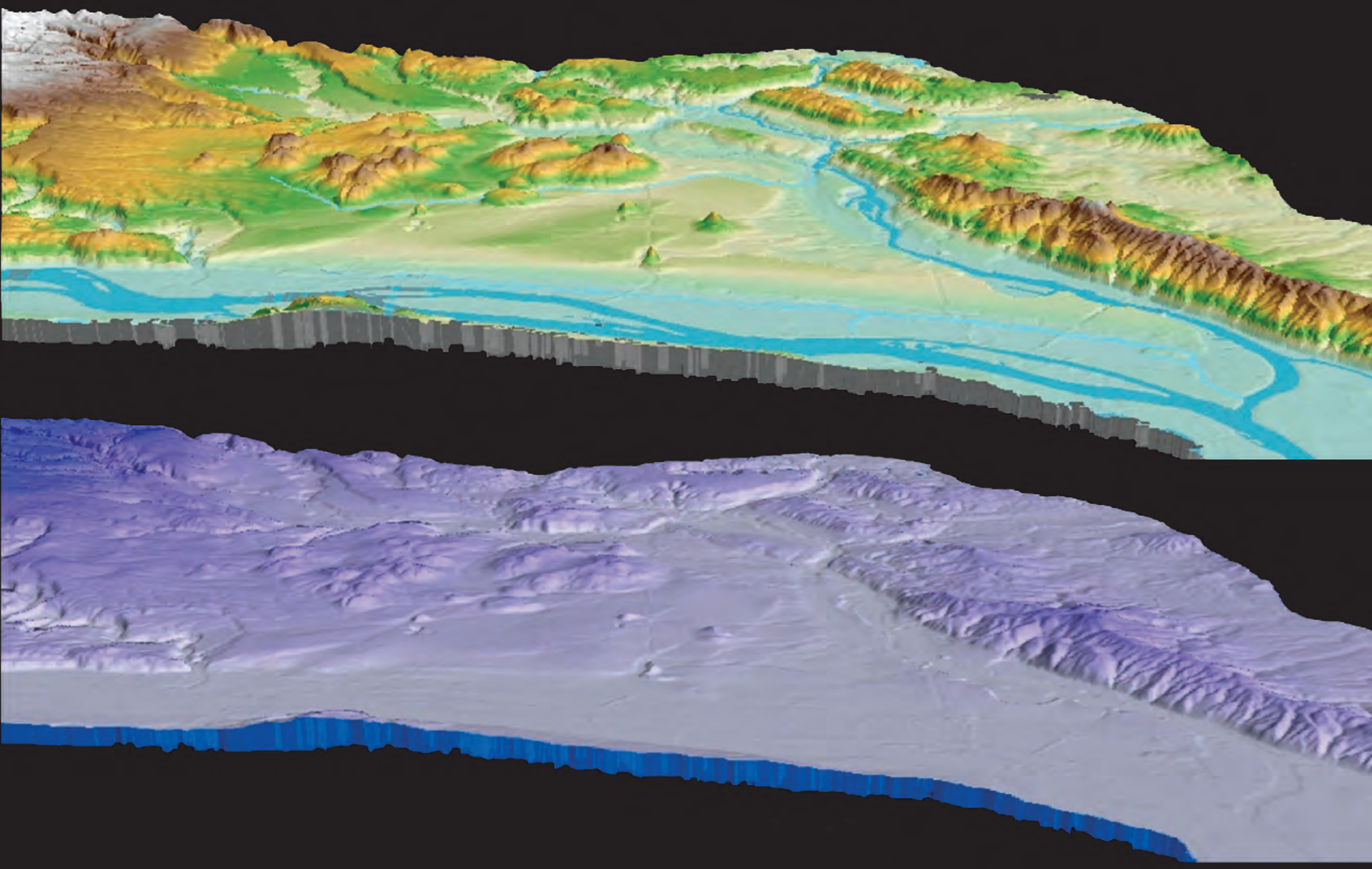
Prepared in cooperation with the City of Portland, the City of Gresham, Clackamas County's Water Environment Services, and Multnomah County

Estimated Depth to Ground Water and Configuration of the Water Table in the Portland, Oregon Area



Scientific Investigations Report 2008–5059

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

Cover: Oblique view from north of Portland, Oregon showing the land-surface topography (top) and the configuration of the water table (bottom). Land-surface elevation is derived from a 2-meter resolution digital elevation model. Water-table surface is derived from interpolation of depth to water as measured in wells and using surface-water features representative of the water table. Vertical scale is exaggerated 1.2X. Separation between land surface and the water table is exaggerated.

