Hydrogeologic Framework and Numerical Simulation of Groundwater Flow in Bellevue, Washington

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A report prepared in partial fulfillment of the
requirements for the degree of

Master of Science
Earth and Space Sciences: Applied Geosciences

University of Washington

May 2017

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MESSAGe Technical Report Number: 054

Abstract

Though the city of Bellevue, Washington is the fifth-most populous and fourth-fastest growing community in Washington, groundwater studies encompassing the city are noticeably few. Population growth, urban development, and recent drought have highlighted the need for a more detailed and comprehensive understanding of Bellevue's groundwater system. In response, this study developed a conceptual hydrogeologic model and numerical groundwater flow model of Bellevue and its immediate vicinity to provide a basic understanding of the groundwater flow system. The numerical model was implemented in MODFLOW-NWT, and focuses on the unconsolidated sediments present in the study area. The study area covers the Bellevue city limits and adjacent areas between Lake Sammamish and Lake Washington.

Simulation of the groundwater flow system indicates that precipitation falling on the study area is the only significant source of recharge to the unconsolidated sediments. Approximately half of all recharge enters the groundwater system directly, while the other half runs off into surface water bodies before leaking into the groundwater system. All kettle lakes in the study area lose water to the groundwater system under steady state conditions. Most of the study area is drained by streams occupying the center of the study area which deliver water to Lake Washington.

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1. Introduction

Interest in the groundwater system of Bellevue, Washington has steadily increased in recent years because of rapid population growth and development. Development has highlighted a need to understand the occurrence and movement of groundwater throughout the area to help resolve challenges related to groundwater management, land use management, stormwater management, water availability, and water quality. Information on the Bellevue groundwater system is very sparse compared to many other areas in Washington because the most common driver for hydrogeologic investigations, reliance on groundwater as a potable water supply source, has not been historically present in Bellevue.

This study was undertaken to integrate existing groundwater data into a comprehensive conceptual hydrogeologic model of groundwater flow in Bellevue and vicinity, and to develop a basic understanding of the regional groundwater flow system. Specific objectives developed to reach this goal included:

- Describe the hydrogeologic framework of the groundwater system
- Identify stresses (sources and sinks) on the groundwater system
- Construct a numerical groundwater flow model to simulate the operation of the groundwater flow system
- Use the numerical flow model to identify which properties of the groundwater flow system exert the greatest influence over flow
- Identify probable areas of groundwater recharge and groundwater discharge

1.1 Purpose and Scope

This report presents a conceptual hydrogeologic model of the Bellevue groundwater flow system, and the development and application of a numerical model to simulate groundwater flow in the Bellevue groundwater system. Section 2 describes the conceptual hydrogeologic model that serves as the basis for the numerical model. The conceptual hydrogeologic model defines the geometry and hydraulic properties of aquifers and confining beds that make up the groundwater system (hydrogeologic framework), and the processes that provide recharge to and remove discharge from the groundwater system (hydrologic boundaries). Section 3 describes the construction of the numerical model from the conceptual hydrogeologic model. Section 4 describes the calibration of the numerical model to observed water levels. Section 5 discusses limitations of the numerical model to simulate the actual groundwater flow system. Section 6 discusses insights gained from the numerical model into the operation of the groundwater flow system.

1.2 Previous Investigations

A 2015 study completed for the City of Bellevue by Troost Geosciences (Troost Geosciences, 2015) represents the most robust investigation of Bellevue groundwater to date. That study compiled and mapped depth-to-groundwater data throughout Bellevue for incorporation into maps and infiltration studies. Troost Geosciences compiled readily available data from 8,788 subsurface explorations within Bellevue city limits. Groundwater was encountered in 2,862 of those explorations, and over 50% of the data came from explorations within 25 feet of ground surface.

The compiled data were presented as a series of maps depicting discrete water levels as points. Water levels were not interpolated among water level measurements because the geometries of specific aquifers and confining units were not mapped. The study recommended further investigation to characterize the flow system (aquifers and confining units).

1.3 Description of the Study Area

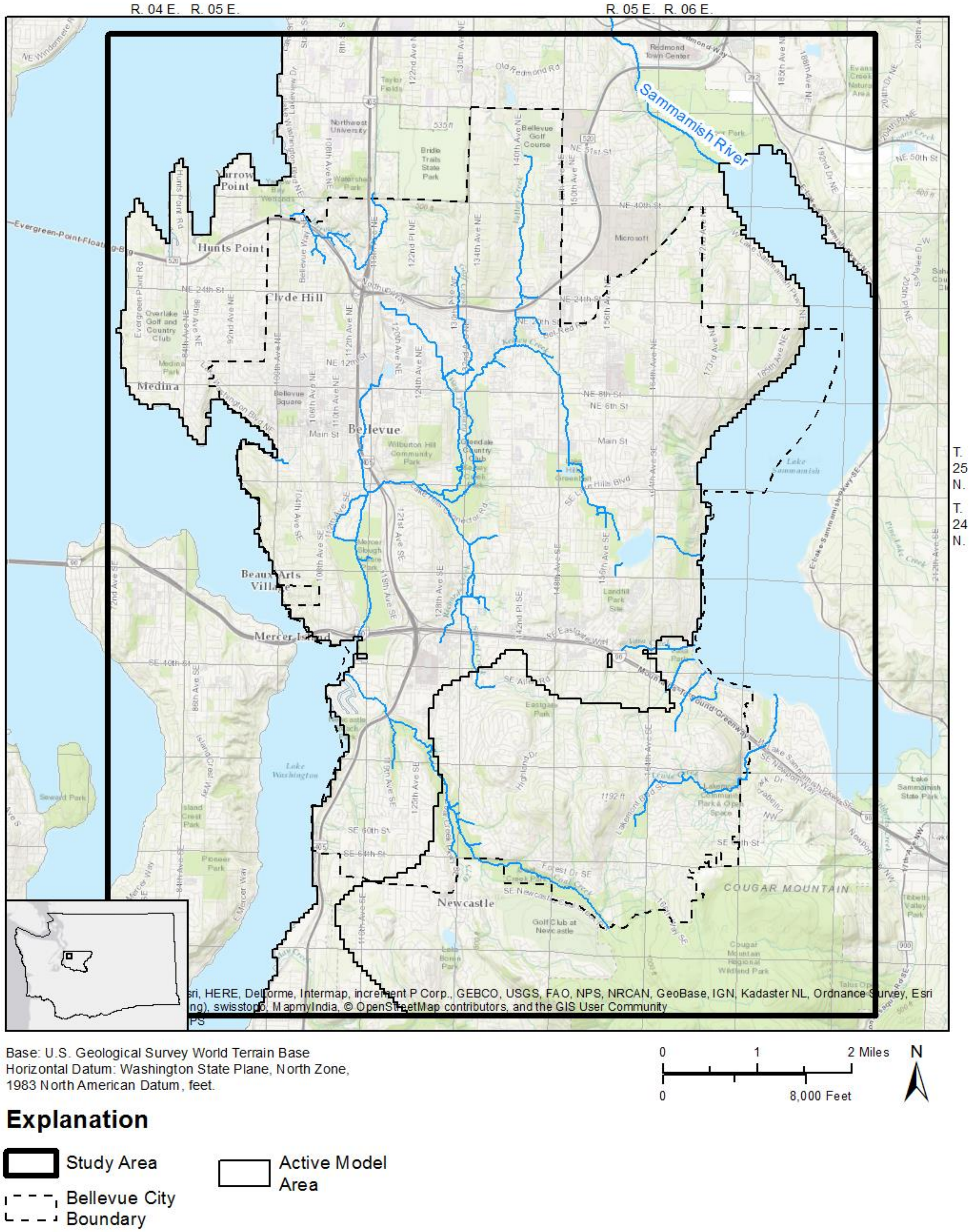
The study area covers about 85 mi^2 in northwestern King County, and includes the City of Bellevue and surrounding areas (Figure 1). The active numerical model domain covers a smaller area (approximately 43 mi^2). Portions of Lake Washington, Lake Sammamish, and Mercer Island are excluded from the active numerical model domain because they have minimal influence on the Bellevue groundwater system. Areas where bedrock is present at ground surface are also excluded. The extent of the study area was chosen to include natural hydrologic boundaries, and lies between Lake Sammamish to the east and Lake Washington to the west. The Newcastle Hills form the southern boundary. The study area terminates approximately 1 mile north of the northernmost extent of Bellevue city limits. The natural northern boundary, the Sammamish River, extends northwesterly from the northeastern corner of the study area. The northern boundary line was not chosen to coincide with the river along its entire length to limit the study focus to the Bellevue vicinity. Instead, the northern boundary is set along an inferred groundwater divide in the highlands west of the Sammamish River.

The study area encompasses portions of two physiographic areas defined by Liesch and others (1963): the Newcastle-Grand Ridge Hills and the Interlake Drift Plain. The southern portion of the study area marks the northwestern extent of the Newcastle-Grand Ridge Hills. The Newcastle Hills are composed of a thin layer of glacial sediments over underlying sedimentary bedrock. Elevations in the hills reach up to 1,176 ft above mean sea level (amsl) and slope down northwards to the Interlake Drift Plain. The glacial and interglacial sediments that compose the Interlake Drift Plain cover the landscape throughout most of the study area, forming a series of north-south oriented highlands interrupted by stream-drained lowlands. Elevations on the drift plain range from 200-500 feet amsl on highlands, to near sea level in lowlands and on the lake shores.

The eastern and western edges of the study area are covered by Lake Sammamish and Lake Washington respectively. Both lakes reside in relatively deep troughs, with Lake Sammamish reaching approximately 30 ft below sea level at its center and Lake Washington reaching over 100 feet below sea level at its center. Several kettle lakes occur on the Interlake Drift Plain in the study area including Phantom Lake, Larson Lake, Swan Lake, and Lake Bellevue. Besides the Sammamish River, which occupies a relatively flat floodplain in the northeast corner of the study area, the landscape is drained by streams that originate in highlands and flow to Lake Sammamish or Lake Washington. All streams but Kelsey Creek are primarily fed by springs emerging from upland hillsides or directly by groundwater flow through streambeds. Several lowlands are occupied by extensive wetland systems, particularly those drained by Mercer Slough and Kelsey Creek.

The study area is mostly urban to suburban, with an estimated 2015 population at 139,820 (United States Census Bureau, 2015). Twenty-seven percent of the study area is listed as developed with high to medium intensity (NRCS, 2011). As of 2008, 46 percent of the total area in the Bellevue city limits was designated as impervious (City of Bellevue, 2016).

A temperate marine climate prevails in the study area. The climate follows a wet season-dry season pattern in which summer and fall are warm and dry, and winter is prolonged, wet, and cool. The study area receives an average of 36.6 inches of rain each year, though rainfall has not followed historical patterns in recent years (City of Bellevue, 2016). Seventy-nine percent of average annual precipitation falls during the winter wet season.



Base: U.S. Geological Survey World Terrain Base
Horizontal Datum: Washington State Plane, North Zone, 1983 North American Datum, feet.

Figure 1. Location of Bellevue and vicinity, Washington

2. Conceptual Model of the Groundwater Flow System

This section presents the conceptual hydrogeologic model that serves as the basis of the numerical groundwater flow model and the methods used to develop each part of the conceptual model. Included in this section are descriptions of the geologic setting, hydrogeologic units, and processes of recharge and discharge from and to the groundwater flow system.

2.1 Geologic Setting

The complex assemblage of unconsolidated sediments present in the Puget Lowland is the result of glacial advances into the Lowland by the Puget Lobe of the Cordilleran ice sheet (Bretz, 1913). Glacial ice occupied the Puget Lowland at least seven times, and likely as many as twelve times, during the Pleistocene Epoch (Troost and Booth, 2008). Ice of the Vashon Stade of the Fraser Glaciation, the most recent glaciation, advanced into the study area approximately 15,000 years ago (Thorson, 1980), and completely covered the landscape under approximately 3,000 ft of ice (Thorson, 1989). With northward drainage through the Strait of Juan de Fuca blocked by ice, surface water bodies coalesced into a large lake as they overfilled with blocked runoff and meltwater from the advancing ice sheet. Troughs located in the present-day locations of Lake Sammamish and Lake Washington were mostly infilled with sediment delivered by streams draining into the ice-front lake and by glacial meltwater (Booth and others, 2012). The ice sheet reached south of Tenino, approximately 60 miles southwest of the study area, at its maximum extent during the Vashon Stade.

The overriding ice scoured the landscape into large drumlin structures and compressed underlying sediments. Sediments of earlier glacial and interglacial periods were extensively reworked and redistributed as ice covered the area. Subglacial meltwater channels also developed while ice occupied the study area. Immense volumes of pressurized water carried through these subglacial channels scoured sediment from the troughs of Lake Washington and Lake Sammamish to depths below the modern-day lake bottoms (Booth, 1994).

Vashon ice began to retreat approximately 13,500 years ago. Scoured subglacial troughs, including Lake Washington and Lake Sammamish, began to fill with proglacial lakes as they were uncovered. These proglacial lakes extended out of the modern-day lake troughs into the lowlands of the study area, leaving lacustrine sediments in inundated locations. As the ice retreated further, a sequence of successive spillways drained the lakes. The Lake Sammamish trough drained through two east-west trending spillways in the study area as they became uncovered: the Eastgate Spillway and the Larson Lake Spillway. The Eastgate and Larson Lake Spillways bisect the study area, and drained the Lake Sammamish trough to the Lake Washington trough until the opening of the Totem Lake Spillway north of the study area (Thorson, 1980). The operation of the Eastgate and Larson Lake Spillways eroded till and advance outwash along the present-day Interstate 90 corridor. Kettle lakes (Phantom Lake, Larson Lake, and Lake Bellevue) dot the drift plain north of the Newcastle Hills where ice blocks calved from the retreating ice sheet became submerged in outwash sediment.

Holocene processes operating since the last glaciation are most pronounced in areas of high relief. Oversteepened slopes along the lakes and stream courses fail regularly, sometimes aided by movement along the Quaternary-aged Seattle Fault Zone which runs along the northern edge of (and is partially responsible for) the Newcastle Hills. Peat and wetland deposits have formed in poorly drained locations, and in locations where early 20th-century lowering of Lake Washington exposed lake-bottom deposits (Troost, 2012). Holocene streams, such as the Sammamish River and Coal Creek, have formed alluvial deposits along their courses.

2.2 Hydrogeologic Units

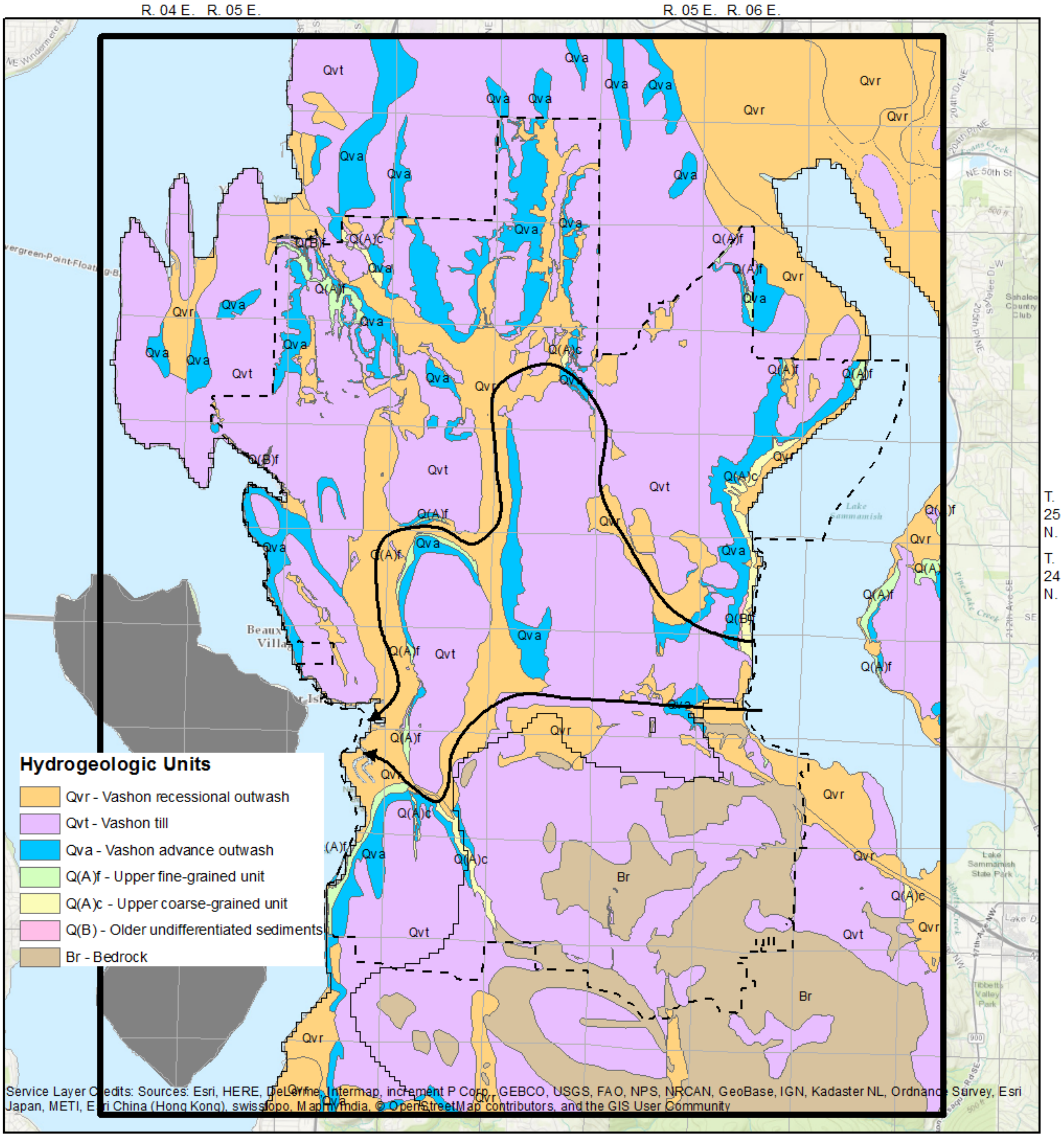
The hydrogeologic units in the study area were defined using geologic data from many sources. These sources included surficial geologic maps, boring and test pit logs from GeoMapNW, and drillers' logs from the Washington State Department of Ecology. Prior investigations of the study area and adjacent areas guided the description and delineation of hydrogeologic units from geologic units. Investigations reviewed included Troost Geosciences (2015) (Bellevue), Liesch and others (1963) (northwestern King County), Woodward and others (1995) (southwestern King County), Turney and others (1995) (east King County), and Savoca and others (2010) (northwestern Pierce County).

The surficial hydrogeologic map of the study area (Figure 2) was generated by merging surficial geology datasets from Troost (2012), Booth and others (2012), and Yount and others (1993). The geologic units depicted in the source maps were reclassified into 7 hydrogeologic units (described below) based on lithologic and hydrologic properties, and on relative stratigraphic position. The bedrock surface was generated by merging depth-to-bedrock contour data from Yount and others (1985) with surface geology data from the above sources.

Lithologic boring data was combined with surficial hydrogeologic data to develop 7 hydrogeologic cross sections to locate contacts between hydrogeologic layers in the subsurface. Subsurface data was sourced from 142 lithologic logs (Ecology, 2017) and 473 exploration logs shared by GeoMapNW (GeoMapNW, 2014) (Figure 3). Contact elevations from surficial data (paired with LiDAR-derived bare earth ground surface elevations [PSLC, 2000]) and all boring logs were used to interpolate the elevations of hydrogeologic layer tops in Earth Volumetric Studio (CTech Development Corporation, 2017) using kriging methods with hierarchy imposed. In Earth Volumetric Studio, hierarchal methods modify the interpolation algorithm so that stratigraphically lower units may not interpolate above surfaces of stratigraphically higher units.

The nomenclature for hydrogeologic units used in this study is slightly modified from Woodward and others (1995) and Turney and others (1995) (Table 1). Widely accepted nomenclature used for the Vashon drift is used in this study for the three uppermost hydrogeologic units. While these hydrogeologic units mostly correspond the geologic units of the same name, they are not identical. All three Vashon-associated hydrogeologic units contain geologic units of different origins and lithologies but similar hydrogeologic properties.

