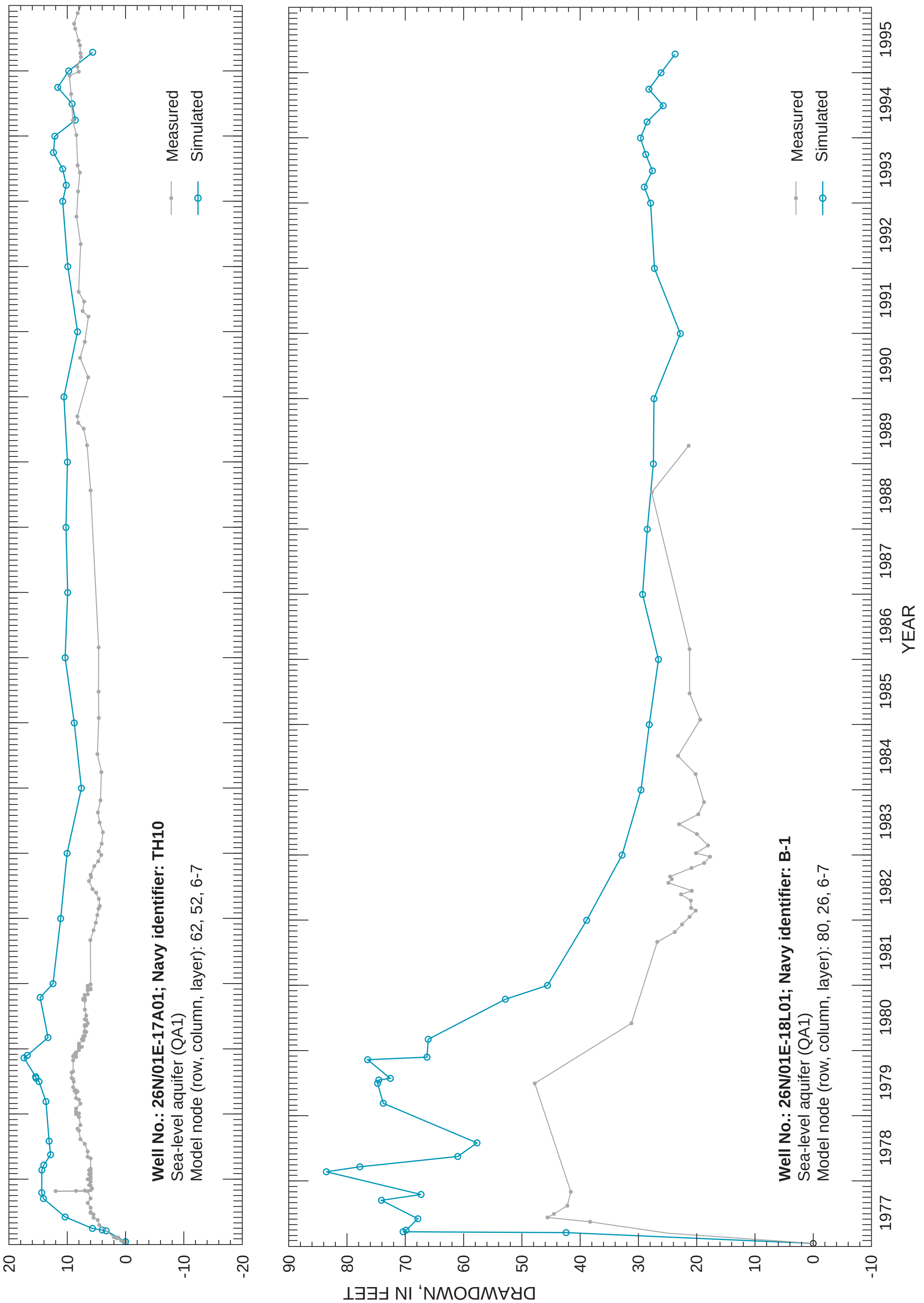
Appendix 2. Original altitude of land surface for wells as used in the hydrogeology study by Kahle (1998), modified altitude of land surface as used in this study, and the difference between the modified and original altitude of land surface, SUBASE Bangor, Kitsap County, Washington

[**Well No.**: See figure 3 for explanation of well-numbering system. Latitudes and longitudes of the wells are on file with the U.S. Geological Survey]