Estimated Depth to Ground Water and Configuration of the Water Table in the Portland, Oregon Area

By Daniel T. Snyder

Prepared in cooperation with the City of Portland, the City of Gresham, Clackamas County's Water Environment Services, and Multnomah County

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U.S. Department of the Interior
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U.S. Department of the Interior
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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
section (640 acres or 1 square mile)	259.0	square hectometer (hm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
meter (m)	1.094	yard (yd)

Datums

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

Sea level, in this report, is used to represent the 0-foot elevation as referenced to NAVD 88. Conversion between NAVD 88 and the commonly used National Geodetic Vertical Datum of 1929 (NGVD 29) varies spatially; however, over most of the study area the following conversion can be used: NGVD 29 = NAVD 88 – 3.5 feet. This conversion generally is accurate within about +/- 0.5 feet. The reader is directed to either the National Geodetic Survey website for VERTCON at http://www.ngs.noaa.gov/TOOLS/Vertcon/vertcon.html or the U.S. Army Corps of Engineers website for Corpscon at http://crunch.tec.army.mil/software/corpscon/corpscon.html for more accurate conversions.

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

Conversion between NAD 83 and the commonly used North American Datum of 1927 (NAD 27) varies spatially, and the difference in lateral positions can be greater than 300 feet. For assistance with conversions, the reader is directed to either the National Geodetic Survey website for NADCON at http://www.ngs.noaa.gov/TOOLS/Nadcon/Nadcon.html or the U.S. Army Corps of Engineers website for Corpscon at http://crunch.tec.army.mil/software/corpscon/corpscon.html.

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

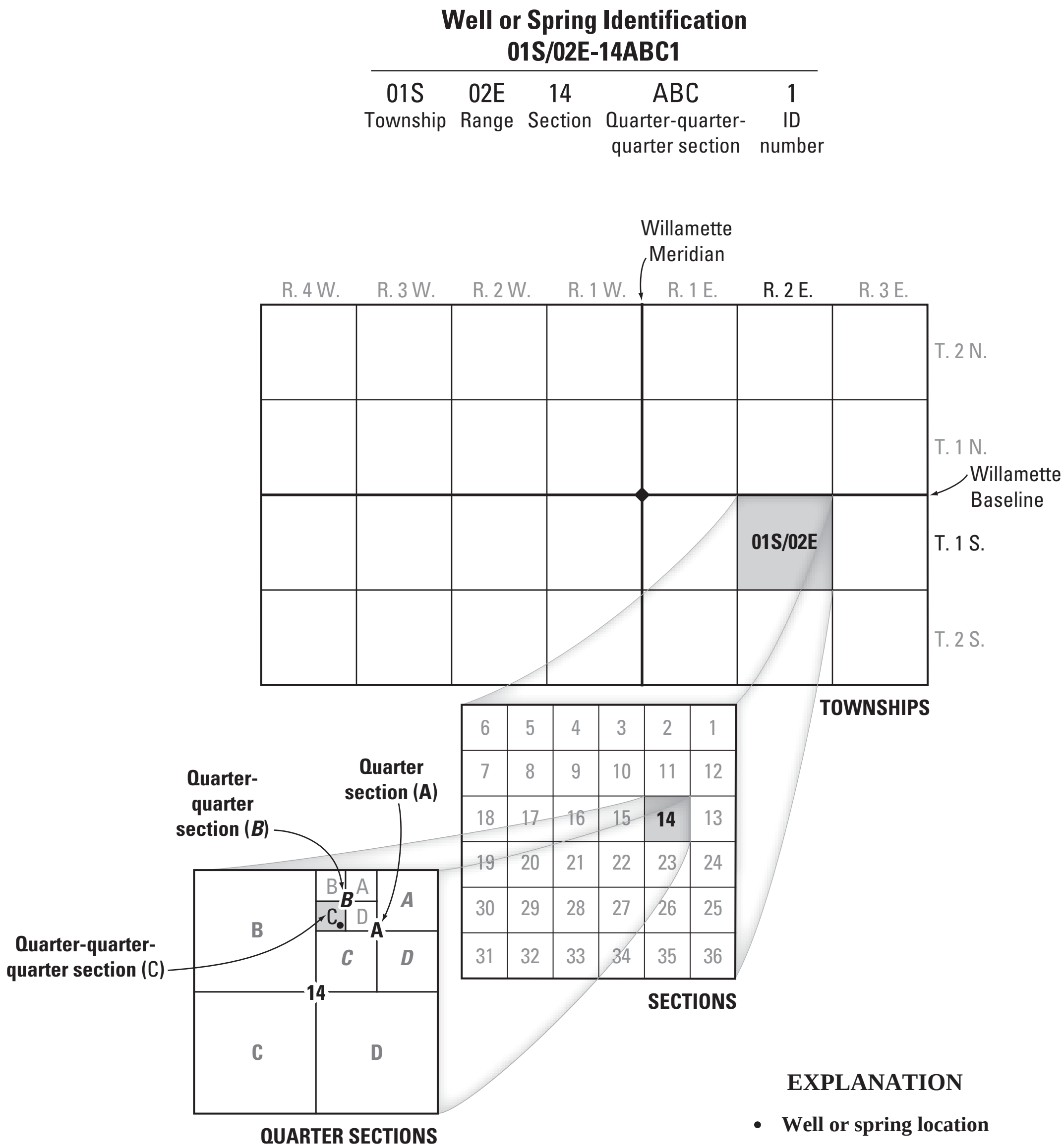
Vertical coordinate information for historical data collected and stored as NGVD 29 has been converted to NAVD 88 for this publication.