Pre-Vashon hydrogeologic units also follow the naming conventions of Woodward and others (1995) and Turney and others (1995). Pre-Vashon unit names do not correspond to accepted geologic unit names, nor do they convey information on depositional mechanisms. Instead, the Pre-Vashon units are named for their relative stratigraphic position and their lithologic character. For example, Unit Q(A)f designates the first fine grained unit beneath Vashon sediments. Unit Q(A)c designates the first coarse grained unit beneath Vashon sediments. Unit Q(B) is an undifferentiated unit overlying the bedrock, and underlying Units Q(A)f and Q(A)c. Full descriptions for each hydrogeologic unit are given below, ordered from stratigraphically highest to stratigraphically lowest.



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Base: U.S. Geological Survey World Terrain Base
Horizontal Datum: Washington State Plane, North Zone,
1983 North American Datum, feet.

0 1 2 Miles
0 8,000 Feet
N

Explanation

Study Area

Bellevue City Boundary

Glacial Lake Spillway

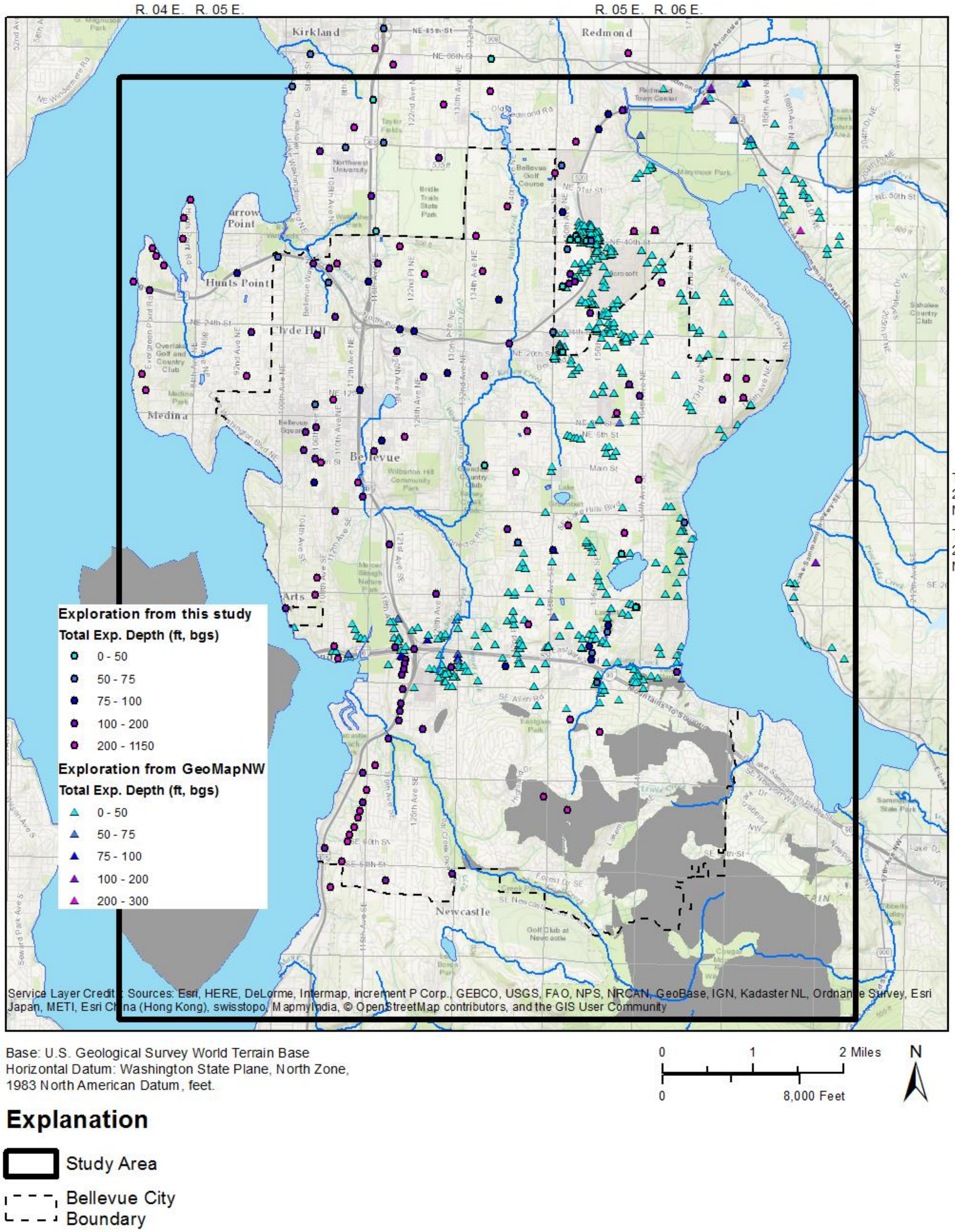
Geologic Data Sources

1. Troost, K.G., 2012, Geologic Map of Bellevue, Washington for the City of Bellevue, Washington: scale 1:24,000.
2. Booth D.B., Walsh, T.J., Goetz Troost, K.G., and Shimel, S.A., 2012, Geologic map of the east half of the Bellevue South 7.5' x 15' quadrangle, Issaquah area, King County, Washington: U.S. Geological Survey Scientific Investigations Map 3211, scale 1:24,000.
3. Yount, J.C., Minard, J.P., and Dembroff, G.R., 1993, Geologic map of surficial deposits in the Seattle 30' x 60' quadrangle: U.S. Geological Survey Open-File Report 93-233, scale 1:100,000, 1 ESRI shapefile.

Figure 2. Surficial Hydrogeology of Bellevue, Washington and vicinity

Table 1. Hydrogeologic units defined in this study and correlation with geologic and hydrogeologic units from other Puget Lowland studies.

Period	**Epoch**	**Hydrogeologic unit defined in this study**	**Geologic units in Troost (2012)**	**Geologic units in Booth and others (2012)**	**Geologic units of Yount and others (1993)**	**Hydrogeologic units of Liesch and others (1963)**	**Hydrogeologic units of Turney and others (1995)**	**Hydrogeologic units of Woodward and others (1995)**	**Hydrogeologic units of Savoca and others (2010)**
Quaternary	Pleistocene, Holocene	**Qvr** aquifer	Qvr, Qve, Qal, Qf, Qoal, Qls, Qp	Qvr, Qal, Qf, Qoal, Qls	Qgo, Qa, Qf	Vashon recessional outwash, Post-Vashon sedimentary deposits, Post-Vashon peat	Qvr, Qal	Qvr, Qal	AL aquifer, A1 aquifer
		Qvt confining unit	Qvt, Qvi, Qvrl, Qvrlb, Qvrlj, Qvrlo, Qvrlbt	Qvt, Qvi	Qgt	Vashon till and Vashon recessional lake deposits	Qvt	Qvt	A2 confining unit
		Qva aquifer	Qva	Qva	Qga, Qga(t)	Vashon advance outwash, unnamed sand	Qva	Qva	A3 aquifer
		Q(A)f confining unit	Qpff, Qpfnf, Qob	Qpff, Qob	--	Upper clay unit	Q(A)f	Q(A)f	B confining unit
		Q(A)c aquifer	Qpoc, Qponc	--	--	Unnamed gravel	Q(A)c	Q(A)c	C aquifer
		Q(B) undifferentiated sediments	--	--	--	--	--	--	--
Tertiary	Eocene to Miocene	**Br** bedrock	Tbh, Tb, Tpr, Tsc, Tu	Tbh, Tb, Tpr, Tsc	Ec(2r), Evc(t)	Eocene, Oligocene, and Miocene sedimentary rocks, Puget Group	Br	Br	Bedrock unit



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Base: U.S. Geological Survey World Terrain Base
Horizontal Datum: Washington State Plane, North Zone, 1983 North American Datum, feet.

Figure 3. Locations of borings used to delineate hydrogeologic units

Qvr – Unit Qvr is an aquifer primarily composed of loose to dense, poorly to moderately sorted sands and gravels of the Vashon recessional outwash. The unit contains minor amounts of silt and clay, particularly near recessional lakes. The Qvr was deposited in large meltwater streams emanating from the retreating ice and is almost completely confined to lowland areas. Unit Qvr includes a north-south oriented esker deposit located in the center of the study area, as well as many Holocene deposits such as alluvium within the Sammamish River Valley and along smaller streams. Fan and landslide deposits, primarily present along the shorelines of Lake Washington and Lake Sammamish are also included in unit Qvr.

The unit is the stratigraphically highest hydrogeologic unit in the study area and is present at ground surface everywhere it occurs in the study area (Figure 4). The Qvr is generally the thinnest hydrogeologic unit, and the most areally limited. The thickness of the Qvr ranges from a thin veneer to greater than 25 feet throughout most of the study area. The Qvr is much thicker within the Sammamish River Valley, as the river has filled the valley with a sequence of alluvium approximately 120 feet thick.

Qvt – Unit Qvt is a confining unit composed of Vashon till; an unsorted mixture of boulders, cobbles, gravel, sand, silt, and clay deposited directly by the ice sheet. This unit is generally very compact, and drillers' logs often describe the unit as "hardpan" or "boulder clay". Thin interlayers of well sorted sand are present within the Qvt, particularly near the bottom of the unit. Unit Qvt includes poorly sorted ice-contact deposits, especially those emplaced around modern day kettle lakes where calved ice blocks were abandoned by the retreating glacier. Fine grained deposits (sandy silts and clays) of recessional lakes are also included in Unit Qvt because of their similar stratigraphic position and hydraulic properties to the till.

Qvt occurs at land surface due throughout most of the study area due to the unit's resistance to erosion and the limited extent of the Qvr. Qvt caps the non-bedrock highlands throughout the study area and is thickest in the interiors of those areas (Figure 5). Where present, thickness ranges from less than 5 to greater than 200 feet.

Qva – Unit Qva is an aquifer composed of dense, stratified, well sorted sands and gravels deposited by meltwater streams draining the advancing ice sheet. The Qva exhibits a coarsening upward sequence throughout much of the study area, corresponding to the greater energy of the depositional environment with greater proximity to the ice front. Qva originally covered the entire model area, including the troughs of ancestral Lakes Washington and Sammamish. The present-day configuration of Qva was shaped by subglacial meltwater, which re-excavated Lakes Washington and Sammamish; and by erosion during and after glacial retreat.

Unit Qva is present throughout the study area except along the main drainages of Kelsey Creek, Richards Creek, and Mercer Slough (Figure 6). Qva is only visible at ground surface in areas of high relief and is otherwise capped by Qvt (highlands) or Qvr (lowlands). Thickness of the Qva ranges from less than 5 feet along major streams to greater than 200 feet beneath the highlands along the northern boundary of the study area. The elevation of highlands on the drift plain is strongly correlated to the thickness of the Qva.

Q(A)f – Unit Q(A)f is a confining unit primarily composed of silts and clays corresponding to the Upper clay unit of Liesch and others (1963), and correlatable to the Lawton clay of Mullineaux and others (1965). The Q(A)f separates the overying Qva aquifer unit and the underlying Q(A)c aquifer unit. Unit Q(A)f marks the transition between Vashon and Pre-Vashon sediments. The silts and clays are primarily the product of deposition in proglacial lakes after Vashon ice blocked the Strait of Juan de Fuca. Silts and clays deposited during the Vashon advance are underlain by silts, clays, peat, and fine sands of likely interglacial origin within the study area. Pre-Vashon tills of indeterminate origin are occasionally present in the base of the Q(A)f, especially in the southeastern interior of the study area.

Q(A)f is present throughout the study area with few exceptions (Figure 7). It is notably absent in the center of the study area where Richards and Kelsey Creeks have eroded through the unit, connecting the overlying Qva aquifer and the underlying Q(A)c aquifer. The Q(A)f is also absent from the Newcastle Hills and the Sammamish River Valley. The unit is thickest in the drift plain along the shores of Lake Sammamish and

Lake Washington (greater than 150 feet). In the southeast, Pre-Vashon tills are responsible for the increased thickness of the unit. Silts and clays make up almost the entire thickness of the confining unit in the northeastern and northwestern portions of the study area.

Q(A)c – Unit Q(A)c is an aquifer unit composed of Pre-Vashon sands and gravels corresponding to the Unnamed gravel of Liesch and others (1963). The Q(A)c typically fines upwards in boring logs, and is often described as dark gray to black in color. In some locations, particularly in the center of the study area, the unit has weathered to a tan color. The Q(A)c is the most heterogeneous of the differentiated units. Interlayers of silt, silty sand, and till approximately five to ten feet thick are common throughout the Q(A)c.

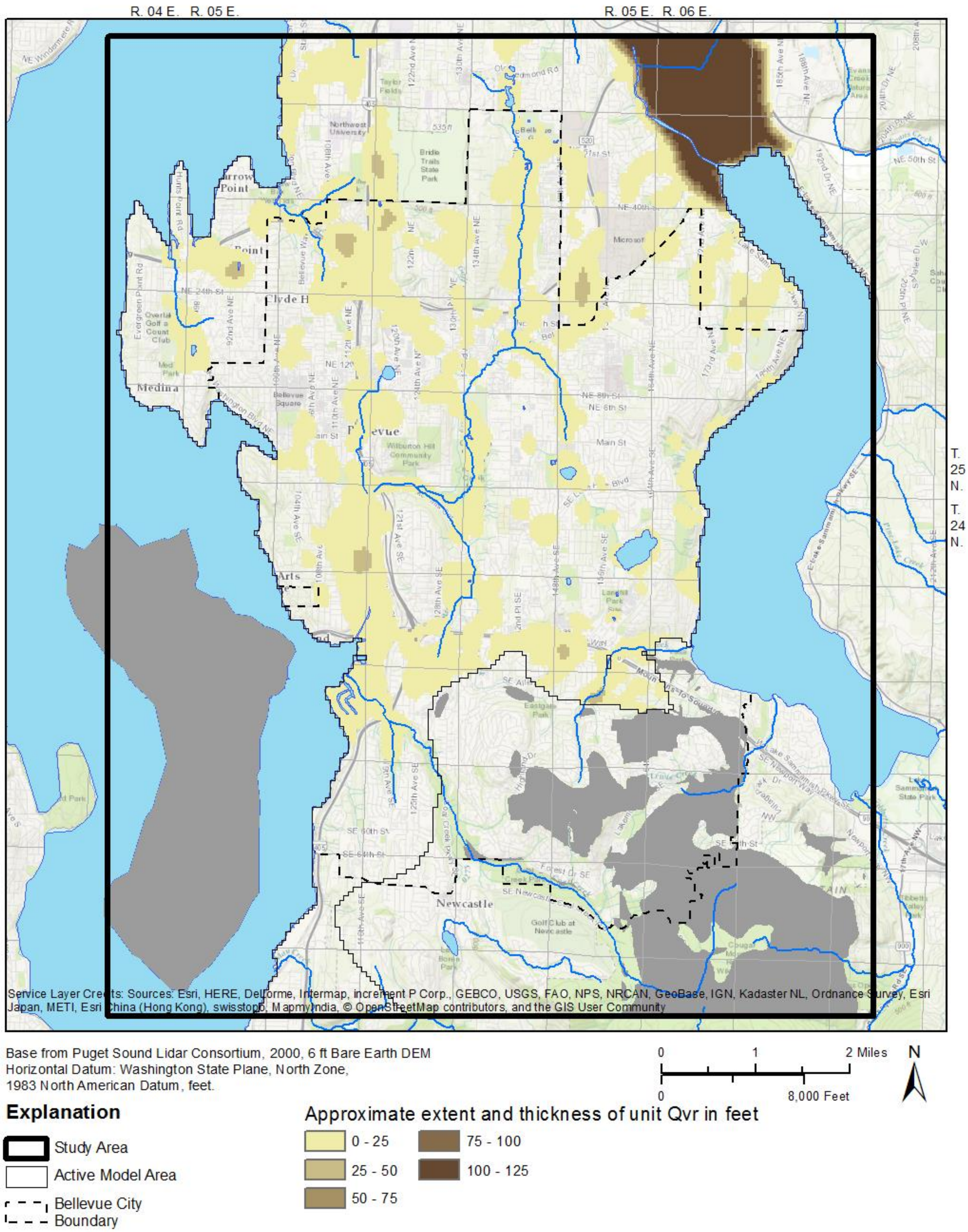
Q(A)c extends throughout the entire study area except for the Newcastle Hills and the Sammamish River Valley (Figure 8). The unit is thickest along the central north-south axis of the drift plain, reaching thicknesses greater than 200 feet, and thins towards the major lakes and the Newcastle Hills. The Q(A)f confining unit is absent beneath Kelsey Creek and Richards Creek, forming a direct connection between the Q(A)c aquifer and the overlying Qva aquifer.

Q(B) – Undiffentiated sediments present beneath the Q(A)c aquifer and above the bedrock surface are grouped into Unit Q(B). The unit is composed of sediments of glacial and nonglacial origin. The uppermost 50 feet of the unit corresponds to the Lower clay unit of Liesch and others (1963), and confines the Q(A)c above it. This upper section is primarily composed of gray, blue, or brown clays and silts. Discontinuous layers of till are common in the unit as well. Interlayers of peat, pumiceous sand, and tuff up to 5 feet thick are commonly reported in drillers' logs near the top of the Q(B).

The upper surface of the undifferentiated sediments is present near sea level throughout most of the study area, dropping to nearly 200 feet bgs in the southeastern area of the drift plain where unit Q(A)f is thickest (Figure 9). The (Q)B thickens following the slope of the bedrock surface from approximately 250 feet thick along Lake Sammamish to greater than 2,000 thick along Lake Washington.

Br – Unit Br (bedrock) underlies the unconsolidated sediments throughout the entire study area. The bedrock is not explicitly included in the numerical simulation, but instead forms the bottom boundary of the model domain. Br forms the Newcastle Hills anticline. It is composed of sedimentary rocks of the Blakely Harbor, Blakely, and Renton Formations (Booth and others, 2012). All three formations consist of sandstones, siltstones, and conglomerates.

The Quaternary Seattle Fault Zone bisects the study area from east to west along Interstate 90 and the northern edge of the Newcastle Hills (Figure 10). Bedrock is exposed south of the fault zone in the Newcastle Hills. North of the fault zone, Yount and others (1985) show the bedrock surface dipping steeply northwards.



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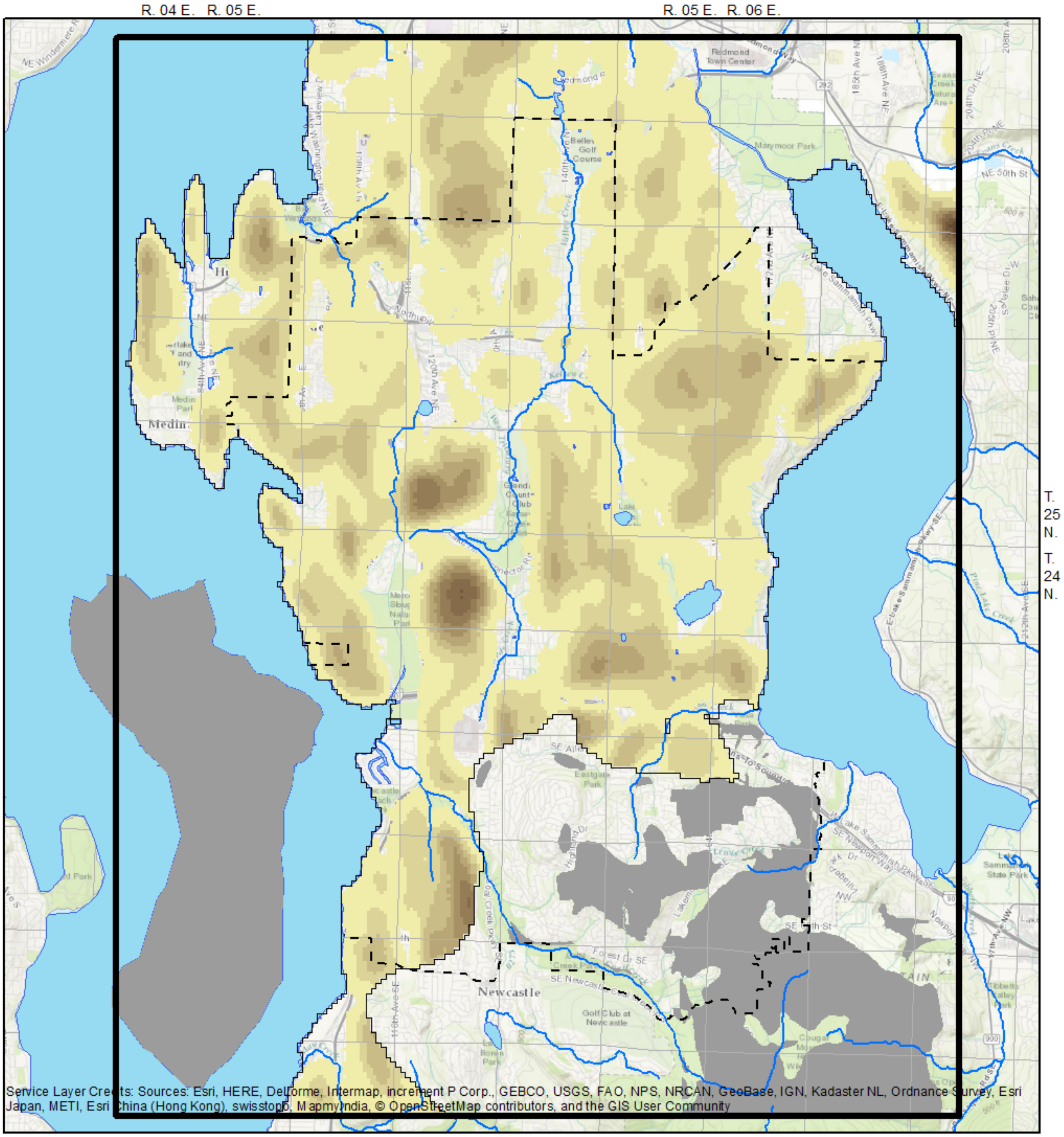
Base from Puget Sound Lidar Consortium, 2000, 6 ft Bare Earth DEM
Horizontal Datum: Washington State Plane, North Zone,
1983 North American Datum, feet.