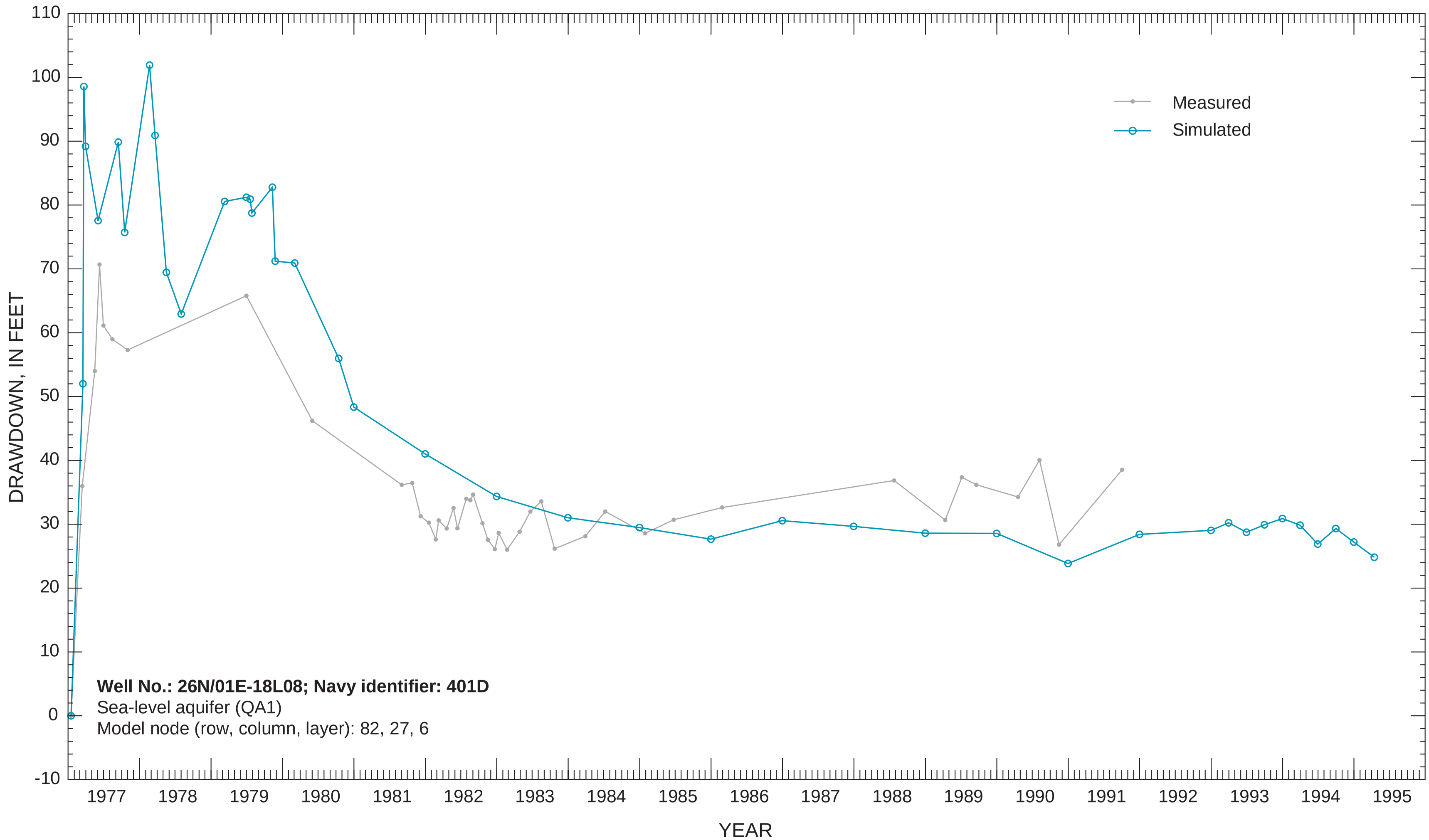
Well No.	Navy identifier	Altitude of land surface (feet above sea level)		
		Original	Modified	Modified minus original
25N/01E-06H01	MW-3	297	339.4	42.4
25N/01E-06J02	MW-6	250	268.4	18.4
26N/01E-06R01	50-MW-2	10	12.8	2.8
26N/01E-08M01	TH3	205	220.9	15.9
26N/01E-17N01	TH4A	363	362.9	-0.1
26N/01E-18F01	B-8	10	9.3	-0.7
26N/01E-18K01	504	210	198.9	-11.1
26N/01E-18L01	B-1	14	13.5	-0.5
26N/01E-18L02	B-7	123	119.9	-3.1
26N/01E-18L07	401 A	17	17.2	0.2
26N/01E-18L07P1	401 A	17	17.2	0.2
26N/01E-18L08	401 D	15	14.2	-0.8
26N/01E-18N01	B-2	14	15.2	1.2
26N/01E-18N02	B-5	50	48.9	-1.1
26N/01E-18P03	501	90	89.4	-0.6
26N/01E-18P04	502	130	129.4	-0.6
26N/01E-18P05	Old 503	175	173.0	-2.0
26N/01E-18P06	New 503	175	173.0	-2.0
26N/01E-19C01	B-6 shallow	95	99.9	4.9
26N/01E-19C01P1	B-6 deep	95	99.9	4.9
26N/01E-19F01	TH5 shallow	134	133.9	-0.1
26N/01E-19F01P1	TH5 deep	134	133.9	-0.1
26N/01E-19Q01	1B-2	295	302.6	7.6
26N/01E-19Q02	1A-1	295	302.7	7.6
26N/01E-19Q03	1C-1	305	298.7	-6.3
26N/01E-20R03	TH9	450	454.2	4.2
26N/01E-29N01	TH7	365	368.4	3.4
26N/01E-30B01P1	TH12 shallow	270	264.8	-5.2
26N/01E-30B01P2	TH12 medium	270	264.8	-5.2
26N/01E-30B01P3	TH12 deep	270	264.8	-5.2
26N/01E-31A03	2C-1	340	355.3	15.3
26N/01E-31B02	2B-2	350	344.5	-5.5
26N/01E-31B03	2A-1	350	345.3	-4.7
26N/01E-31C01P1	F-MW43S	340	361.5	21.5
26N/01E-31C01P2	F-MW43	340	361.5	21.5
26N/01E-31E01	TH2 shallow	340	353.9	13.9
26N/01E-31E01P1	TH2 deep	340	353.9	13.9
26N/01E-31R01	505 (TH18)	410	429.9	19.9
26N/01W-24A01	B-4	80	75.2	-4.8