Figure 4. Extent and thickness of hydrogeologic unit Qvr in Bellevue and vicinity, Washington



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Base from Puget Sound Lidar Consortium, 2000, 6 ft Bare Earth DEM
Horizontal Datum: Washington State Plane, North Zone,
1983 North American Datum, feet.

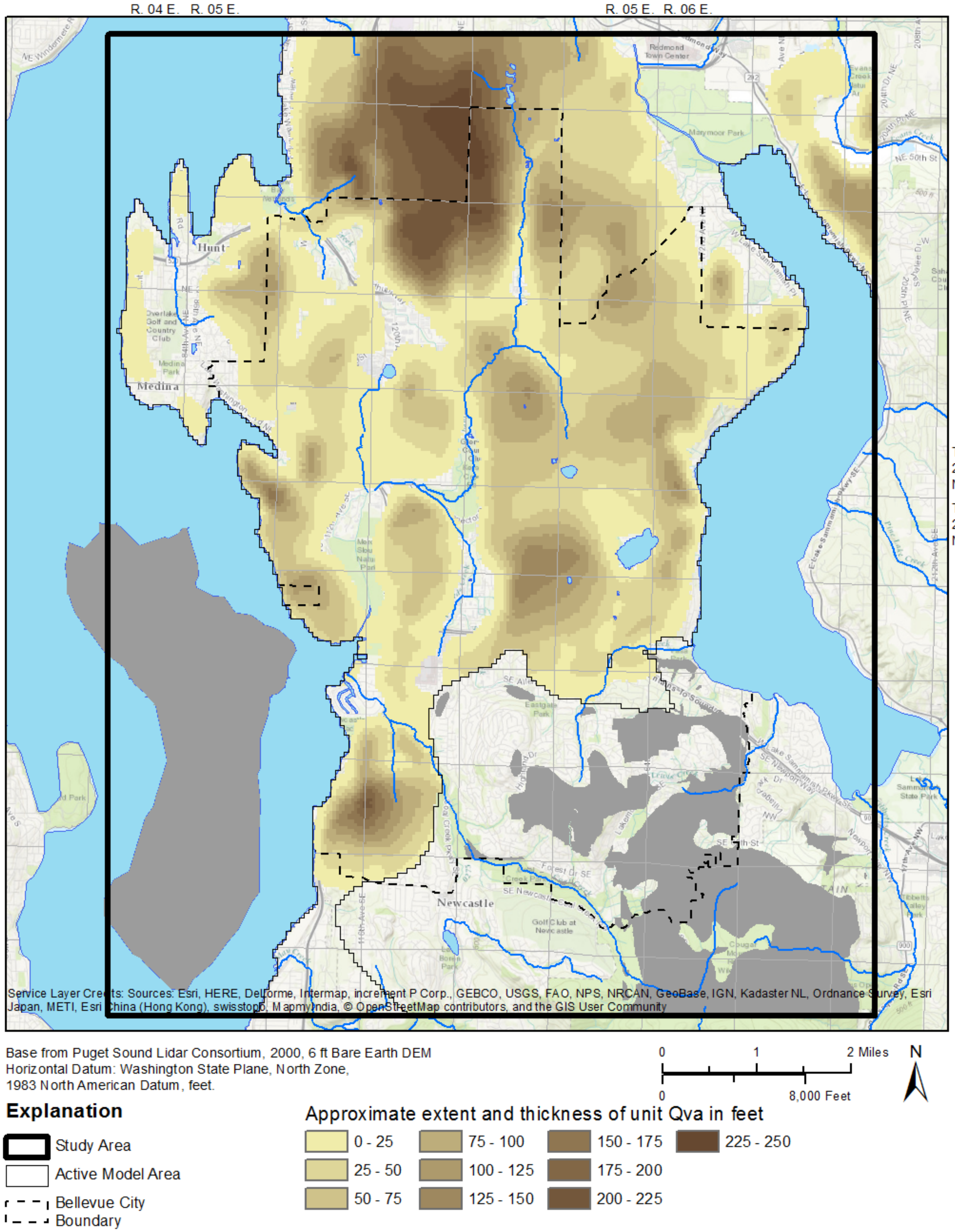
Explanation

☐ Study Area
☐ Active Model Area
┆ Bellevue City Boundary

Approximate extent and thickness of unit Qvt in feet

- ▨ 0 - 25
- ▨ 25 - 50
- ▨ 50 - 75
- ▨ 75 - 100
- ▨ 100 - 125
- ▨ 125 - 150
- ▨ 150 - 175
- ▨ 175 - 200
- ▨ 200 - 225

Figure 5. Extent and thickness of hydrogeologic unit Qvt in Bellevue and vicinity, Washington



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Horizontal Datum: Washington State Plane, North Zone,
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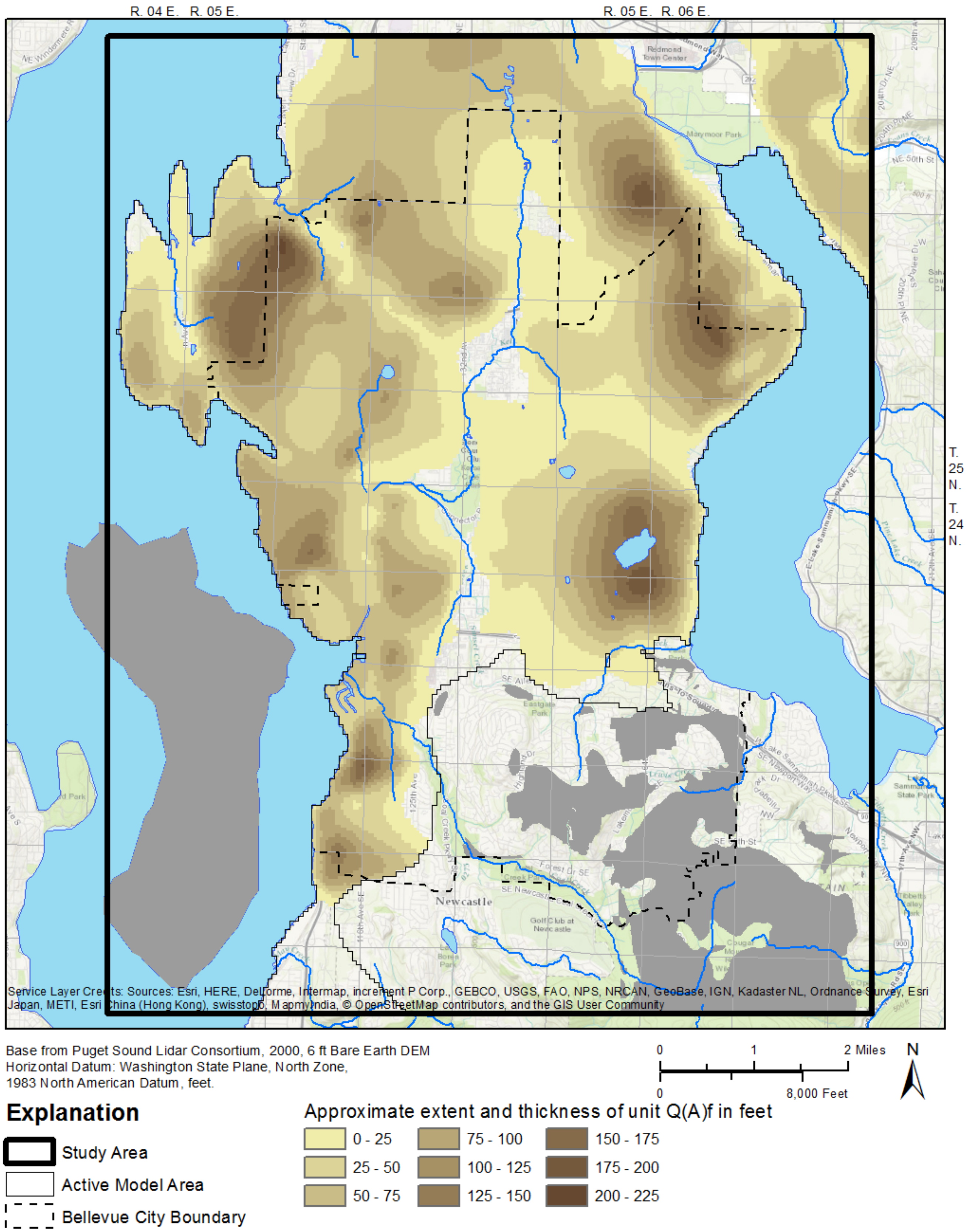
Figure 6. Extent and thickness of hydrogeologic unit Qva in Bellevue and vicinity, Washington



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Base from Puget Sound Lidar Consortium, 2000, 6 ft Bare Earth DEM
Horizontal Datum: Washington State Plane, North Zone,
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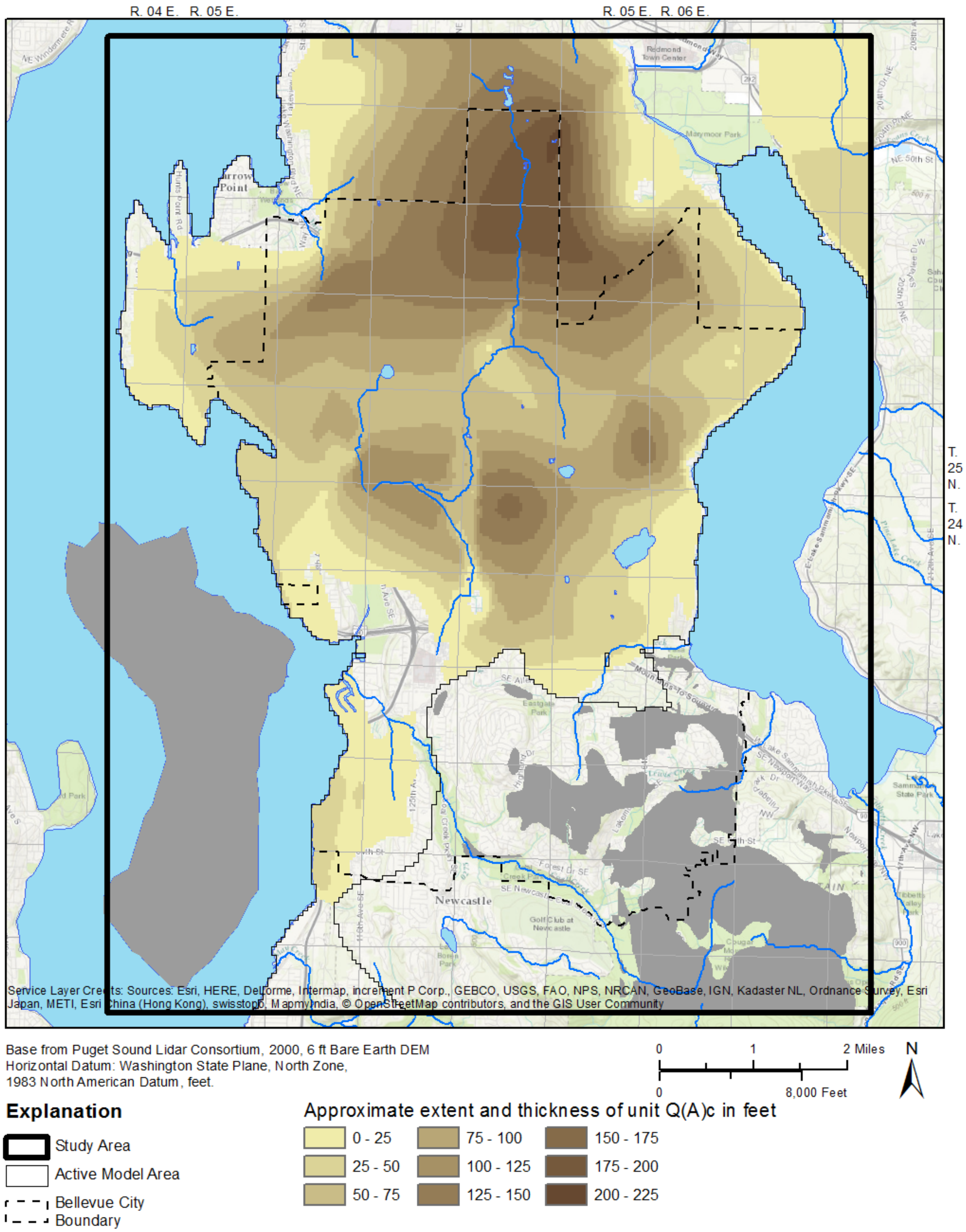
Figure 7. Extent and thickness of hydrogeologic unit Q(A)f in Bellevue and vicinity, Washington



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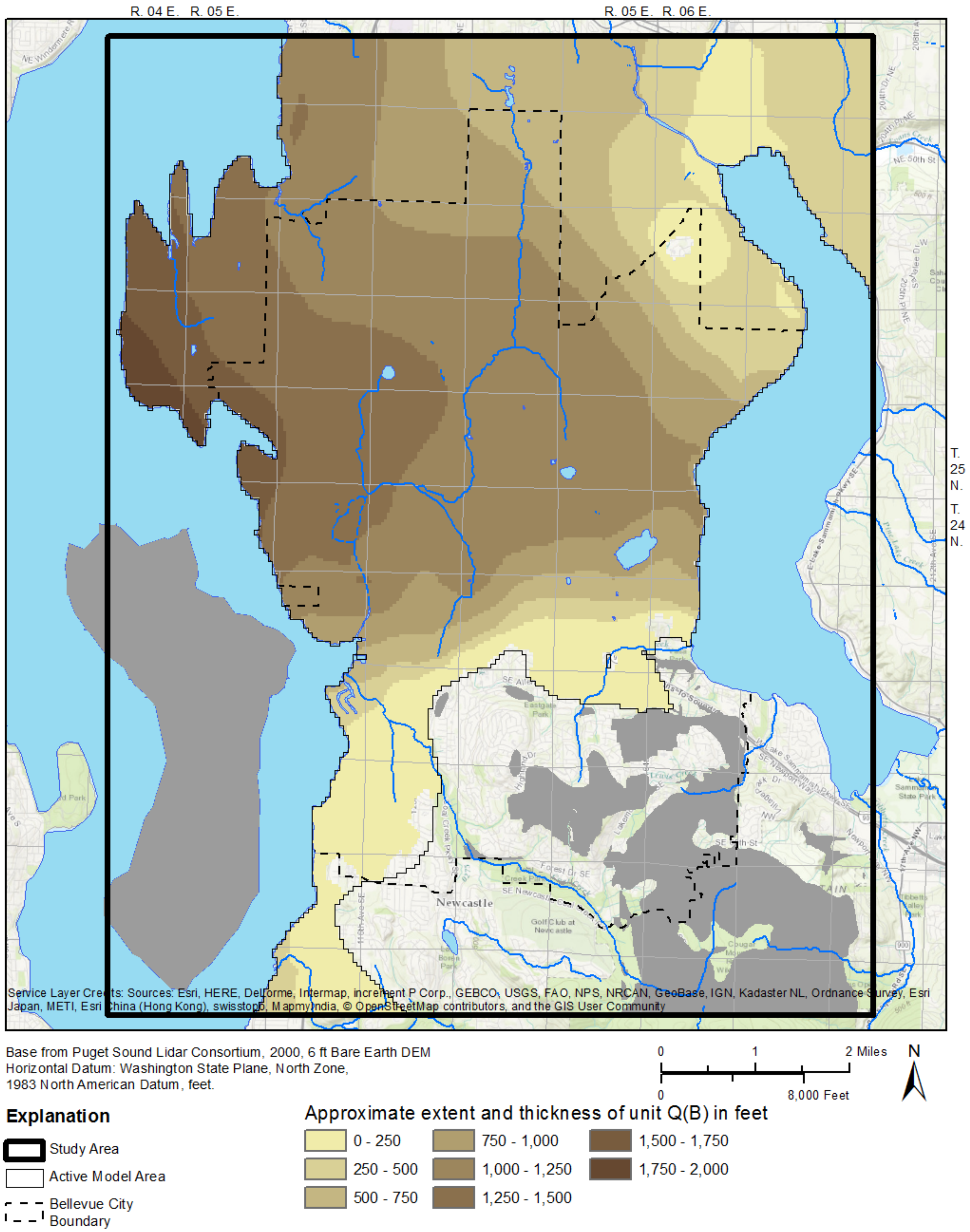
Horizontal Datum: Washington State Plane, North Zone,
1983 North American Datum, feet.

Figure 8. Extent and thickness of hydrogeologic unit Q(A)c in Bellevue and vicinity, Washington



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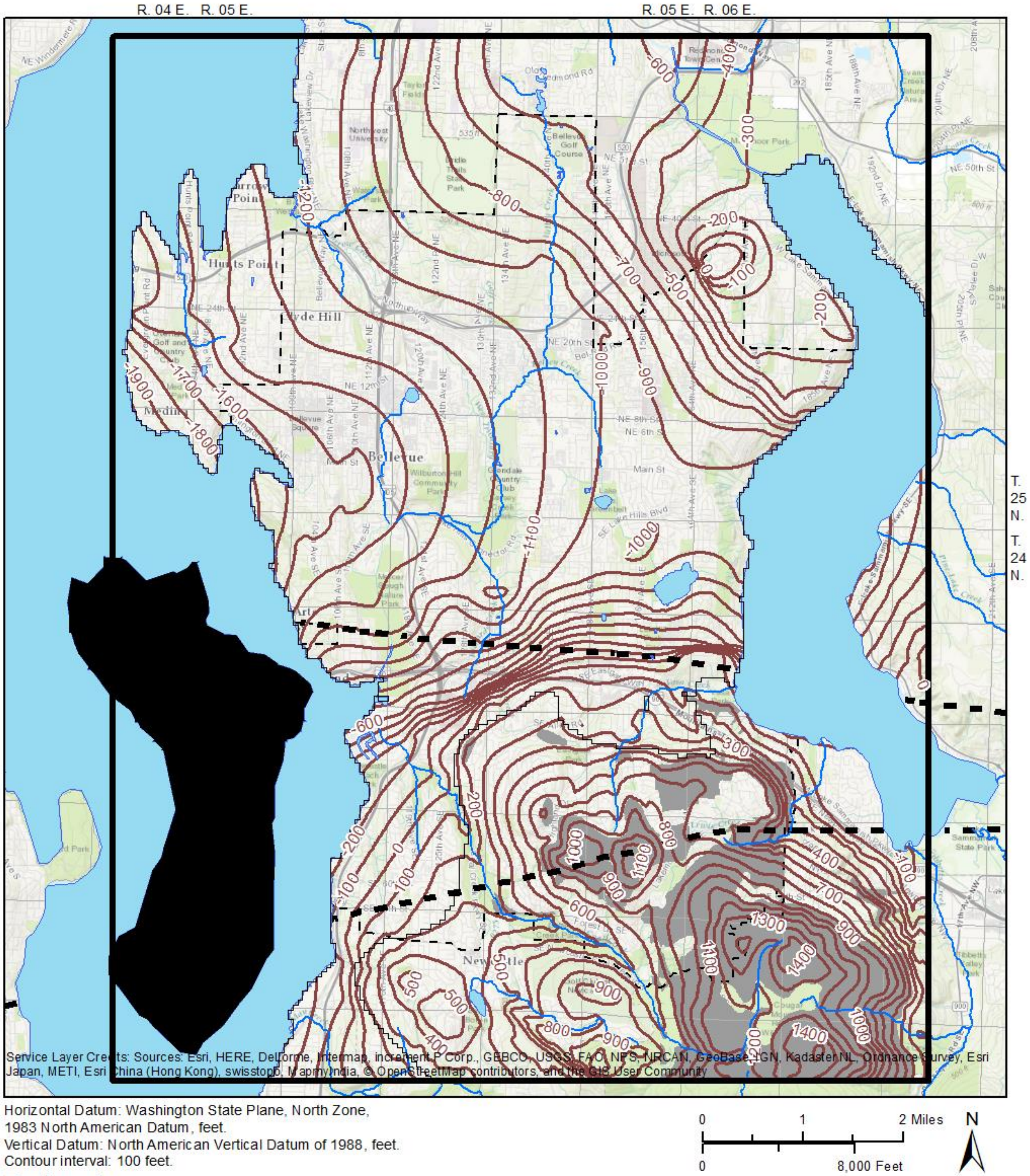
Base from Puget Sound Lidar Consortium, 2000, 6 ft Bare Earth DEM
Horizontal Datum: Washington State Plane, North Zone,
1983 North American Datum, feet.

Figure 9. Extent and thickness of hydrogeologic unit Q(B) in Bellevue and vicinity, Washington



Horizontal Datum: Washington State Plane, North Zone, 1983 North American Datum, feet.
Vertical Datum: North American Vertical Datum of 1988, feet.
Contour interval: 100 feet.

Explanation

▭	Study Area
▭	Active Model Area
┆	Bellevue City Boundary
—	Bedrock elevation contour (100 foot interval)
▨	Bedrock exposed at ground surface
■	Not included in study area
▬ ▬	Seattle Fault Zone strands

Figure 10. Elevation of the bedrock surface (Br) in Bellevue and vicinity, Washington

2.3 Hydraulic Conductivity

The ability of a hydrogeologic unit to transmit water is known as the hydraulic conductivity (K). Hydrogeologic units with large hydraulic conductivities transport water through the unit more easily than hydrogeologic units with low hydraulic conductivities. Hydraulic conductivity in unconsolidated materials is a function of the grain size distribution, the packing of grains, and the interconnectedness of pores. Frequently, the hydraulic conductivity varies with the direction of flow within the material. Horizontal hydraulic conductivity (K_h), the ability of the hydrogeologic unit to transmit water horizontally, is frequently larger than vertical hydraulic conductivity (K_v), the ability of the unit to transmit water in the vertical direction. This anisotropy is common in unconsolidated sediments due to the horizontal orientation of grains and sedimentary structures by depositional processes (Kruseman and de Ridder, 2000, p.16).

Estimates of hydraulic conductivity for hydrogeologic units in the study area were taken from investigations by Woodward and others (1995) for southwest King County and Turney and others (1995) for east King County (Table 2). Values from these two studies were chosen because of their proximity to the study area and because the hydrogeologic units defined for Bellevue study area were based on those of the east King County and southwest King County studies. These values compare favorably to horizontal hydraulic conductivity ranges compiled for the entire Puget Lowland by Vaccaro and others (1998).

Horizontal hydraulic conductivity estimates presented in Woodward and others (1995) and Turney and others (1995) were computed from specific capacity information derived from reported results of well tests in their respective study areas. Well tests in both studies were analyzed for hydraulic conductivity using the Theis equation as modified for leaky artesian aquifers by Ferris and others, 1962. It is important to note that values estimated from these tests are likely higher than the actual bulk hydraulic conductivities for the tested layers because the wells analyzed were preferentially screened in materials capable of producing useful amounts of water (Woodward and others, 1995). Abnormally high estimates are most prevalent within confining units.

Table 2. Estimates of horizontal hydraulic conductivity from hydrogeologic studies in King County, Wash.

	K_h (ft/day) as reported by (1)				**K_h (ft/day) as reported by (2)**				**Ranges of K_h (ft/day) as compiled in (3)**	
Hydr. Unit	Number of wells	Min.	Median	Max.	Number of wells	Min.	Median	Max.	Number of values	Range
Qvr	39	0.43	61	670	Not Reported				15	6.2 - 915
Qvt	24	0.04	51	1,900	Not Reported				NR	0.0003 - 14.2
Qva	94	0.13	35	6,100	68	0.09	83	2,990	178	0.02 - 6,790
Q(A)f	24	0.03	9.0	37	Not Reported				3	7e-5 - 2.9e-3
Q(A)c	51	0.38	37	1,700	74	1	51	5,174	37	4.5 - 6,998
Q(B)	Not Reported				Not Reported				50	3.7 - 2,680

(1) Turney and others (1995)

(2) Woodward and others (1995)

(3) Vaccaro and others (1998)

NR – not reported

2.4 Recharge

Recharge is the flow of water into the groundwater system. In many Puget Sound basins, infiltration of precipitation is the principal source of recharge (Bauer and Mastin, 1996). Other potential sources of recharge include leakage from surface water features, irrigation, return flows from on-site sewage disposal systems, leaking of buried water transmission pipes, and artificial recharge through engineered structures. For this study, only the recharge contribution from precipitation was calculated because precipitation is likely the most important source of inflow to the Bellevue groundwater system, and because little to no readily available data exists for the other sources.

Recharge to groundwater within the Puget Lowland is controlled by precipitation, surficial geology, and land cover (Morgan and Jones, 1999). Surficial coarse-grained deposits, such as the Qvr and Qva, are capable of rapidly infiltrating precipitation to the water table whereas fine-grained deposits, such as the Qvt and Q(A)f, cause more precipitation to run off rather than infiltrating (Dinicola, 1990). Fine-grained units that occur immediately at the surface intercept percolating water before it reaches the water table. Till or other fine-grained sediments underlying more permeable sediments can cause downward percolating water to begin moving horizontally over the surface of the fine-grained unit and out of the soil profile through seeps, springs, and streams.

Land cover beyond geologic material also affects the fraction of precipitation that becomes recharge. Dinicola (1990) found that impervious surfaces such as concrete and asphalt greatly decreased the fraction of precipitation that becomes recharge in Puget Lowland basins because impervious surfaces promote Hortonian overland flow. The presence of vegetation can also significantly reduce recharge in Puget Lowland basins through interception loss (precipitation that is caught on foliage and evaporates before reaching ground surface) and transpiration (moisture removed from the soil profile above the water table by vegetation) (Bidlake and Payne, 2001).

Recharge to the Bellevue groundwater system was estimated using regression equations relating annual precipitation to annual recharge developed by Bidlake and Payne (2001) for a series of 5 land cover classifications. The Bidlake and Payne (2001) land cover classifications, as implemented by Savoca and others (2010), are described in Table 3.

Table 3. Relations used to predict annual recharge to groundwater from annual precipitation

Description from Bidlake and Payne (2001)	**Hydrogeologic Units**	**Percent of tree cover**	**Percent of impervious area**	**Equation for estimating annual recharge (in/yr) as a function of annual precipitation (in/yr)**
Non-forest vegetation on soils formed on glacial outwash and other alluvium	Qvr, Qva, Q(A)c	≤50	NA	$R = 0.806P - 8.87$
Forest vegetation and soils formed on glacial outwash and other alluvium	Qvr, Qva, Q(A)c	>50	NA	$R = 0.633P - 6.96$
Forest and nonforest vegetation on soils formed on glacial till or other fine-grained sediments	Qvt, Q(A)f, Q(B)	NA	≤50	$R = 0.388P - 4.27$
Developed or urban land	Qvt, Q(A)f, Q(B)	NA	50	$R = 0.194P - 2.13$
Water and wetlands	NA	NA	NA	$R = 0$

Mean annual precipitation data used in recharge calculations were obtained from datasets generated from the Parameter-elevation Regression on Independent Slopes Model (PRISM) for the years 1971-2000 (Daly and others, 1994; Oregon State University, 2009). PRISM is a statistical model that estimates the distribution of precipitation based on spatial variations and elevation. Figure 11 presents contours of annual precipitation in the study area derived from PRISM estimates and land cover information used to determine land cover classifications and to calculate recharge values.

2.5 Discharge

Discharge is the movement of water out of the groundwater system. Discharge occurs throughout the study area and from all hydrogeologic units. Discharge features include springs and seepage into surface water bodies (lakes, streams, rivers, and wetlands), seepage from bluff faces, and groundwater removals through wells. Figure 12 depicts the locations of discharge features where they known or likely to occur at ground surface.

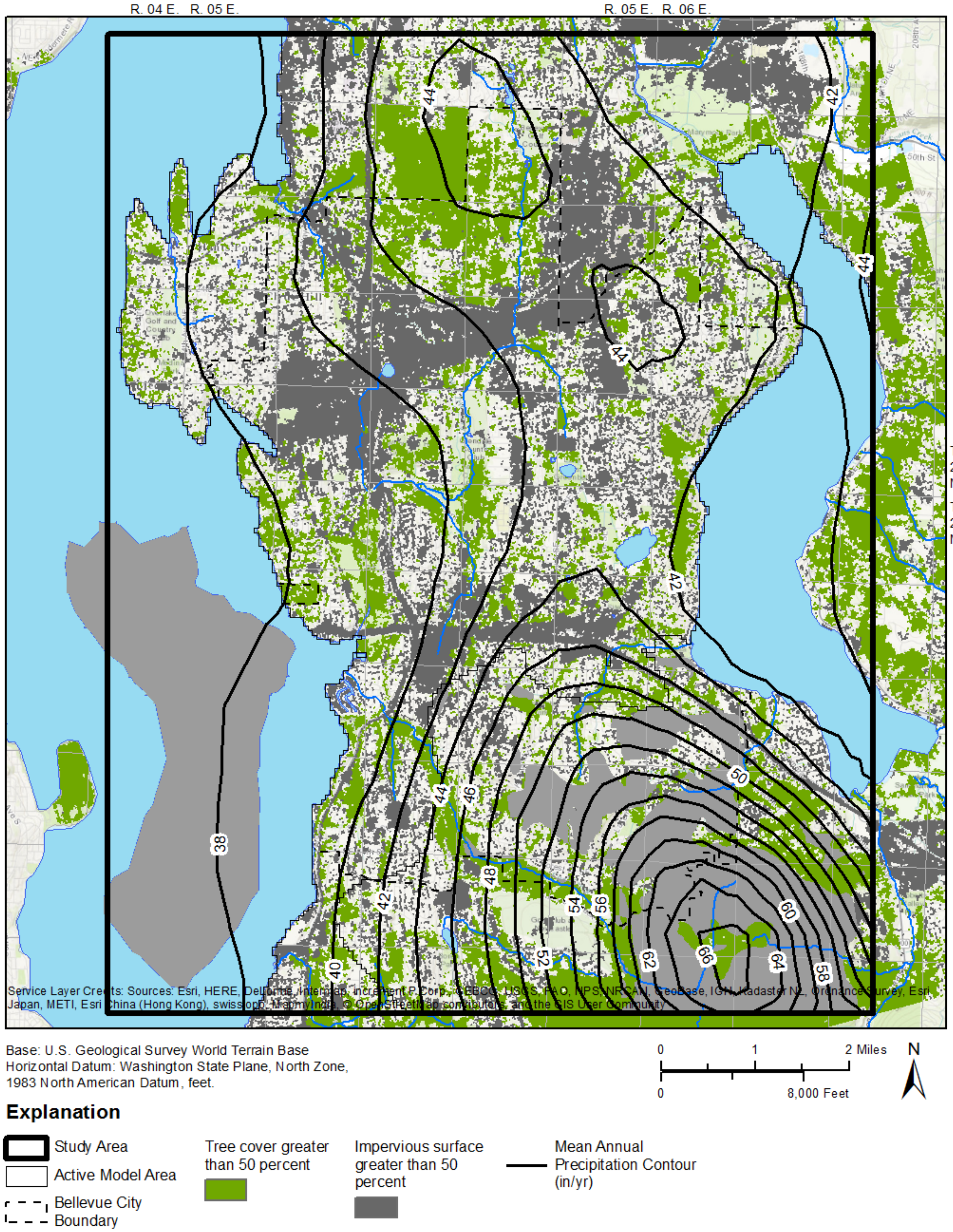
Many of these discharge features are present throughout the year, such as lakes and perennial streams. Others flow only when groundwater levels are high, such as seeps and intermittent streams. Features that exist throughout the year may not always function as discharge features. Streams and lakes may receive discharge from or lose water to the groundwater system depending on the time of year (City of Bellevue, 2016). Discharge features also vary spatially, especially streams. Many streams within the study area may receive discharge from the groundwater system at or near their headwaters, and recharge the groundwater system downstream.

2.6 Groundwater-Surface Water Interactions

Surface water features occur throughout the study area and form its eastern and western boundaries (Figure 12). As described previously, surface water features interact with the groundwater system both by receiving discharge and providing recharge to the groundwater. The direction of flow is dependent on difference in hydraulic head (h) between the surface water feature and the hydrogeologic unit with which the surface water feature is interacting. Flow moves from the feature with greater hydraulic head to the feature with less hydraulic head. The flowrate is determined by the magnitude of the difference in head between the features (a greater difference causes greater flow), the area through which flow is occurring, and the hydraulic conductivity (K) of the materials through which flow is occurring.

The head of a surface water feature is equivalent to the elevation of the water surface in the feature. Water levels in some surface water features (Lake Sammamish and Lake Washington) within the study area are tightly controlled and vary little over time. Lake Sammamish’s water level is controlled by a weir structure operated by US Army Corps of Engineers located at its outlet into the Sammamish River in Marymoor Park at the north end of the lake (Figure 13). Lake Washington’s water level is maintained within a 2-foot range by the US Army Corps of Engineers (USACE, 2017; Figure 14).

Water levels in perennial streams and lakes included in the National Hydrography Dataset (USGS, 2017a), except for Lake Washington and Lake Sammamish, were estimated from Light Detection and Ranging (LiDAR) datasets (PSLC, 2000). Levels estimated from LiDAR were compared to sparse measured water level data to confirm reasonable agreement.



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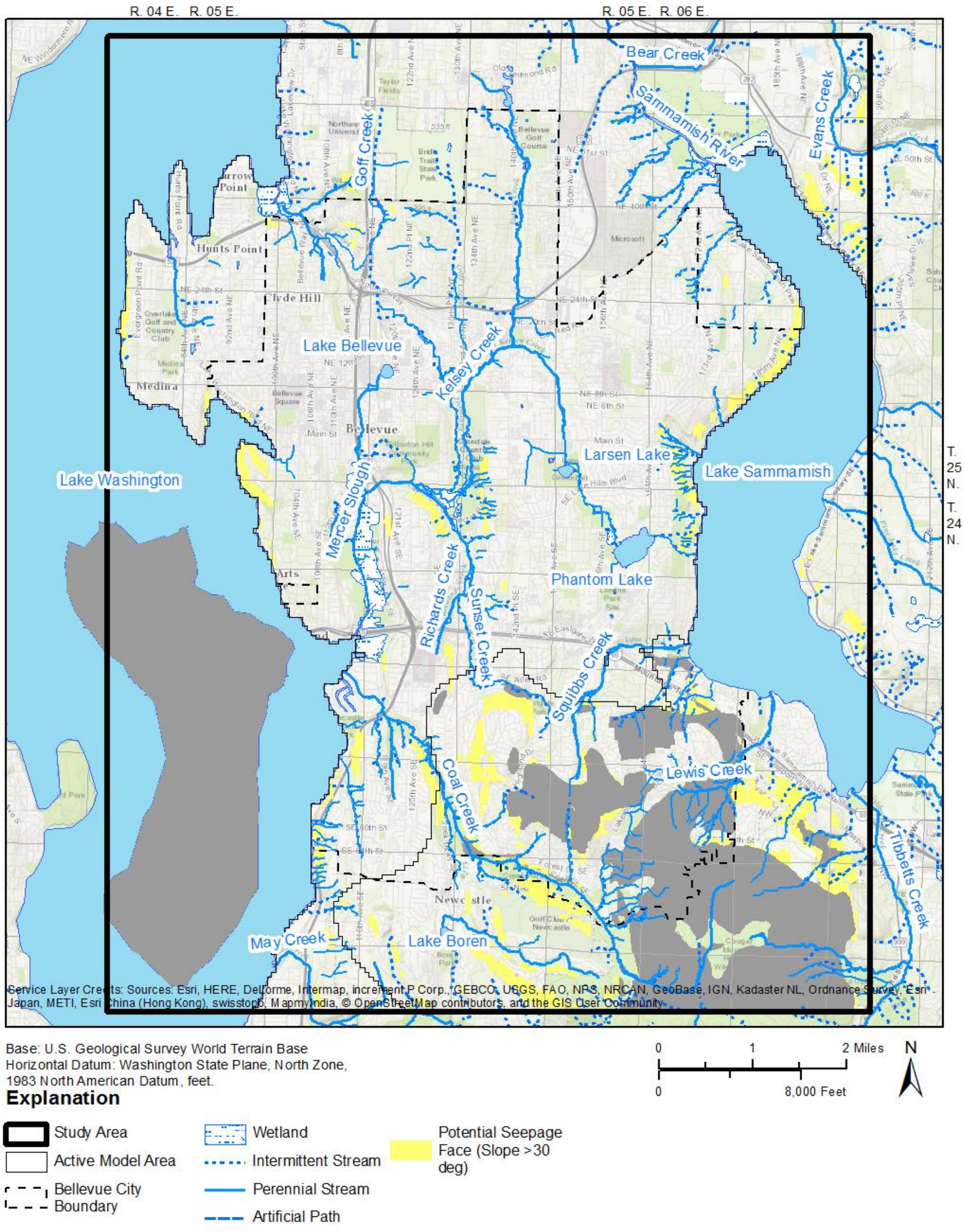
Base: U.S. Geological Survey World Terrain Base
Horizontal Datum: Washington State Plane, North Zone, 1983 North American Datum, feet.

Figure 11. Land cover and PRISM-estimated average annual precipitation in Bellevue and Vicinity



Base: U.S. Geological Survey World Terrain Base
Horizontal Datum: Washington State Plane, North Zone,
1983 North American Datum, feet.