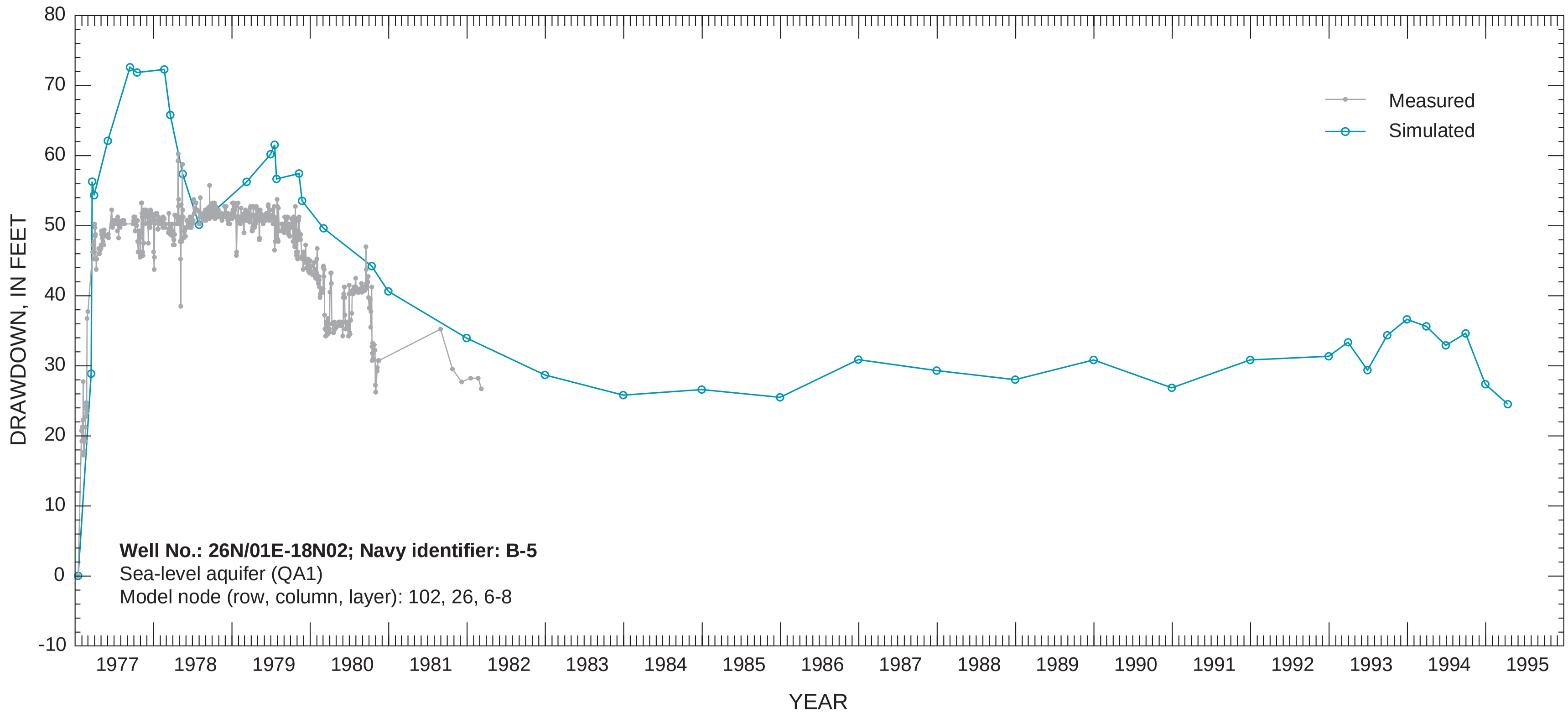
Appendix 3. Graphs showing simulated and measured drawdowns since predevelopment in wells open to selected aquifers, SUBASE Bangor and vicinity, Kitsap County, Washington.