Explanation

- Study Area
- Active Model Area
- Bellevue City Boundary
- Wetland
- Intermittent Stream
- Perennial Stream
- Artificial Path
- Potential Seepage Face (Slope >30 deg)

Figure 12. Surface water features and potential seepage locations in Bellevue and vicinity

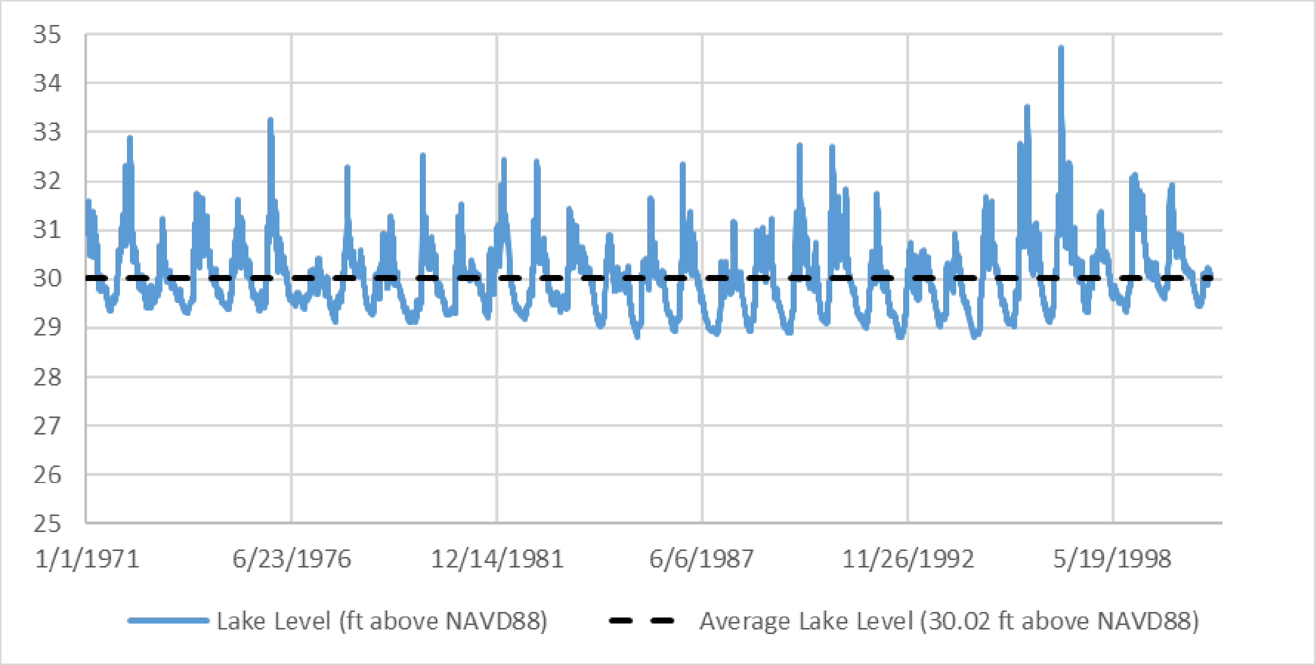


Figure 13. Lake Sammamish Hydrograph at USGS Gage 12122000 (1971-2000), data from USGS (2017b)

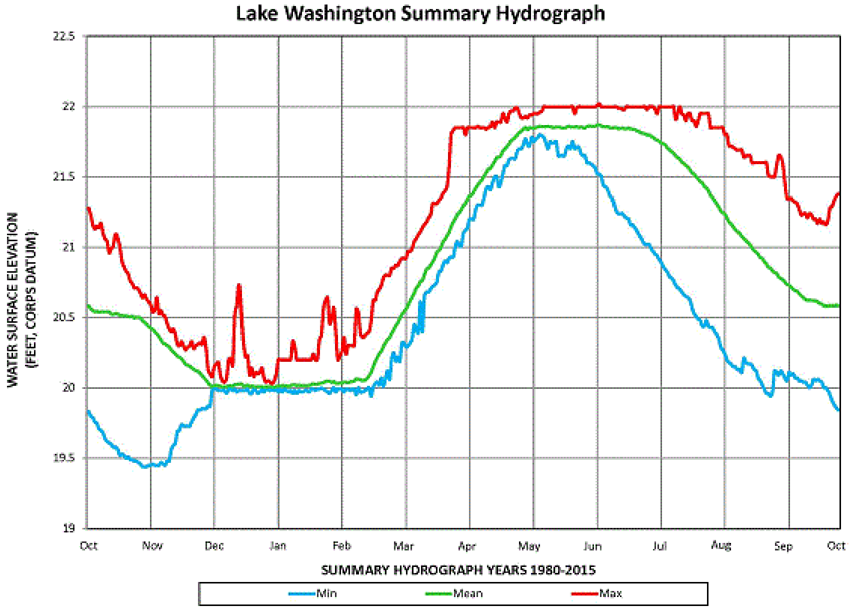


Figure 14. Lake Washington Summary Hydrograph (1980-2000), reproduced from USACE (2017).

3. Numerical Simulation of the Groundwater Flow System

This section describes the construction of the numerical groundwater flow model. Included in this section are descriptions of the modeling code, the construction and discretization of the study area, and the implementation of features identified in the conceptual model.

Flow in the Bellevue groundwater flow system was simulated using the U.S. Geological Survey's modular groundwater flow model, MODFLOW-NWT (Niswonger and others, 2011). MODFLOW-NWT is a computer program which numerically solves the three-dimensional groundwater flow equation for porous media using the finite-difference method. MODFLOW is modular, meaning that each process acting on the groundwater flow system is simulated by individual sub-routines called packages. The full MODFLOW simulation runs the core process, called the groundwater flow process, and an assemblage of packages representing the processes acting on the groundwater system to simulate the distribution of heads and flows throughout the model domain. MODFLOW-NWT was used to simulate the Bellevue groundwater system because MODFLOW-NWT's Newton-Raphson solver is particularly well suited to solve groundwater flow problems in variably saturated systems. MODFLOW versions that employ non-Newton-Raphson solvers suffer instability when simulating systems in which parts of the flow system may become unsaturated (Anderson and others, 2015).

3.1 Spatial and Temporal Discretization

The study area was divided into a grid of three-dimensional rectilinear blocks called cells. The location of each cell is described in terms of rows, columns, and layers. Rows and columns describe a cell's relative horizontal location from the model origin. A cell's layer describes its relative vertical location from the model origin. 220 rows, 172 columns, and 6 layers were used to represent the Bellevue groundwater system, resulting in 227,040 total cells. 131,830 of the 227,040 total cells are active, meaning that groundwater flows through those cells. Inactive cells represent locations where bedrock is present in the study area or where hydrogeologic units truncate into Lake Sammamish or Lake Washington. Each model cell is 250 feet wide by 250 long, and has variable thickness. Cell dimensions were chosen to be small enough to provide adequate resolution of the hydrogeologic features to meet study objectives, while limiting the number of active cells to allow for reasonable computation times.

The model simulates steady-state conditions meaning that the storage term of the groundwater flow equation is fixed at zero, and that hydraulic parameters and fluxes do not vary with time. Steady-state systems therefore simulate time-averaged conditions for the study period (1971-2000) such as average groundwater flow patterns, and average discharge and recharge flow rates. True steady-state conditions do not exist in groundwater systems as recharge and discharge processes fluctuate in real-world systems. However, steady-state results are sufficient to meet the objective of this study, developing a basic understanding of the groundwater flow system.

3.2 Model Layering

Six model layers were used to represent the six unconsolidated hydrogeologic units described in Section 3.2. Each model layer corresponds with only one hydrogeologic unit, and layers are numbered from stratigraphically highest to stratigraphically lowest (Table 4). Unit Br was not simulated in the model because the unit is assumed to be impermeable in comparison with the unconsolidated unit. Instead, Unit Br forms the bottom of the bottom of the model domain through which no water is simulated to flow.

The thickness of each model layer varies with the hydrogeologic unit the layer represents. MODFLOW-NWT requires that layers extend laterally across the entire model domain, even if the unit represented by that layer is discontinuous over the same area. Layers simulating hydrogeologic units that pinch out into Lake Sammamish or Lake Washington, or against bedrock were simulated as inactive cells. Hydrogeologic units that are discontinuous in other parts of the model domain, such as the Qvr, were simulated as having layer thicknesses of 0.1 feet where the layer was absent.

Table 4. Model layers and initial hydraulic property values used in the steady-state calibration

Hydrogeologic Unit	**Model Layer**	**Hydraulic Conductivity (ft/d)**		**Vertical Anisotropy (K_h/K_v)**
		Horizontal (K_h)	**Vertical (K_v)**	
Qvr aquifer	1	61	6.1	10
Qvt confining unit	2	14.2	0.142	100
Qva aquifer	3	35	3.5	10
Q(A)f confining unit	4	2.3	0.023	100
Q(A)c aquifer	5	37	3.7	10
Q(B) undifferentiated sediments	6	3.7	0.12	30

3.3 Hydraulic Properties

Layers were simulated as having uniform hydraulic properties throughout the full extent of each layer. Only hydraulic conductivity was specified because storage coefficients are not required for steady-state simulations. Initial horizontal hydraulic conductivity values were taken from Turney and others (1995), and initial horizontal hydraulic conductivity values for confining units were taken from Vaccaro and others (1998). Confining unit values were sourced from Vaccaro and others (1998) because values reported in Turney and others skew abnormally high (see discussion in Section 3.3).

Values for vertical hydraulic conductivity were not identified during in previous investigations, so vertical hydraulic conductivity was estimated using the method described in Drost and others (1999) for another Puget Lowland groundwater flow model. Drost and others (1999) assigned vertical anisotropy values to each layer, then calculated vertical hydraulic conductivity from horizontal conductivity values. Anisotropy is the quotient of the horizontal and vertical hydraulic conductivities (K_h/K_v). Aquifer units were assigned a vertical anisotropy of 10. Confining units were assigned a vertical anisotropy of 100. The Q(B) undifferentiated sediments were assigned an anisotropy of 30 to reflect the likely presence of aquifers and confining materials within the layer.

3.4 Boundary Conditions and Implementation of MODFLOW Packages

Specified flux and head-dependent flux conditions were used to simulate different hydrologic boundaries where those boundaries occur in the model domain. Specified flux boundaries are cells that are instructed to add water to or remove water from the groundwater system at constant rates independent of other model conditions. Recharge from precipitation was modeled as a specified flux in the simulation. Head-dependent flux boundaries add or remove water in response to the head gradient between the boundary cell and adjacent cells. Surface water features and seeps were modeled as head-dependent flux conditions.

A special type of specified flux boundary, called a no-flow boundary, was used to simulate impermeable boundaries. As the name implies, no-flow boundaries allow no water to pass into or through them. Examples of no-flow boundaries include bedrock and groundwater divides. Where no-flow boundaries occur within the model domain, such as in the Newcastle Hills and where layers are absent in Lake Sammamish and Washington, no-flow conditions are explicitly simulated using no-flow boundary cells located in the model domain. No-flow conditions located outside of, yet still acting on, the modeled system are simulated implicitly. Implicit no-flow boundaries occur along the edges and bottom of the model domain instead of occupying cells within the domain. The inferred groundwater divide along the northern edge of the study area and bedrock present below the model domain are simulated as implicit no-flow boundaries.

3.4.1 Recharge Package

Recharge from precipitation was simulated using the MODFLOW Recharge Package (RCH). Recharge was simulated as a specified flux into the cell occupying the highest active model layer. Recharge was calculated for each cell as the mean annual recharge following the relationships described in Bidlake and Payne (2001) and Savoca and others (2010) (further discussion in Section 2.4 of this report). Figure 15 depicts the spatial distribution of recharge values used in the simulation.

3.4.2 River Package

Steams and lakes (excluding Lake Sammamish and Lake Washington) were simulated using the River Package (RIV) (Figure 16). The River Package specifies head-dependent fluxes through the tops of the cells where it is active. The River Package calculates the flux to a cell as the difference between the boundary head (the head in the surface water feature being modeled, h_{RIV}) and the head in the cell (h) multiplied by the conductance (C) of the boundary. When the head within the boundary is larger than the head in the cell, water moves into the cell. When the head within the cell is larger than the head in the boundary, water moves into the boundary. The conductance of the boundary describes the ability of water to move from the boundary into the specified cell and is calculated using (Equation 1).

$$C_{RIV} = \frac{K_{RIV}A}{m} \qquad (1)$$

Where

C_{RIV} = conductance of the river boundary

K_{RIV} = the vertical hydraulic conductivity of the riverbed or lakebed sediments

A = the area occupied by the river in the specified cell

As described in Section 3.6, surface water heads were estimated using LiDAR data from PSLC (2000) and checked against gage observations where available. The vertical hydraulic conductivity of the riverbed sediments was estimated as the vertical hydraulic conductivity of the underlying cell. No data concerning the thickness of riverbed or lakebed sediments was identified during conceptualization, so the thickness of riverbed sediments was assumed to be 3 feet for all features. The area of the boundary within each model cell was estimated from the National Hydrography Dataset (USGS, 2017a). A constant width of 8 feet was assumed for features in the National Hydrography dataset with only the length of the feature reported.

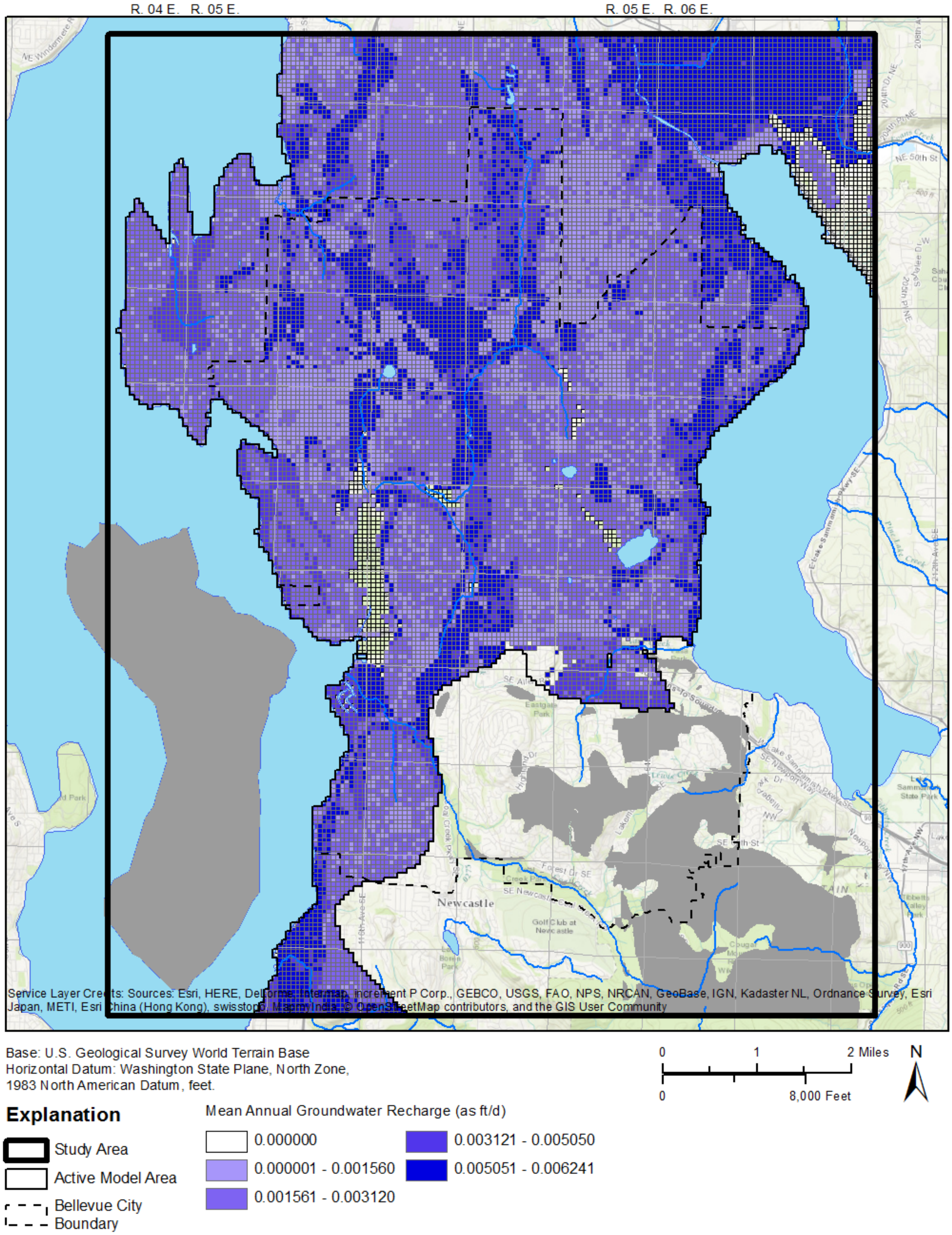
3.4.3 Drain Package

Seeps were simulated using the Drain Package (DRN) (Figure 16). No information on seep locations, except that they exist along stream valley and shoreline bluffs, was identified during conceptual model development. Drain boundaries were located in aquifer cells where LiDAR data (PSLC, 2000) indicated surface slopes greater than 30 degrees to estimate the edges of layers terminating in bluffs.

Like the River Package, the Drain Package specifies head-dependent fluxes through the tops of cells where it is active. Unlike the River Package, water may flow only from the cell into the boundary and out of the model domain. The flux into the boundary is calculated in the same manner as for the River Package except the flux is equal to the difference between a specified drain elevation and the head in the cell multiplied by the conductance of the boundary. The drain elevation simulates the elevation at which water exits the model domain and was specified as the LiDAR-derived ground surface elevation at the drain location. Conductances for drain boundaries were set arbitrarily high (1,000,000 ft^2/day) to allow the hydraulic properties of the cell to limit flux following Anderson and others (2015).

3.4.4 General Head Package

Lake Sammamish and Lake Washington were simulated using the General Head Boundary Package (GHB) (Figure 16). General Head Boundaries are head-dependent flux boundaries that occupy cells within the model grid and operate similar to other head-dependent flux packages. Flux from the General Head Boundary cell into adjacent cells is calculated as the difference in head between the boundary cell and the adjacent cell multiplied by the conductance of the boundary cell. Heads in General Head Boundary cells were set to 30.02 feet NAVD88 for cells simulating Lake Sammamish and 17.88 feet NAVD88 for cells simulating Lake Washington following average lake levels described in Section 3.6. Conductances for General Head Boundaries were calculated using the hydraulic conductivity of the hydrogeologic unit the cell is in contact with and the area of the cell face.



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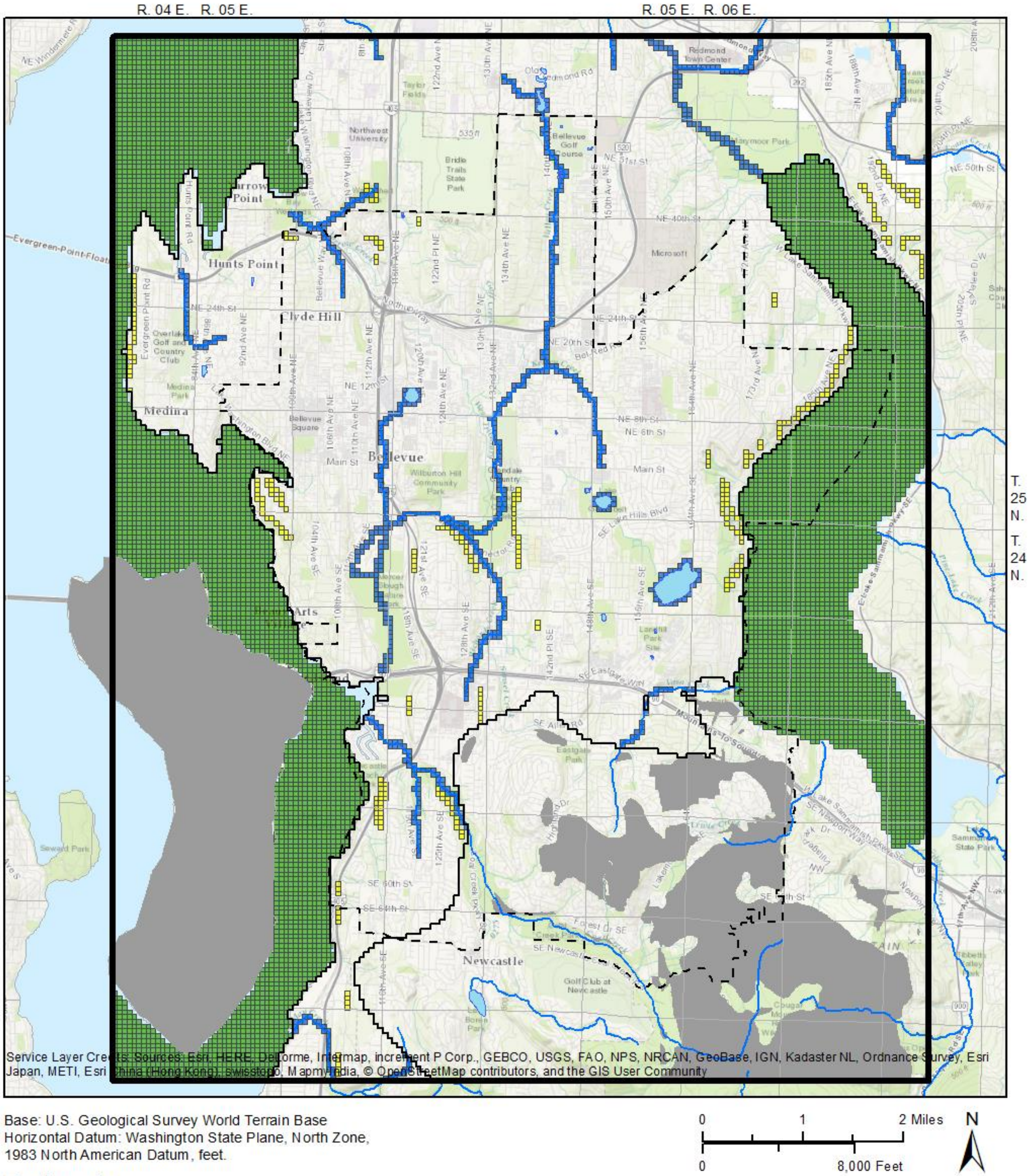
Base: U.S. Geological Survey World Terrain Base
Horizontal Datum: Washington State Plane, North Zone,
1983 North American Datum, feet.

Figure 15. Distribution of mean annual groundwater recharge from precipiation in Bellevue and Vicinity



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Base: U.S. Geological Survey World Terrain Base
Horizontal Datum: Washington State Plane, North Zone, 1983 North American Datum, feet.

Explanation

- ▭ Study Area
- ▭ Active Model Area
- ┌ ─ ┐ Bellevue City Boundary

Model boundary conditions

- 🟨 Drain (Seeps)
- 🟦 River (Streams and small lakes)
- 🟩 General head (Lake Washington and Lake Sammamish)

Figure 16. Locations of model boundary conditions in Bellevue and Vicinity

4. Model Calibration

This section describes the adjustment of model parameters to improve the model's ability to match field observations of the groundwater system. This adjustment process, known as calibration, was undertaken to evaluate the completeness of the conceptual model and to gain insight into the modeled system by identifying which parameters exert the greatest control over the system. Conceptual model completeness was evaluated by checking if observed values could be reproduced using reasonable model parameters (i.e. parameters within a range of values possible in the real world). Identifying which parameters held the greatest influence over simulation results provided insight into which aspects of the groundwater system would most benefit from future real-world investigation.

4.1 Calibration Procedure

Water level observations compiled by Troost Geosciences (2015) were used to calibrate the groundwater flow model (Figure 17). Calibration was performed using the parameter estimation program PEST (Doherty, 2016). PEST was used to adjust selected hydrogeologic parameters until simulated water levels most closely matched the observed Troost Geosciences (2015) water levels. All observed values were given equal weight in the calibration process. PEST was allowed to automatically adjust horizontal and vertical hydraulic conductivities for each layer within two orders of magnitude of the initial value. The conductances of RIV boundaries in each of 6 sub-basins (Figure 18) and the conductances for GHB boundaries in Lake Sammamish and Lake Washington were allowed to vary by three orders of magnitude of the initial value.

4.2 Parameter Sensitivity

Parameter sensitivity describes the relative influence a parameter exerts on the simulation solution. Sensitive parameters are parameters for which incremental changes produce large changes in simulation results. Parameters which cause small or no changes to simulation results are relatively insensitive. Parameter sensitivity for each parameter is expressed as the composite sensitivity coefficient in Figure 19. The composite sensitivity coefficient is equal to the average change in simulated heads at all calibration points divided by the change in the value of the parameter.

The sensitivity analysis indicates that the vertical hydraulic conductivity of Layer 2 (kz2; the vertical hydraulic conductivity of the Qvt) is approximately 1.5 times more sensitive than any other parameter. Horizontal hydraulic conductivities for Layer 3 (kx3; the horizontal hydraulic conductivity of the Qva) and Layer 5 (kx5; the horizontal hydraulic conductivity of the Q(A)c) are also significantly more sensitive than any other parameter except the vertical hydraulic conductivity of Layer 2.

4.3 Final Parameter Values

Calibrated parameter values are presented in Table 5. Horizontal hydraulic conductivity values all experienced changes less than one order of magnitude. Calibrated horizontal hydraulic conductivities for all layers declined except those of Layer 3. Values of vertical hydraulic conductivity were similarly decreased, except for Layer 1 and Layer 3 where values increased by approximately 1.5 times. Values for RIV boundary conductance were all strongly changed in the calibration process. River boundary cells in sub-basins 1,4, and 5 were increased by nearly two orders of magnitude. GHB conductances all declined by at least two orders of magnitude.

Though calibration resulted in substantial changes to many parameters, particularly conductance values, all values appear reasonable. Final hydraulic conductivity values fall within ranges described in Vaccaro and others (1998). River conductance values generally increased, indicating closer (but still realistic) communication with the groundwater system. Greatly diminished GHB conductances are consistent with the presence of significant lakebed silts and clays in Lakes Washington and Sammamish.

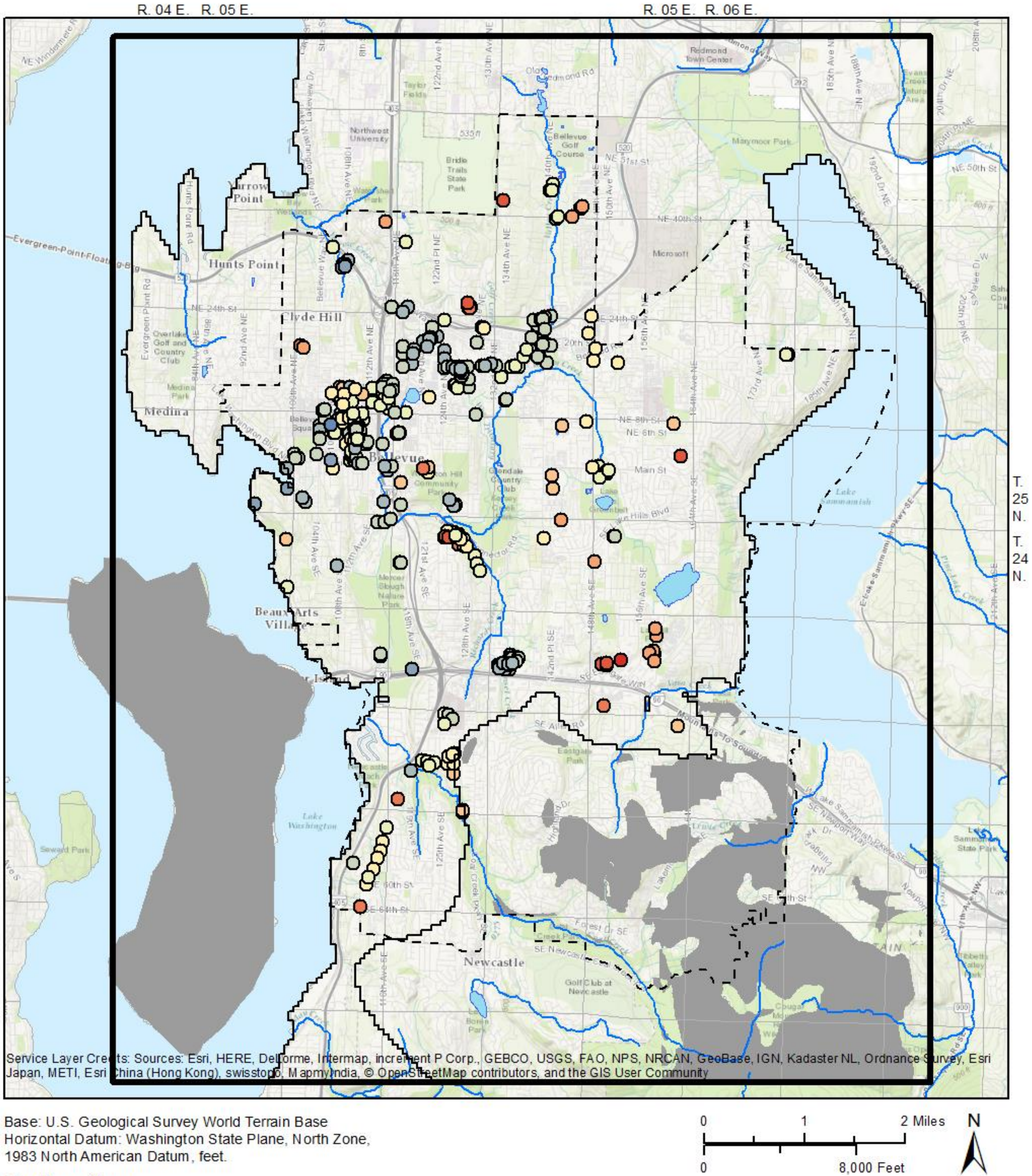
Table 5. Final calibrated parameter values

Hydraulic Conductivity						
	K_h (ft/d)			K_v (ft/d)		
Layer	Initial Value	Final Value	Fractional Change	Initial Value	Final Value	Fractional Change
1	61	28.27	0.46	6.1	8.84	1.45
2	14.2	3	0.21	0.142	1.22E-03	0.01
3	35	92.97	2.66	3.5	6.03	1.72
4	2.3	1.36	0.59	0.023	9.34E-03	0.41
5	37	17.67	0.48	3.7	1.98	0.54
6	3.7	0.86	0.23	0.12	8.47E-02	0.71

RIV Conductance (ft^2/d)					
Sub-basin	Initial Conductance			Final Value	Fractional Change[1]
	Minimum	Mean	Maximum		
rv0	0.04	825.87	3381.55	761.4	0.92
rv1	1.93	1456.3	6206.81	98684.19	67.76
rv2	19.28	3893.35	6250	87613.04	22.50
rv3	4.7	3151.21	16106.53	1635.86	0.52
rv4	0.86	1241.44	2480.6	99987.2	80.54
rv5	6.3	1063.18	3190.98	99412.91	93.51
rv6	1.22	18260.85	82396.48	101	0.01
rv7	0.53	486.74	3274.94	69.53	0.14

(1) Change computed compared to the mean initial conductance

GHB Conductance (ft^2/d)			
GHB Zone	Initial Value	Final Value	Fractional Change
gh2	562.5	17.81	0.03
gh3	23125	18.98	0.001
gh4	937.5	17.93	0.02
gh5	937.5	30.17	0.03



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Base: U.S. Geological Survey World Terrain Base
Horizontal Datum: Washington State Plane, North Zone,
1983 North American Datum, feet.

Explanation

Study Area

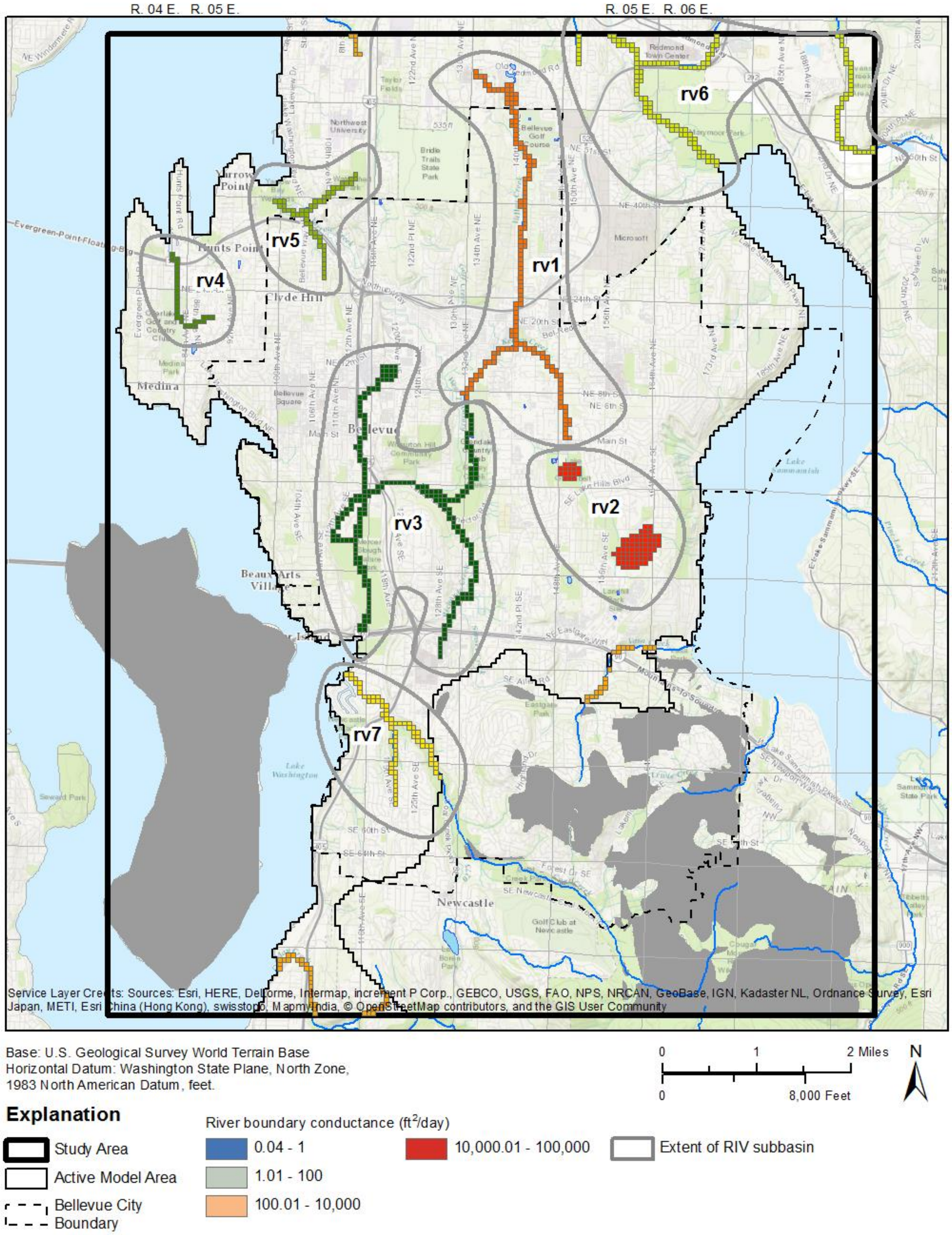
Active Model Area

Bellevue City Boundary

Water level used in calibration (color indicates residual in feet)

- ● -110 - -100
- ● -90 - -75
- ● -74 - -50
- ○ -49 - -25
- ○ -24 - 0.0
- ○ 0.010 - 25
- ○ 26 - 50
- ○ 51 - 75
- ● 76 - 100
- ● 110 - 130
- ● 140 - 150
- ● 160 - 180

Figure 17. Locations of water level data used in model calibration, Bellevue and vicinity, Washington



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Base: U.S. Geological Survey World Terrain Base
Horizontal Datum: Washington State Plane, North Zone,
1983 North American Datum, feet.

Figure 18. Locations of RIV sub-basins and final conductance values, Bellevue and vicinity, Washington

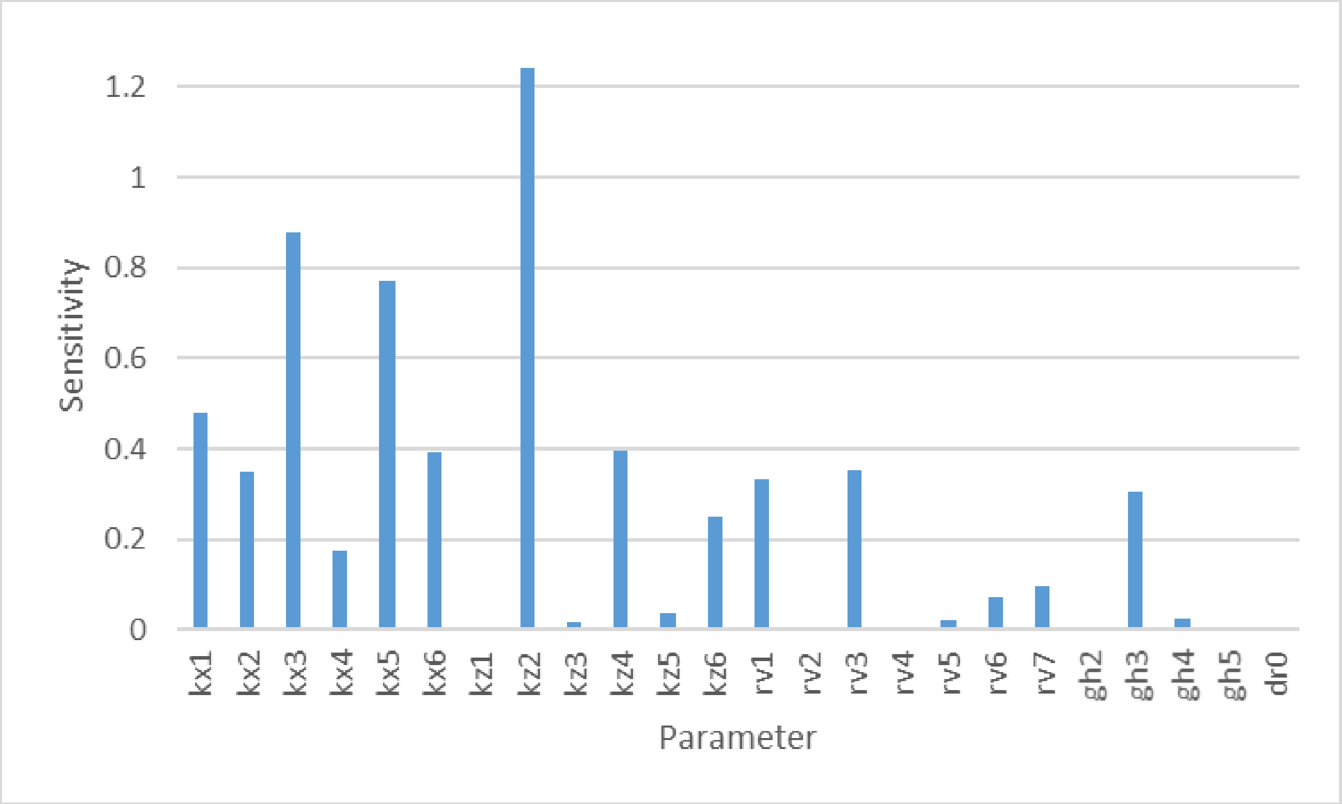


Figure 19. Sensitivity coefficients for parameters used in model calibration. Parameter names correspond to the parameter type (rv = river counductance, kx = horizontal hydraulic conductivity, kz = vertical hyraulic conductivity, gh = general head boundary conductance) and parameter layer or sub-basin (RIV boundaries only). For example, rv1 is the river conductance for RIV cells in sub-basin 1 and kx3 is the horizontal hydraulic conductivity of Layer 3.

4.4 Assessment of Calibration

The adequacy of the model calibration was assessed by examining the magnitude and distribution of residuals (the difference between simulated and observed values following calibration) and the reasonableness of calibrated values for model parameters (Section 5.3). Table 6 provides commonly reported calibration statistics for residual values, including the sum of squared residuals. PEST attempts to minimize the sum of squared residuals during calibration runs.

Figure 20 presents a graphical comparison of simulated water levels and observed water levels. The diagonal line in Figure 20 represents perfect agreement of simulated and observed water levels. Figure 20 indicates that simulated water levels generally agree with observations at lower elevations (less than approximately 250 feet NAVD88), but heads simulated at greater elevations are generally underpredicted (plot beneath the agreement line). The figure further indicates that water levels in Layers 2 and 3 are generally under predicted, regardless of elevation.

The spatial distribution of water level observations and their residuals are plotted in Figure 17. Review of the spatial distribution that residuals are smallest in the Downtown area, and that residuals generally increase with increasing distance from Downtown.