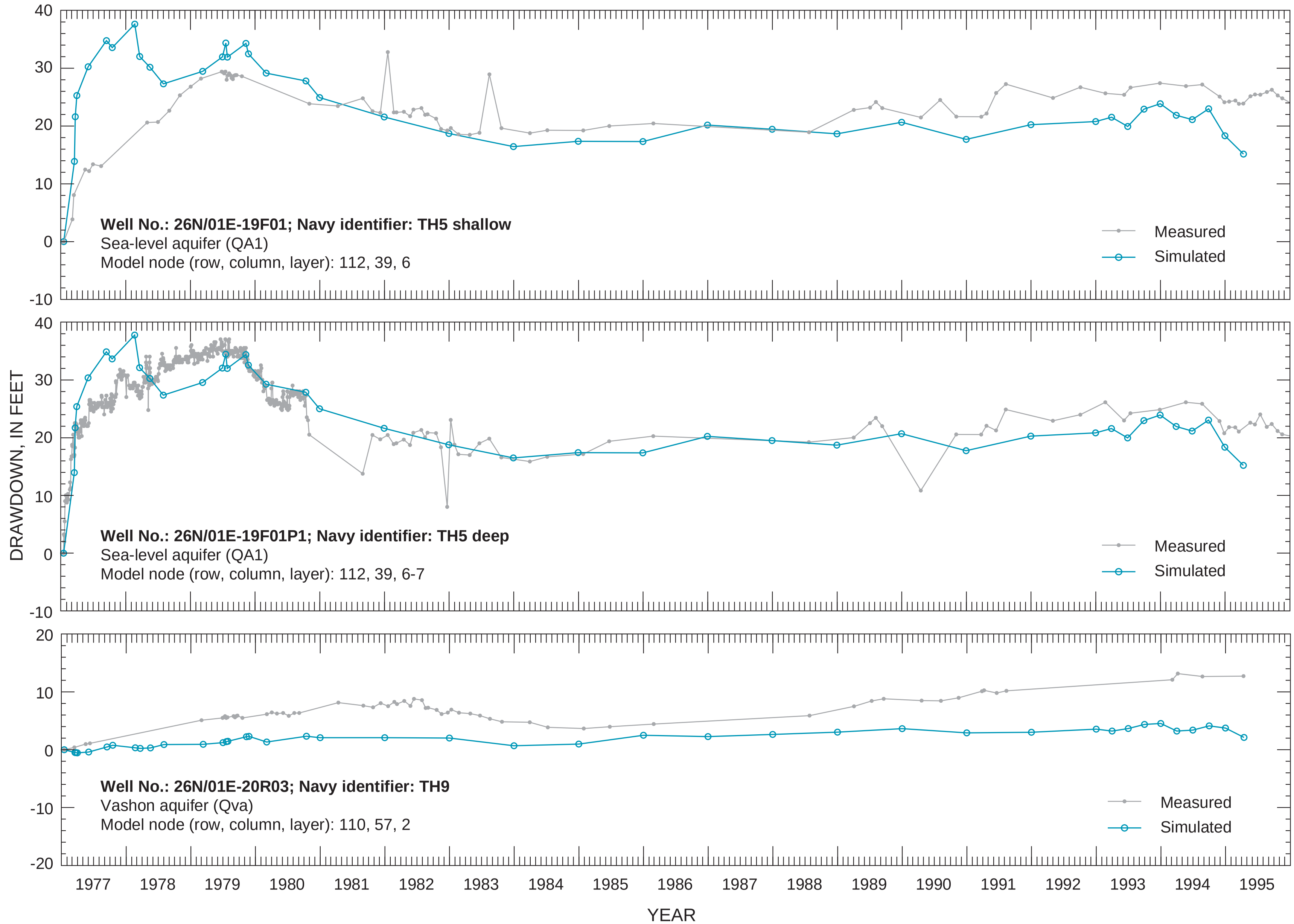
Appendix 3.—*Continued.*



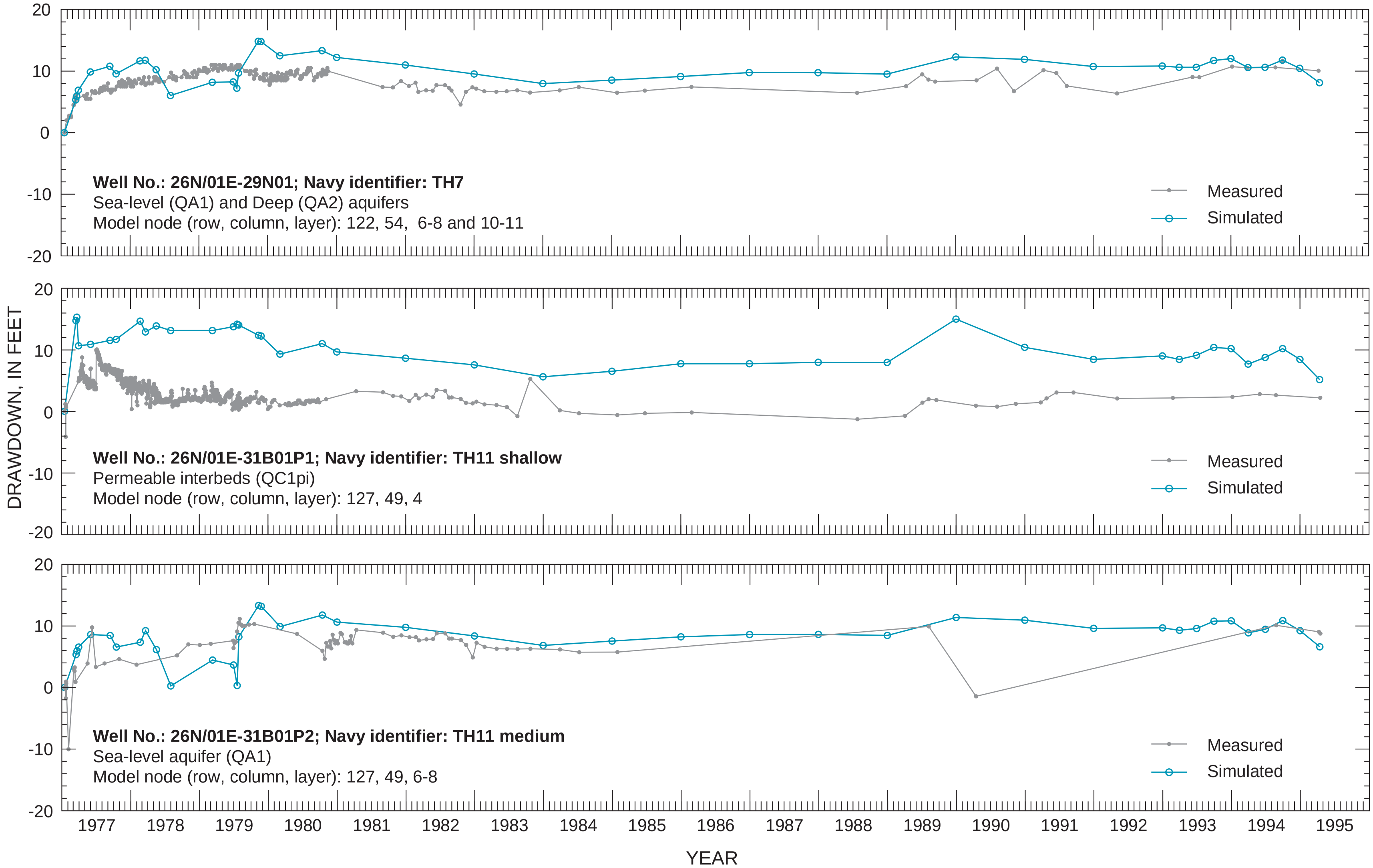
Appendix 3.—*Continued.*



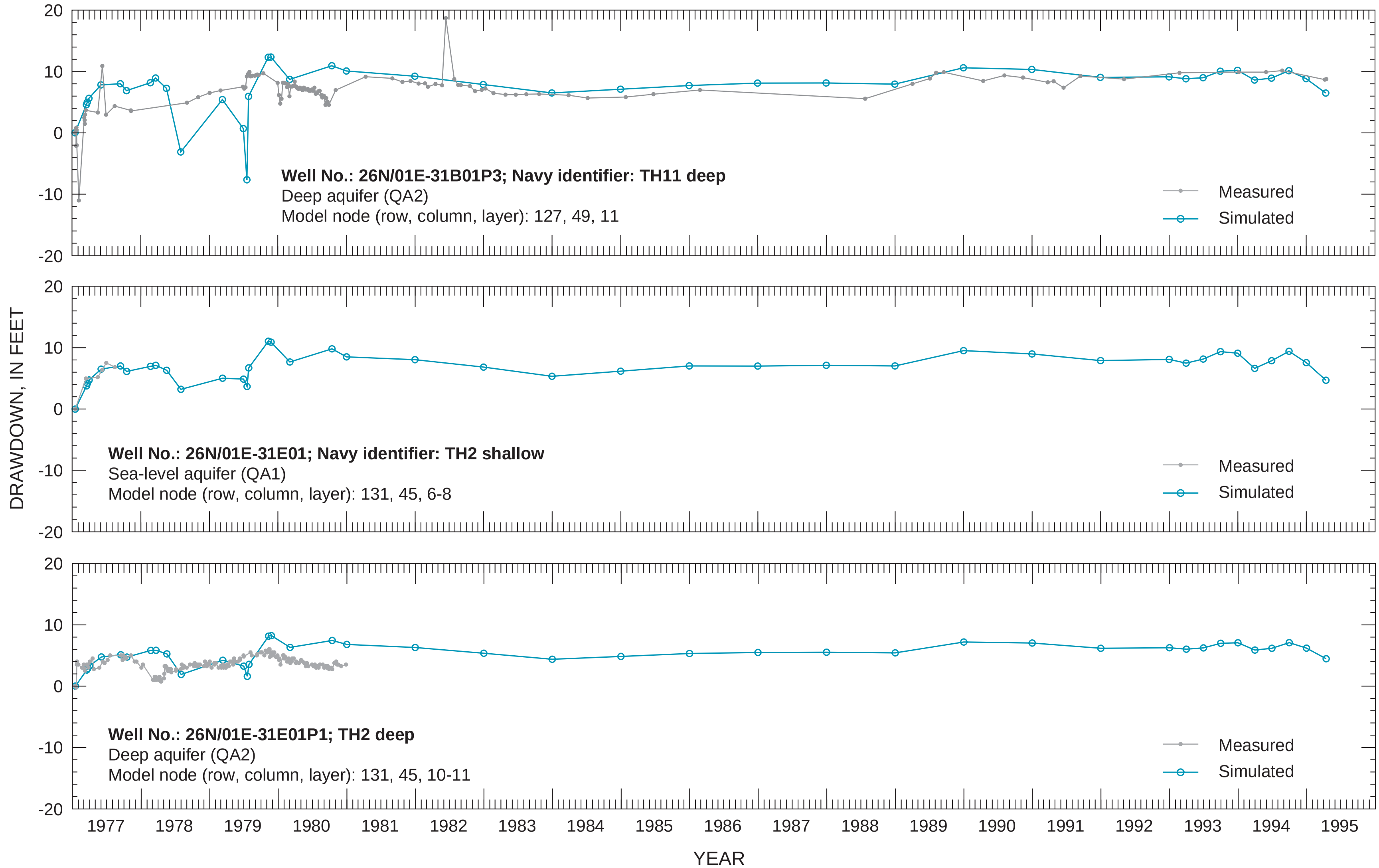
Appendix 3.—*Continued.*



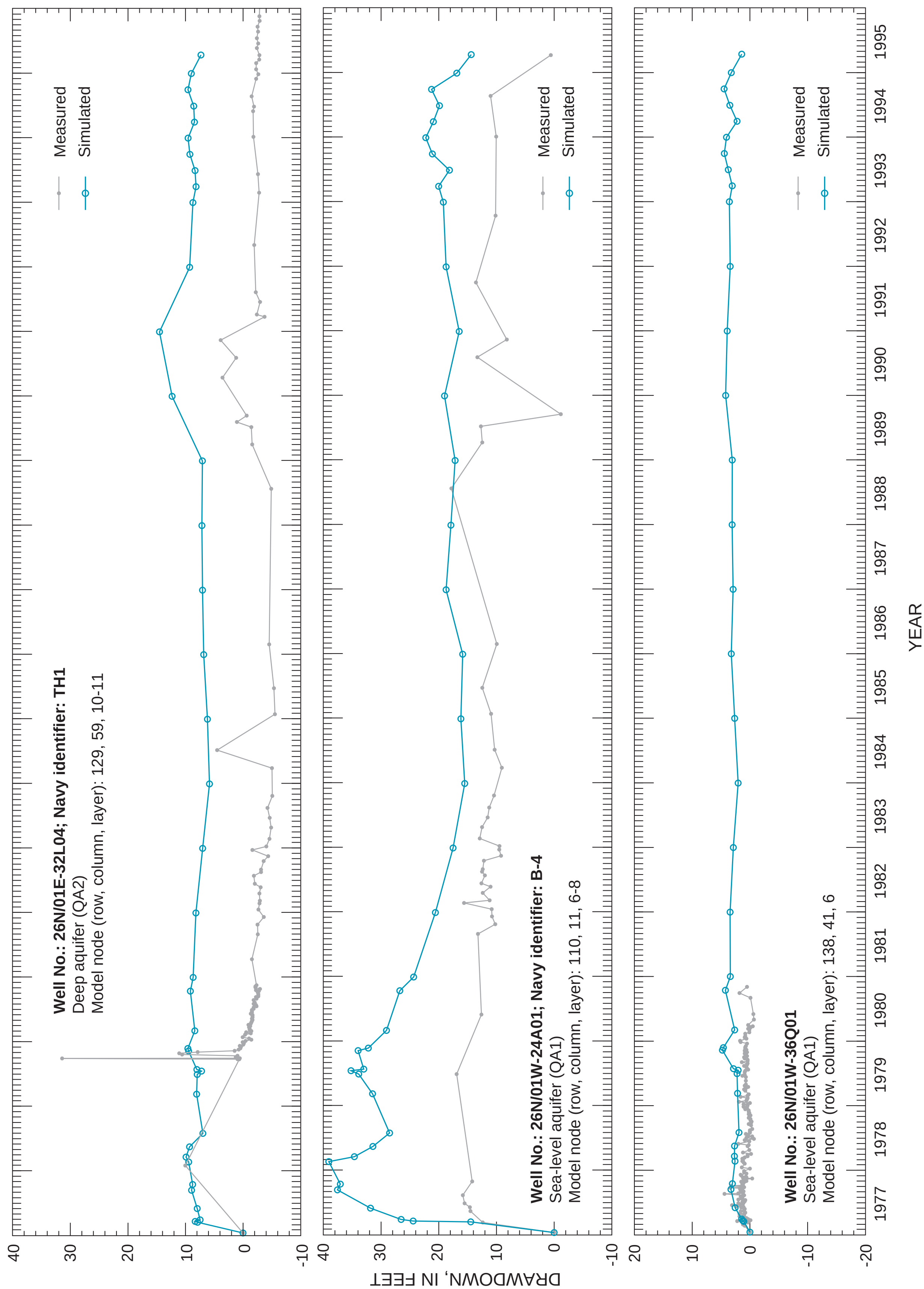
Appendix 3.—*Continued.*



Appendix 3.—*Continued.*



Appendix 3.—*Continued.*



Appendix 3.—*Continued.*

Appendix 4. Simulated and measured drawdowns from predevelopment until July 1, 1979, and the difference between simulated and measured drawdowns, SUBASE Bangor and vicinity, Kitsap County, Washington

[**Well No.**: See figure 3 for explanation of well-numbering system. **Navy identifier**: –, site not located on SUBASE Bangor. **Drawdown for July 1, 1979**: A positive drawdown indicates a water-level decrease from predevelopment until July 1, 1979]