Table 6. Calibration statistics by hydrogeologic unit

Layer	Count of observations	Residual Mean (ft)	Residual Standard Deviation (ft)	Minimum Residual (ft)	Maximum Residual (ft)	Sum of Squared Residuals (ft^2)	Root Mean Square Error (ft)
1	41	0.10	40.06	-57.64	109.10	6.50E+04	40.06
2	109	23.22	41.14	-48.80	155.74	2.43E+05	74.24
3	98	25.16	41.24	-75.11	143.63	2.29E+05	48.31
4	81	-15.58	28.72	-66.96	115.76	8.65E+04	32.67
5	45	-16.42	38.84	-108.39	148.12	8.00E+04	42.17
6	10	11.01	50.09	-40.81	114.26	2.63E+04	51.29
All	384	8.10	42.86	-108.39	155.74	7.31E+05	43.62

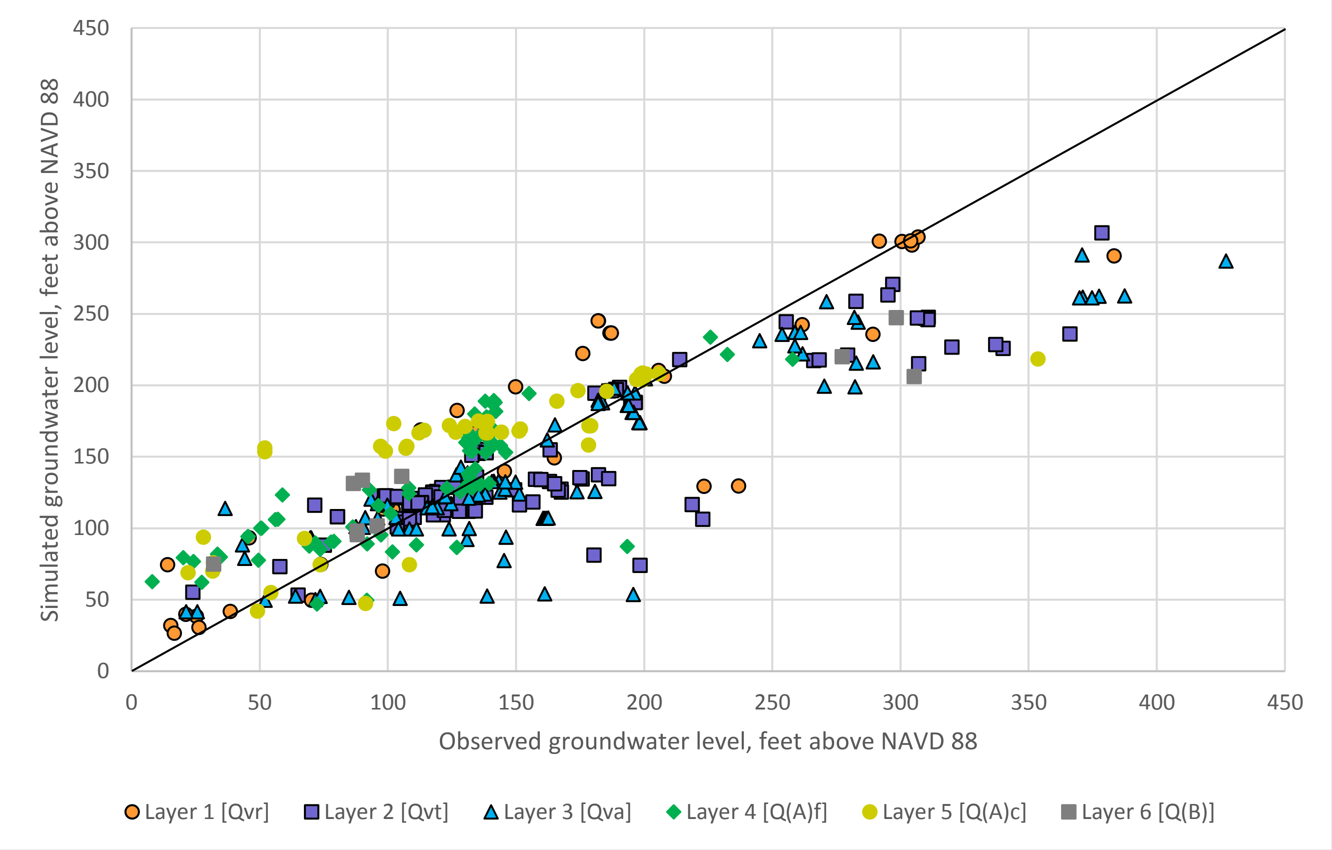


Figure 20. Comparison of simulated and observed water levels

5. Numerical Model Limitations

This section describes the adequacy of the calibrated model for its intended purpose as described in Section 2. Numerical models are inherently simplified representations of complex natural systems built for a specific purpose. Numerous interpretations, approximations, and assumptions documented in this report all contribute error to model results. Although assessment of model calibration indicates the numerical model is suitable for its intended use to simulate regional groundwater flow directions and zones of recharge and discharge, the model is limited in its usefulness in simulating more localized conditions.

The water level dataset used in model calibration is temporally and spatially biased. Water levels naturally fluctuate with time, making perfect agreement between observed heads, which reflect the groundwater system in a transient state, and simulated steady-state heads, which reflect the expected average all transient heads at a location unlikely without a dataset that captures the full range of possible transient water levels. This effect could not be quantified for this study because no locations with multiple water level measurements were present within the calibration dataset.

Water levels used in the calibration exhibit strong spatial bias. Ideally, observations would cover the entire study area in a well-distributed manner without clusters of observations. Observations in the dataset used for calibration are clustered near Downtown Bellevue. Because no correction was made for clustering of calibration points, the calibration was biased to reproduce water levels in the downtown area better than areas with few calibration points.

The use of water level data from wells also introduces bias. Water level observations used in this study came from measurements made in wells, most of which were completed in the shallowest unit capable of producing groundwater in the quantities necessary for the intended use. Wells are therefore often biased towards shallow and permeable hydrogeologic units. Clustering of wells in aquifer units means the calibration used for this study placed greater emphasis on those units. Observations in confining units are also suspect as wells completed in those units are likely to target the most permeable parts of the unit.

Finally, flow data were not used in model calibration. Flow data, especially data collected in flowing surface water features, represent an important check on the accuracy of simulated boundary conditions. No readily available flow data was identified during the conceptual model build, and so none was used in the numerical modeling.

6. Model Application

This section describes estimated components of the water budget, areas of discharge and recharge, and regional flow directions simulated by the calibrated numerical model. Results presented in this section are subject to the uncertainties described in Section 6.

6.1 Model-Derived Groundwater Budget

The model-derived groundwater budget describing the simulated inflows to and outflows from the model domain is presented in Table 7. The overall water balance, the difference between inflows and outflows, was calculated to be -0.5 ft^3/d (0.000001% of total inflows). This means the calibrated model simulated 0.5 ft^3/d more water leaving the model domain than leaving it. This error is very small and is caused by the numerical approximation.

The groundwater budget indicates that more water enters the groundwater system through leakage from surface water features such as streams and small lakes than from precipitation recharge. Conceptually this distribution of inflows may be interpreted to mean that a significant fraction of precipitation runs off into surface water features and then leaks into the groundwater system. The presence of Qvt at or near the surface across most of the model domain is likely the reason than river leakage contributes roughly equal flow as direct recharge from precipitation because the Qvt's low hydraulic conductivities cause run off sooner than more permeable units. The distribution of RIV cells receiving water from and contributing water to the groundwater system reinforces the possibility (Figure 21). Cells situated at higher elevations are simulated to lose water to surface water features, while those at lower elevations (below the bottom of the Qvt) are simulated to gain water from the surface water features.

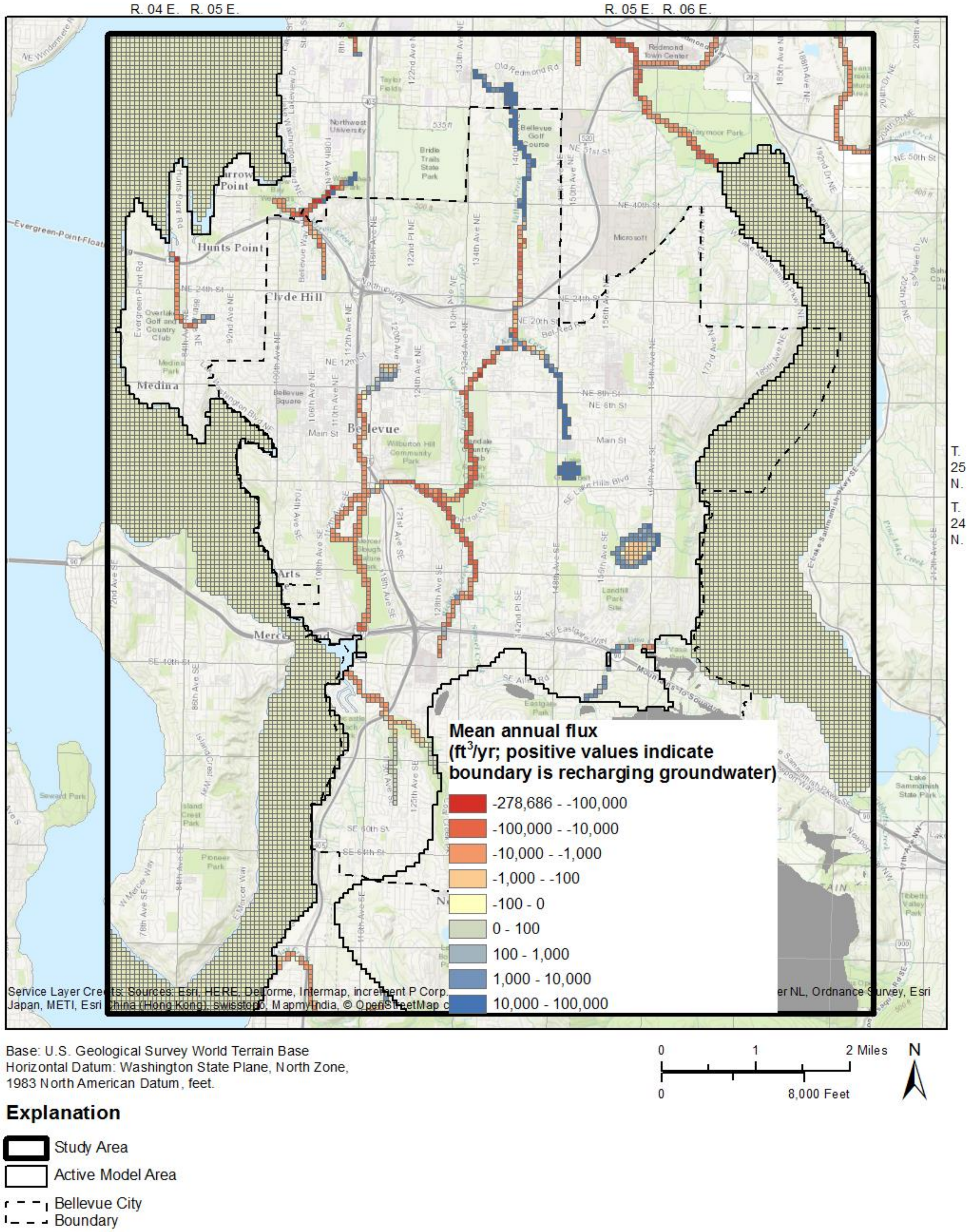
Absent from the inflow column are the General Head Boundaries (GHB) that represent Lakes Sammamish and Lake Washington. Both lakes receive outflow from the model domain (Figure 21), yet neither provides inflow. This designates that one lake or the other is the ultimate destination for water moving through the groundwater system (except for losses to evapotranspiration during surface transport).

Outflows are far less evenly distributed than inflows with 76 percent of water exiting the model through RIV boundaries. This distribution is misleading, as groundwater discharged to surface water bodies at high elevations is likely to leak back into the groundwater system at lower elevations as described above. Discharge to drains also potentially reenters the groundwater system as seeps encounter different hydrogeologic units, though this phenomenon is likely weaker as many seepage faces are relative close to the shores of Lake Washington and Lake Sammamish.

Importantly, both outflows and inflows are significantly smaller than the mean annual precipitation over the model domain. Model inflows are approximately 35 percent of total precipitation, which is firmly within the typical range of reported precipitation-recharge ratios for the Puget Lowland.

Table 7. Model-derived groundwater budget

Boundary	**Inflows (ft^3/d)**	**Percent of Total Inflow**	**Boundary**	**Outflows (ft^3/d)**	**Percent of Total Outflow**
RIV	4.37E+07	56%	RIV	5.96E+07	76%
RCH	3.48E+07	44%	DRN	1.21E+07	15%
			GHB	6.77E+06	9%
Total	7.85E+07		Total	7.85E+07	
		Inflows - Outflows =	-0.5	ft3/d	
		Percent Discrepancy =	-0.000001%		



Base: U.S. Geological Survey World Terrain Base
Horizontal Datum: Washington State Plane, North Zone, 1983 North American Datum, feet.

Figure 21. Simulated exchange of water with surface water features, Bellevue and vicinity, Washington

6.2 Model-Derived Groundwater Flow Directions

Simulated heads indicate a strong regional gradient towards the confluence of Mercer Slough and Lake Washington for all layers (Figures 22 though 27). Several smaller gradients also exist that move water directly towards the nearest major lake, including in the Medina Peninsula and along the shoreline of Lake Sammamish. As suggested by the groundwater budget, heads indicate flow into streams in the highlands and from streams in the lowlands. The simulated heads reveal an important consequence of this flow regime: every kettle lake is simulated to lose significant flows to groundwater due to their position on top of the drift plain.

The Qvr aquifer is receives direct recharge from precipitation and from surface water leakage. The Qvr primarily discharges within lowlands into major streams within the study area. The Qva aquifer is recharged by precipitation slowly percolating through the Qvt confining unit and by surface water features where they intersect the Qva. The Qva primarily discharges into lowland streams like the Qvr, but also discharges through seeps throughout the study area. Nearly all recharge to the Q(A)c aquifer occurs within lowland areas where erosional processes have removed or thinned the Qvt and Q(A)f confining units. This occurs primarily in the former spillways of Glacial Lake Sammamish. The Q(A)c discharges though seeps, into streams, and directly into Lakes Washington and Sammamish.

7. Summary

Bellevue, Washington is rapidly developing and seeks to better understand the groundwater resources available to the city. This study integrated existing data into a conceptual model of the hydrogeologic framework and groundwater flow within the city and surroundings. A numerical groundwater flow model was developed from the conceptual model to simulate the natural operation of the groundwater system, and to identify hydrologic features and properties of regional importance.

The study area covers about 85 mi^2 in northwestern King County, and includes the City of Bellevue and surrounding areas (Figure 1). The active numerical model domain covers a smaller area (approximately 43 mi^2); and excludes areas where bedrock is present at the surface and portions of Lake Washington Lake Sammamish, and Mercer Island. The extent of the study area was chosen to include natural hydrologic boundaries, and lies between Lake Sammamish to the east and Lake Washington to the west. The Newcastle Hills form the southern boundary. An inferred groundwater divide approximately 1 mile north of the Bellevue city boundary form the northern boundary.

Unconsolidated sediments in the study area are composed of glacial materials deposited during the Vashon stade of the Fraser Glaciation, and underlying materials of earlier glacial and interglacial periods. This study defined 3 aquifer units, 2 confining units, and an underlying zone of undifferentiated sediments. The unconsolidated sediments rest upon consolidated bedrock. Consolidated bedrock is present at the surface in the Newcastle Hills at the southern extent of the study area. The bedrock surface dips sharply the north to approximately 1,000 feet below ground surface as it crosses the Seattle Fault Zone. The unconsolidated sediments thicken in conjunction with the decline in the bedrock surface.

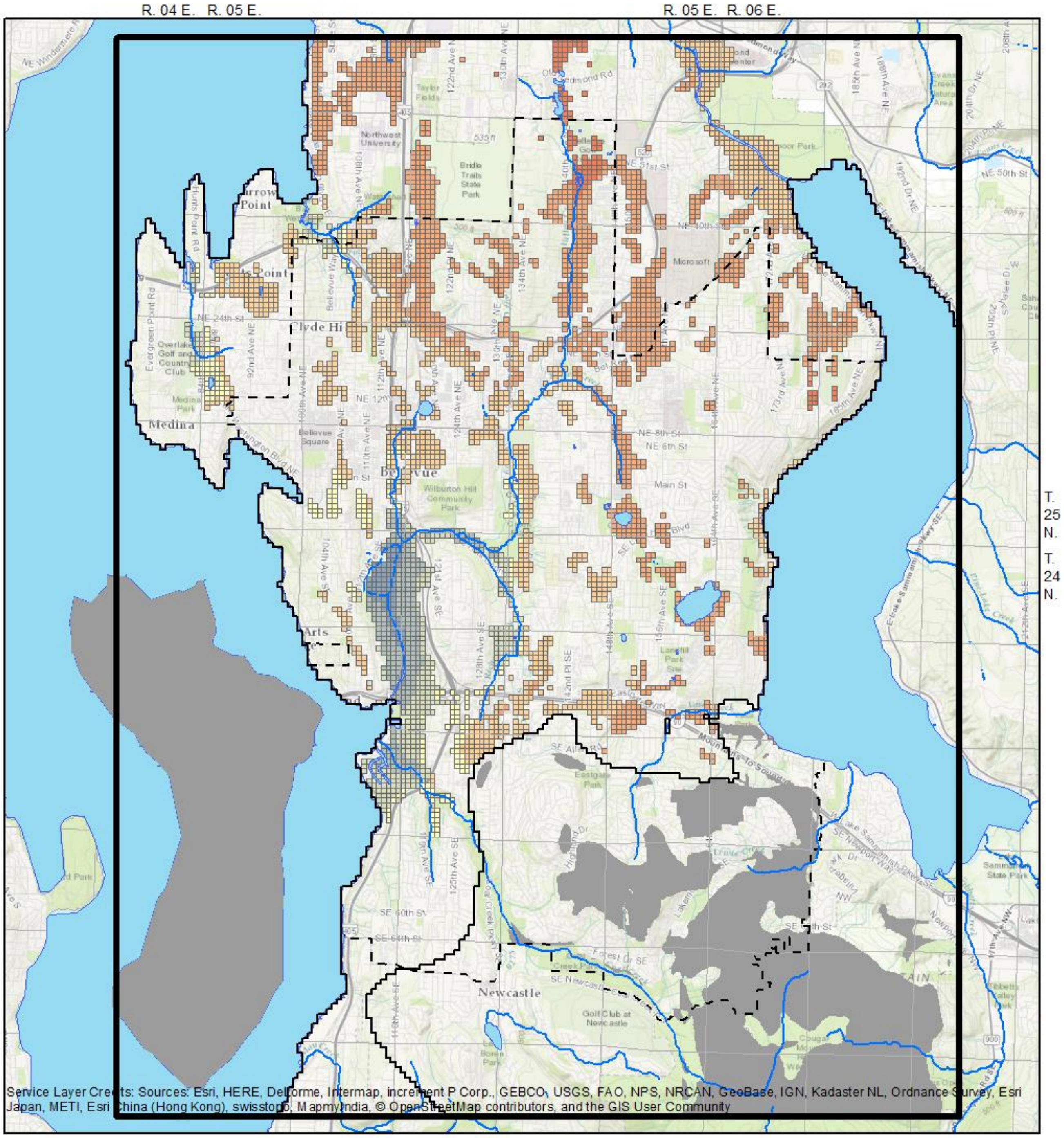
The numerical groundwater flow model of the study area was coded using MODFLOW-NWT to simulate steady-state groundwater flow and features of regional importance. The model used 131,830 active cells defined by 220 rows, 172 columns, and 6 layers. Each layer directly corresponded to a hydrogeologic unit defined in this study. Cells were uniformly 250 feet long by 250 feet wide and varied in thickness in conjunction with the cell's assigned layer. Bedrock was simulated as impermeable where it occurred within the study area. Precipitation recharge to the groundwater system was simulated using the MODFLOW Recharge Package. The General-Head Boundary Package was used to simulate Lake Washington and Lake Sammamish. All other surface water features (kettle lakes, streams, rivers) were simulated using the River Package. Groundwater seeps were simulated using the Drain Package.

The numerical model was calibrated using PEST, a parameter estimation program, and water level data collected by others. PEST varied initial estimates for selected parameters within a specified range to minimize the discrepancy between simulated and observed heads. Parameters open to adjustment included hydraulic conductivity for all layers and conductances at all boundary conditions except drain boundaries. The calibrated model has a standard deviation of 42.86 feet for heads in all layers. Sensitivity analyses conducted during calibration indicated that the vertical hydraulic conductivity of the uppermost confining unit (the Vashon till) exerted the greatest influence on simulation results.

The simulated water budget indicates that recharge enters the groundwater through percolation of precipitation, and surface water leakage from streams and kettle lakes approximately equally. Approximately three-fourths of groundwater is discharged from the groundwater system into streams. The remainder discharges though bluff shoreline bluff faces as seeps, and as direct discharge into Lake Sammamish and Lake Washington.

8. Acknowledgements

The author wishes to thank Jonathan Turk of Brown and Caldwell, for his mentoring, assistance, and review during this investigation. The author would like to further thank Kathy Troost of the University of Washington and Troost Geosciences for facilitating the study and providing access to her data from previous investigations of the Bellevue area. The author also thanks Juliet Crider and J. Michael Brown of the University of Washington for serving on the reading committee that reviewed this paper. Brown and Caldwell generously provided workspace, access to software, and flexible scheduling to the author for this investigation.