Well No.	Navy identifier	Model node (row, column, layer)	Drawdown for July 1, 1979 (feet)		
			Simulated	Measured	Simulated minus measured
Wells open to the Vashon aquifer (Qva)					
26N/01E-17N02	TH4B	87, 46, 2	1.2	9.8	-8.6
26N/01E-20R03	TH9	110, 57, 2	1.2	5.5	-4.3
Wells open to the Permeable interbeds (QC1pi)					
25N/01E-05P01	TH8 shallow	141, 63, 4	9.2	2.4	6.8
26N/01E-30B01P1	TH12 shallow	117, 44, 4	17.9	20.8	-2.9
26N/01E-31B01P1	TH11 shallow	127, 49, 4	13.7	0.6	13.1
Wells open to the Sea-level aquifer (QA1)					
25N/01E-05P01P1	TH8 deep	141, 63, 6-7	4.9	6.9	-2.0
26N/01E-17A01	TH10	62, 52, 6-7	14.8	8.9	5.9
26N/01E-18F01	B-8	71, 26, 6-8	48.8	35.4	13.4
26N/01E-18K01	504	87, 38, 7	66.1	68.9	-2.8
26N/01E-18L01	B-1	80, 26, 6-7	74.7	47.7	27.0
26N/01E-18L02	B-7	77, 31, 6-7	61.6	59.7	1.9
26N/01E-18L08	401 D	82, 27, 6	81.2	65.7	15.5
26N/01E-18N01	B-2	107, 22, 6-8	51.1	51.7	-0.6
26N/01E-18N02	B-5	102, 26, 6-8	60.2	50.9	9.3
26N/01E-18P03	501	104, 32, 6-7	73.3	64.2	9.1
26N/01E-18P05	Old 503	95, 36, 6-7	61.3	66.7	-5.4
26N/01E-19C01	B-6 shallow	110, 34, 8	40.2	51.9	-11.7
26N/01E-19D01	B-3	109, 19, 6-8	43.2	51.1	-7.9
26N/01E-19F01	TH5 shallow	112, 39, 6	31.9	29.4	2.5
26N/01E-19F01P1	TH5 deep	112, 39, 6-7	32.0	35.0	-3.0
26N/01E-19Q02	1A-1	116, 45, 6-8	14.6	16.9	-2.3
26N/01E-19Q03	1C-1	115, 45, 6-8	13.8	18.1	-4.3
26N/01E-30B01P2	TH12 medium	117, 44, 6-8	16.6	23.8	-7.2
26N/01E-30D01	TH6	119, 37, 6-8	16.1	21.1	-5.0
26N/01E-31B01P2	TH11 medium	127, 49, 6-8	3.6	6.4	-2.8
26N/01W-24A01	B-4	110, 11, 6-8	33.9	16.9	17.0
26N/01W-25B02	TH14 shallow	122, 21, 6-8	9.1	0.3	8.8
26N/01W-36Q01	–	138, 41, 6	2.2	0.9	1.3

Appendix 4. Simulated and measured drawdowns from predevelopment until July 1, 1979, and the difference between simulated and measured drawdowns, SUBASE Bangor and vicinity, Kitsap County, Washington—*Continued*

Well No.	Navy identifier	Model node (row, column, layer)	Drawdown for July 1, 1979 (feet)		
			Simulated	Measured	Simulated minus measured
Wells open to the Deep aquifer (QA2)					
26N/01E-08M01	TH3	62, 43, 10-11	11.3	8.3	3.0
26N/01E-19C01P1	B-6 deep	110, 34, 10-11	35.5	42.2	-6.7
26N/01E-30B01P3	TH12 deep	117, 44, 10	16.6	18.3	-1.7
26N/01E-31B01P3	TH11 deep	127, 49, 11	0.7	7.4	-6.7
26N/01E-31E01P1	TH2 deep	131, 45, 10-11	3.2	4.8	-1.6
26N/01W-25B02P1	TH14 deep	122, 21, 11	8.0	-1.3	9.3
Wells open to multiple aquifers					
26N/01E-17N01	TH4A	88, 46, 6-7 and 10-11	30.0	50.5	-20.5
26N/01E-29N01	TH7	122, 54, 6-8 and 10-11	8.2	10.3	-2.1

Appendix 5. Simulated and measured drawdowns from predevelopment until April 15, 1995, and the difference between simulated and measured drawdowns, SUBASE Bangor and vicinity, Kitsap County, Washington

[**Well No**.: See figure 3 for explanation of well-numbering system. **Navy identifier**: –, site not located on SUBASE Bangor. **Drawdown for April 15, 1995**: A positive drawdown indicates a water-level decrease from predevelopment until April 15, 1995]

Well No.	Navy identifier	Model node (row, column, layer)	Drawdown for April 15, 1995 (feet) Simulated	Measured	Simulated minus measured
Wells open to the Vashon till confining unit (Qvt)					
26N/01E-32Q01	–	133, 62, 1	0.1	3.6	-3.5
Wells open to the Vashon aquifer (Qva)					
25N/01E-03E03	–	133, 78, 2	80.7	[1]16.0	64.7
25N/01E-03E04	–	133, 77, 2	46.2	[1]18.8	27.4
25N/01E-18J03	–	162, 64, 2	1.2	-2.8	4.0
25N/01E-20L02	–	171, 73, 2	0.5	-23.4	23.9
25N/01W-12R02	–	158, 52, 2	0.4	-8.5	8.9
26N/01E-20R03	TH9	110, 57, 2	2.1	12.7	-10.6
27N/01E-34L01	–	34, 57, 2	-0.9	-0.3	-0.6
27N/01E-34L02	–	34, 57, 2	-0.9	-1.5	0.6
Wells open to the Upper confining unit (QC1)					
26N/01E-26Q02	–	111, 87, 3	0.6	-0.5	1.1
Wells open to the Permeable interbeds (QC1pi)					
25N/01E-05J01	–	138, 66, 4	16.8	[2]4.2	12.6
25N/01E-08Q03	–	152, 68, 4	9.4	0.6	8.8
25N/01E-10A03	–	138, 88, 4	4.4	[1]11.1	-6.7
25N/01E-20F01	–	167, 70, 4	42.6	[1]14.3	28.3
25N/01E-22F02	–	162, 90, 4	37.0	[1]23.7	13.3
26N/01E-30B01P1	TH12 shallow	117, 44, 4	6.0	14.4	-8.4
26N/01E-30L01	SWFPAC 6610	125, 45, 4	5.1	13.4	-8.3
26N/01E-31B01P1	TH11 shallow	127, 49, 4	5.1	2.2	2.9
Wells open to the Sea-level aquifer (QA1)					
25N/01E-01N01	–	130, 101, 6	1.2	[2]9.5	-8.3
25N/01E-06E01	–	143, 49, 6	1.5	1.6	-0.1
25N/01E-07D01	–	149, 50, 6	-1.9	2.8	-4.7
25N/01E-10N01	–	146, 82, 6-7	46.9	[1]80.4	-33.5
26N/01E-02L05	–	41, 71, 8	27.8	18.0	9.8
26N/01E-09C02	–	51, 52, 6	3.8	13.5	-9.7
26N/01E-17A01	TH10	62, 52, 6-7	5.6	7.8	-2.2
26N/01E-18F01	B-8	71, 26, 6-8	16.8	19.0	-2.2
26N/01E-18K01	504	87, 38, 7	54.5	33.5	21.0
26N/01E-18L02	B-7	77, 31, 6-7	22.9	29.7	-6.8

Appendix 5. Simulated and measured drawdowns from predevelopment until April 15, 1995, and the difference between simulated and measured drawdowns, SUBASE Bangor and vicinity, Kitsap County, Washington—*Continued*

Well No.	Navy identi-fier	Model node (row, column, layer)	Drawdown for April 15, 1995 (feet)		
			Simulated	Measured	Simulated minus measured
Wells open to the Sea-level aquifer (QA1)—*Continued*					
26N/01E-18P03	501	104, 32, 6-7	30.8	31.2	-0.4
26N/01E-18P04	502	101, 34, 6-8	33.9	30.6	3.3
26N/01E-19C01	B-6 shallow	110, 34, 8	18.3	27.8	-9.5
26N/01E-19D01	B-3	109, 19, 6-8	18.1	28.1	-10.0
26N/01E-19F01	TH5 shallow	112, 39, 6	15.1	23.9	-8.8
26N/01E-19F01P1	TH5 deep	112, 39, 6-7	15.2	21.8	-6.6
26N/01E-19Q02	1A-1	116, 45, 6-8	11.3	6.2	5.1
26N/01E-19Q03	1C-1	115, 45, 6-8	12.1	9.1	3.0
26N/01E-30B01P2	TH12 medium	117, 44, 6-8	10.4	12.7	-2.3
26N/01E-30D01	TH6	119, 37, 6-8	5.6	11.3	-5.7
26N/01E-31A03	2C-1	126, 51, 7-8	7.0	11.8	-4.8
26N/01E-31B01P2	TH11 medium	127, 49, 6-8	6.6	8.9	-2.3
26N/01E-31B03	2A-1	126, 50, 6-8	6.9	5.8	1.1
26N/01W-24A01	B-4	110, 11, 6-8	14.4	0.5	13.9
26N/01W-25B02	TH14 shallow	122, 21, 6-8	3.3	5.1	-1.8
26N/01W-25G01	–	124, 20, 6	2.8	0.6	2.2
Wells open to the Deep aquifer (QA2)					
26N/01E-08M01	TH3	62, 43, 11	5.9	6.7	-0.8
26N/01E-19C01P1	B-6 deep	110, 34, 10-11	16.3	25.2	-8.9
26N/01E-19Q01	1B-2	116, 45, 11	10.9	2.6	8.3
26N/01E-30B01P3	TH12 deep	117, 44, 10	10.2	10.4	-0.2
26N/01E-31B01P3	TH11 deep	127, 49, 11	6.5	8.7	-2.2
26N/01E-32L04	TH1	129, 59, 10-11	7.3	-2.8	10.1
26N/01W-25B02P1	TH14 deep	122, 21, 11	4.1	-0.7	4.8
Wells open to multiple aquifers					
26N/01E-17N01	TH4A	88, 46, 6-7 and 10-11	15.5	33.4	-17.9
26N/01E-29N01	TH7	122, 54, 6-8 and 10-ll	8.1	10.0	-1.9

[1]Actual drawdown may be smaller by more than 5 feet.

[2]Actual drawdown may be smaller by up to 5 feet.

van Heeswijk and Smith

Simulation of the Ground-Water Flow System, Naval Submarine Base Bangor, Washington

WRIR 02-4261