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Base: U.S. Geological Survey World Terrain Base
Horizontal Datum: Washington State Plane, North Zone,
1983 North American Datum, feet.

0 1 2 Miles
0 8,000 Feet
N

Explanation

Study Area
Active Model Area
Bellevue City Boundary

Simulated groundwater levels in feet above NAVD 88

0 - 25
25 - 50
50 - 75
75 - 100
100 - 200
200 - 300
300 - 400
400 - 500
500 - 600

Figure 22. Simulated steady-state water levels in hydrogeologic unit Qvr, Bellevue and vicinity, Washington

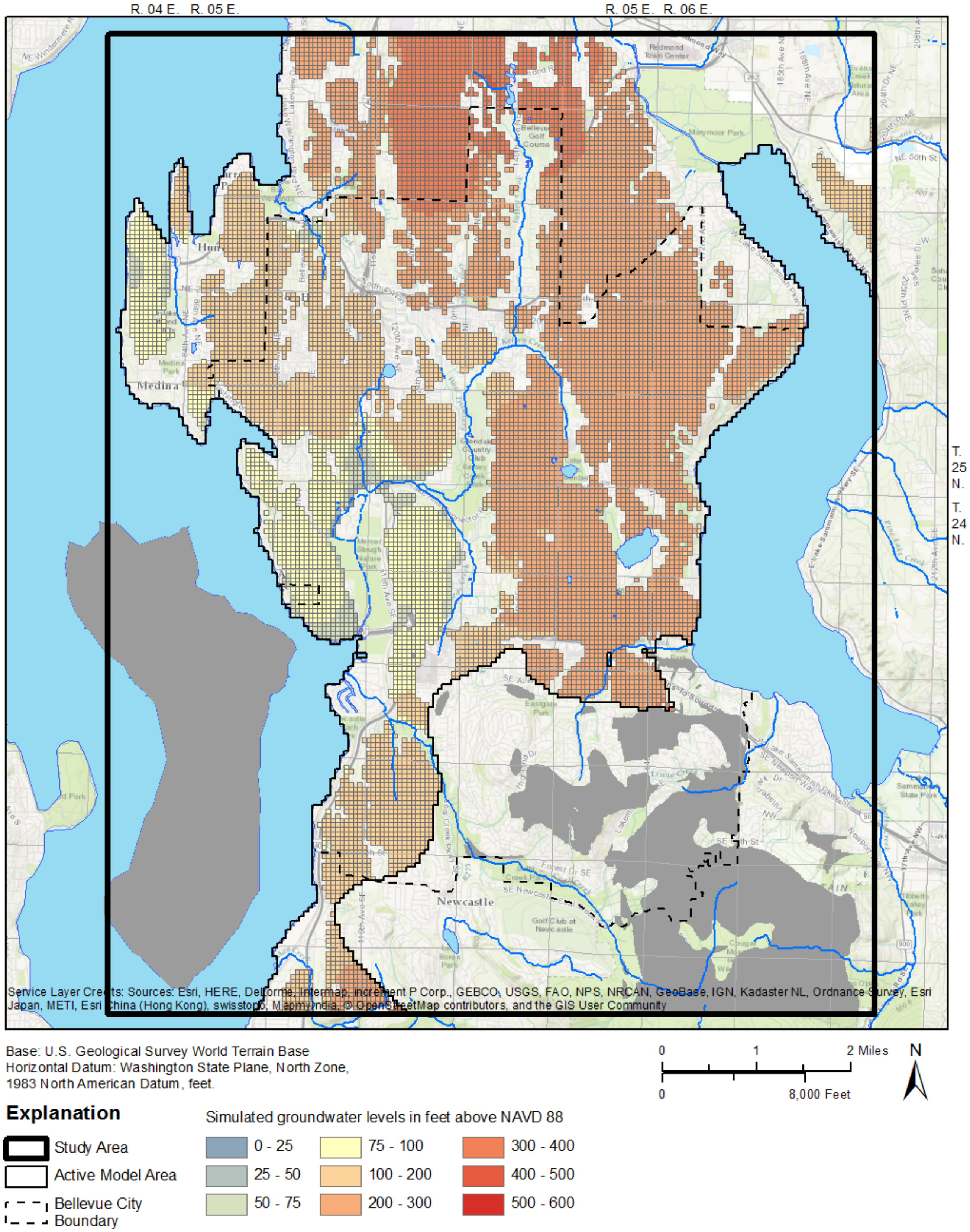
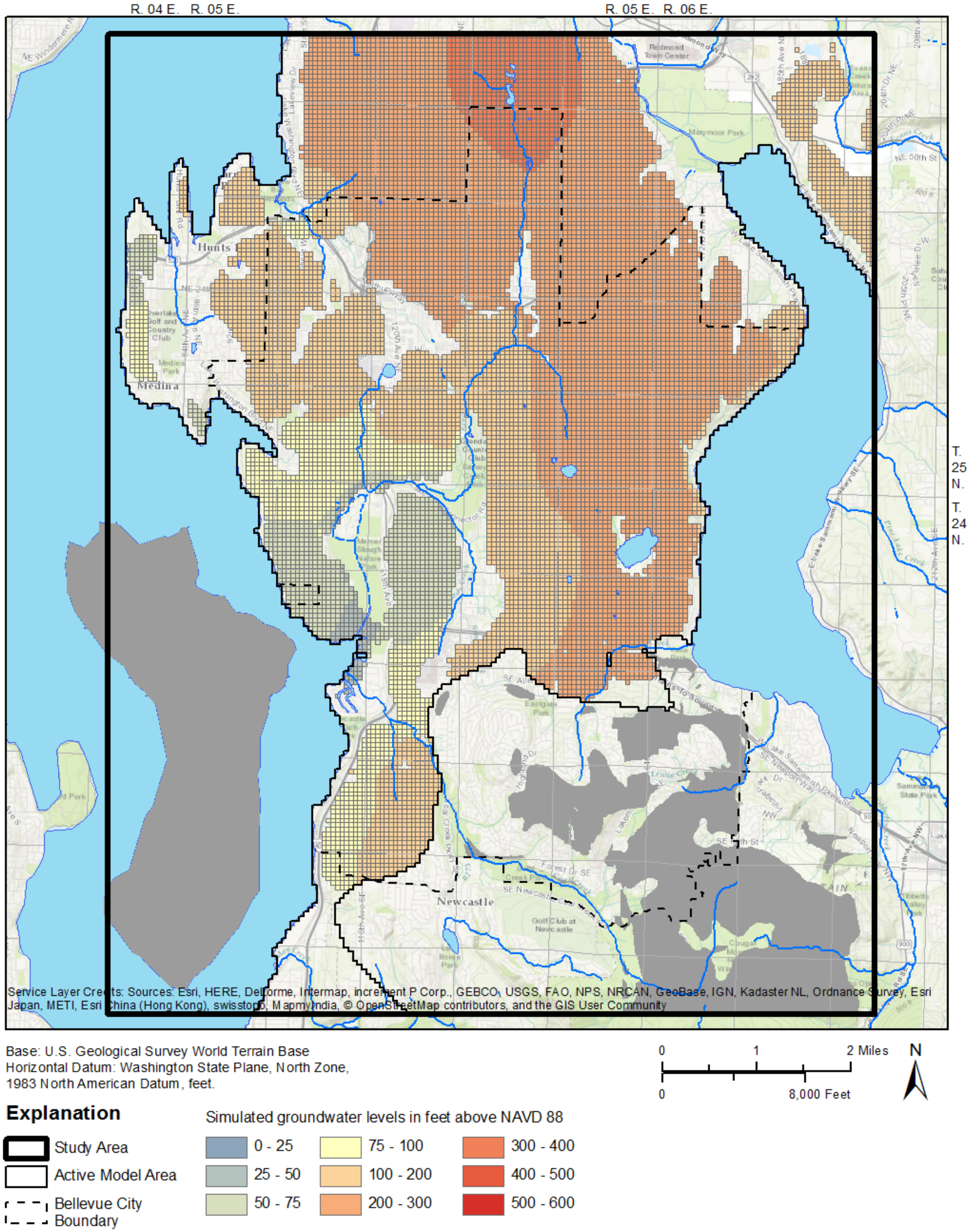


Figure 23. Simulated steady-state water levels in hydrogeologic unit Qvt, Bellevue and vicinity, Washington



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Base: U.S. Geological Survey World Terrain Base
Horizontal Datum: Washington State Plane, North Zone,
1983 North American Datum, feet.

Figure 24. Simulated steady-state water levels in hydrogeologic unit Qva, Bellevue and vicinity, Washington

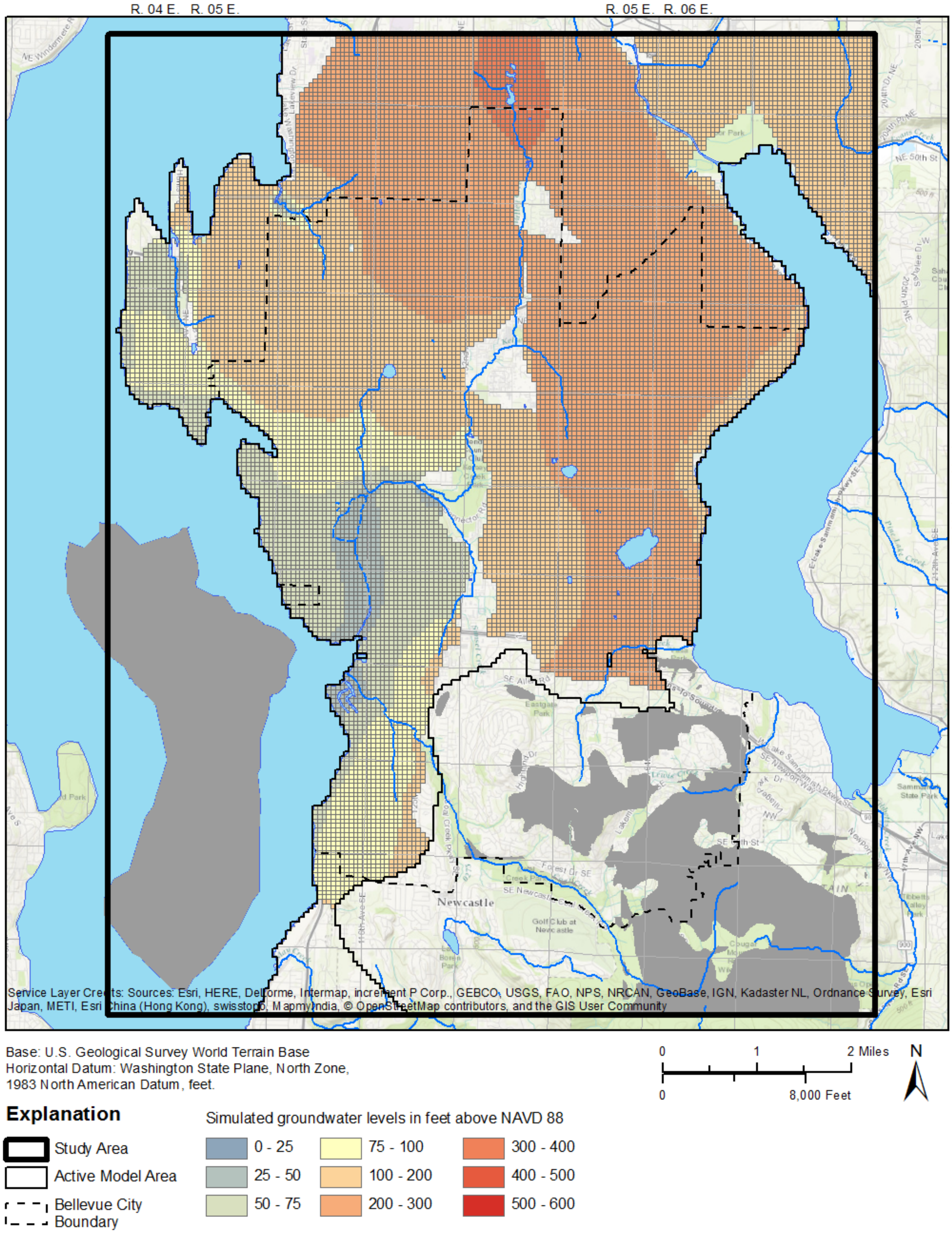


Figure 25. Simulated steady-state water levels in hydrogeologic unit Q(A)f, Bellevue and vicinity, Washington

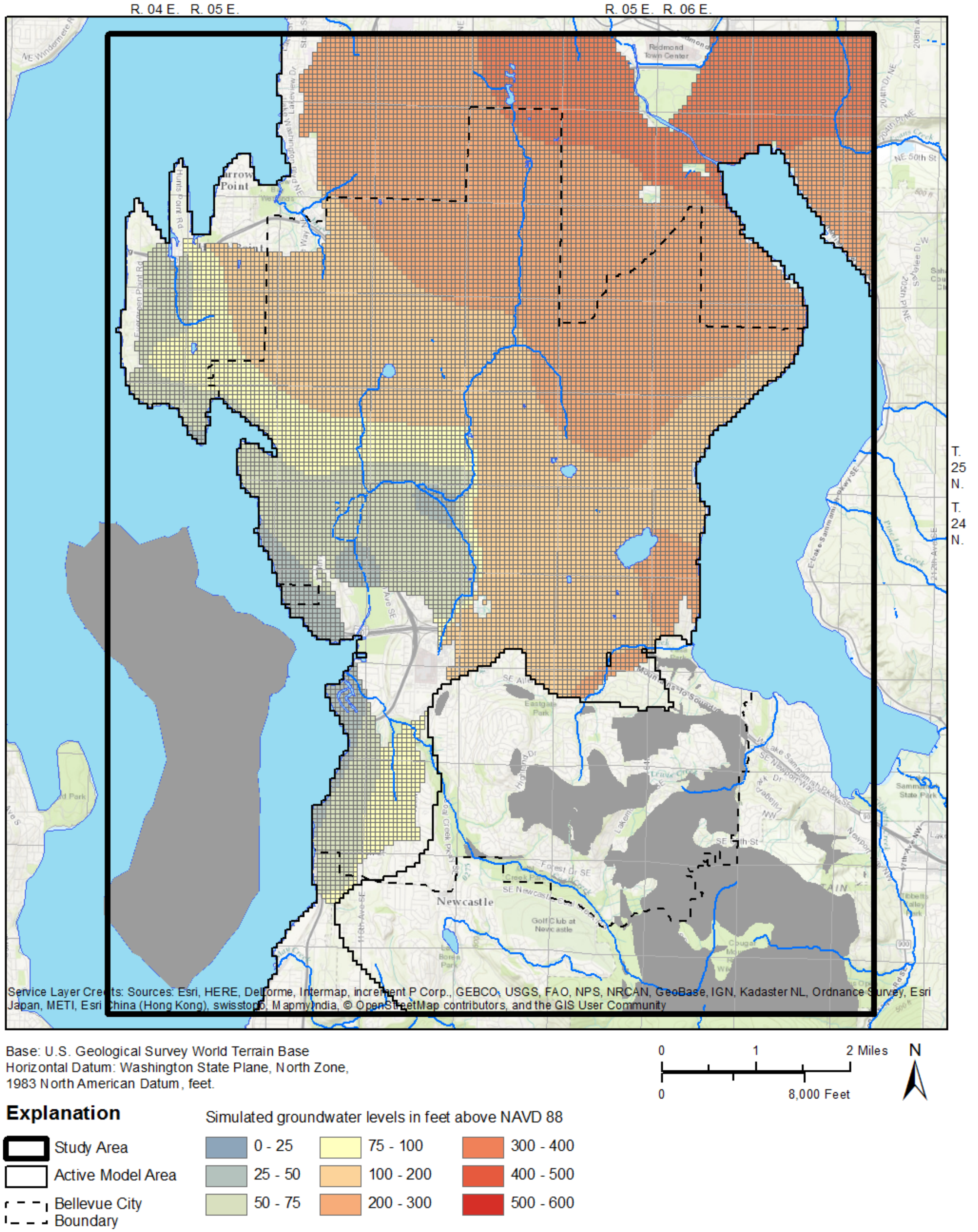
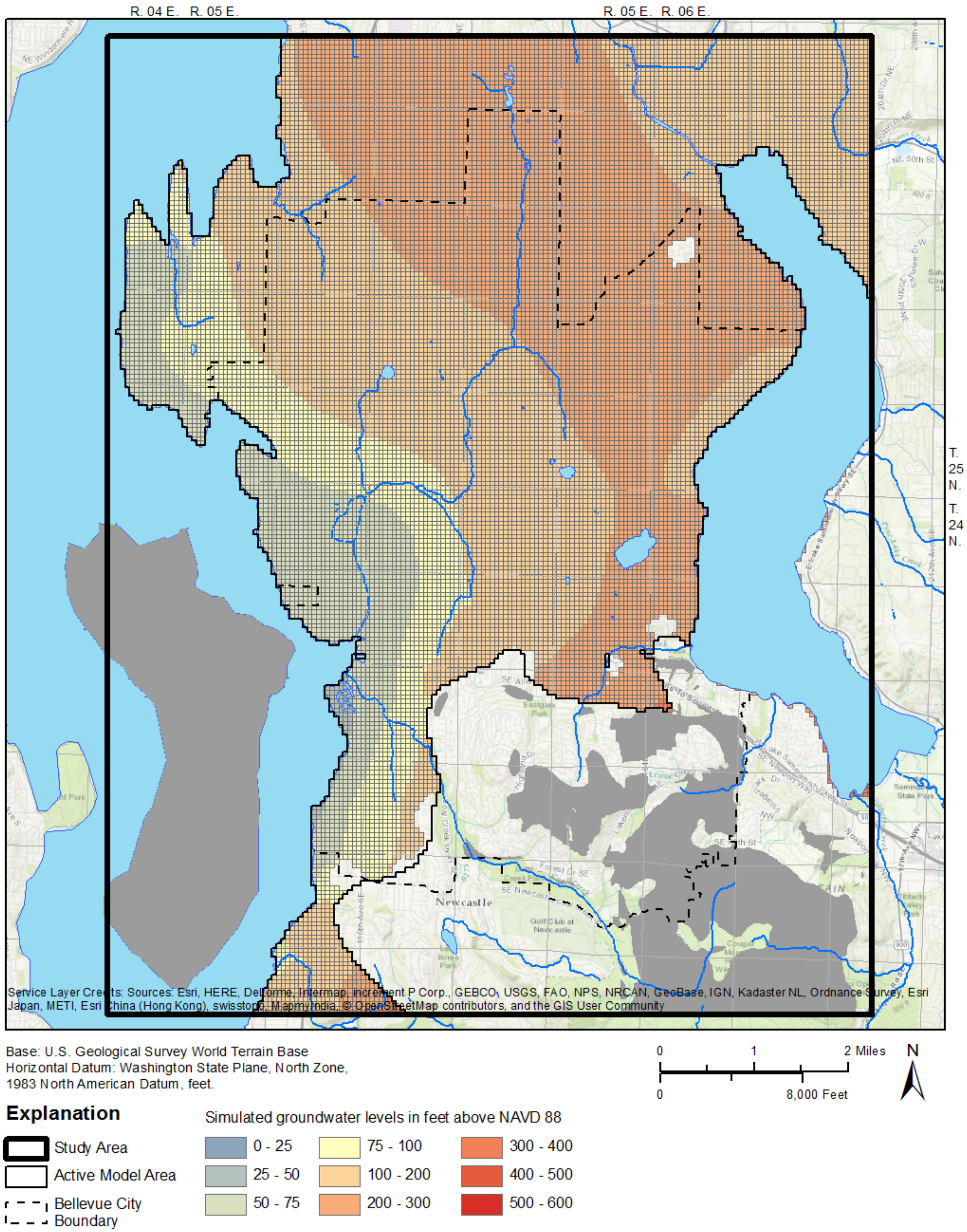


Figure 26. Simulated steady-state water levels in hydrogeologic unit Q(A)c, Bellevue and vicinity, Washington



Service Layer Credits: Sources: Esri, HERE, DeLorme, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, Mapmyindia, © OpenStreetMap contributors, and the GIS User Community

Base: U.S. Geological Survey World Terrain Base
Horizontal Datum: Washington State Plane, North Zone,
1983 North American Datum, feet.

Figure 27. Simulated steady-state water levels in hydrogeologic unit Q(B), Bellevue and vicinity, Washington

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