Horizontal coordinate information for historical data collected and stored as NAD 27 has been converted to NAD 83 for this publication.

Location System and Well and Spring Identifiers

The system used for locating wells, springs, and surface-water sites in this report is based on the Public Land Survey System, a set of rectangular surveys that is used to identify land parcels. The State of Oregon is divided into townships of 36 square miles numbered according to their location relative to the east-west Willamette baseline and a north-south Willamette meridian. The position of a township is given by its north-south "Township" position relative to the baseline and its east-west "Range" position relative to the meridian. Each township is divided into 36 one-square-mile (640-acre) sections numbered from 1 to 36. A well designated as 01S/02E-14ABC1, for example, is located in Township 1 south, Range 2 east, section 14. Letters following the section number correspond to the location within the section; the first letter (A) identifies the quarter section (160 acres); the second letter (B) identifies the quarter-quarter section (40 acres); and the third letter (C) identifies the quarter-quarter-quarter section (10 acres). Therefore, well 14ABC is located in the SW quarter of the NW quarter of the NE quarter of section 14. When more than one designated well occurs in the quarter-quarter-quarter section, a serial number is appended.

Location System and Well and Spring Identifiers—Continued



Well- and Spring-Location System

Each well and spring also is assigned a unique 15-digit "USGS Site Number," which is a site-identification number permanently designated by the U.S. Geological Survey and recorded in the National Water Information System (NWIS), a national computer database maintained by the U.S. Geological Survey.

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Estimated Depth to Ground Water and Configuration of the Water Table in the Portland, Oregon Area

By Daniel T. Snyder

Abstract

Reliable information on the configuration of the water table in the Portland metropolitan area is needed to address concerns about various water-resource issues, especially with regard to potential effects from stormwater injection systems such as UIC (underground injection control) systems that are either existing or planned. To help address these concerns, this report presents the estimated depth-to-water and water-table elevation maps for the Portland area, along with estimates of the relative uncertainty of the maps and seasonal water-table fluctuations.

The method of analysis used to determine the water-table configuration in the Portland area relied on water-level data from shallow wells and surface-water features that are representative of the water table. However, the largest source of available well data is water-level measurements in reports filed by well constructors at the time of new well installation, but these data frequently were not representative of static water-level conditions. Depth-to-water measurements reported in well-construction records generally were shallower than measurements by the U.S. Geological Survey (USGS) in the same or nearby wells, although many depth-to-water measurements were substantially deeper than USGS measurements. Magnitudes of differences in depth-to-water measurements reported in well records and those measured by the USGS in the same or nearby wells ranged from –119 to 156 feet with a mean of the absolute value of the differences of 36 feet. One possible cause for the differences is that water levels in many wells reported in well records were not at equilibrium at the time of measurement. As a result, the analysis of the water-table configuration relied on water levels measured during the current study or used in previous USGS investigations in the Portland area. Because of the scarcity of well data in some areas, the locations of select surface-water features including major rivers, streams, lakes, wetlands, and springs representative of where the water table is at land surface were used to augment the analysis.

Ground-water and surface-water data were combined for use in interpolation of the water-table configuration. Interpolation of the two representations typically used to define water-table position—depth to the water table below land surface and elevation of the water table above a datum—can produce substantially different results and may represent the end members of a spectrum of possible interpolations largely determined by the quantity of recharge and the hydraulic properties of the aquifer. Datasets of depth-to-water and water-table elevation for the current study were interpolated independently based on kriging as the method of interpolation with parameters determined through the use of semivariograms developed individually for each dataset. Resulting interpolations were then combined to create a single, averaged representation of the water-table configuration. Kriging analysis also was used to develop a map of relative uncertainty associated with the values of the water-table position.

Accuracy of the depth-to-water and water-table elevation maps is dependent on various factors and assumptions pertaining to the data, the method of interpolation, and the hydrogeologic conditions of the surficial aquifers in the study area. Although the water-table configuration maps generally are representative of the conditions in the study area, the actual position of the water-table may differ from the estimated position at site-specific locations, and short-term, seasonal, and long-term variations in the differences also can be expected. The relative uncertainty map addresses some but not all possible errors associated with the analysis of the water-table configuration and does not depict all sources of uncertainty.

Depth to water greater than 300 feet in the Portland area is limited to parts of the Tualatin Mountains, the foothills of the Cascade Range, and much of the Boring Hills. In addition to the low-lying areas along major rivers and streams, areas of notably shallow depths to water include the area consisting of former alluvial channels extending from the confluence of Johnson and Crystal Springs Creeks northward to the Willamette River and southward to the Clackamas River, much of the area adjacent to Johnson Creek, the area extending from Beggars Tick Marsh eastward to Holgate Lake at the west end of Powell Butte, the area around Fairview Creek, and the west end of Lake Oswego. These regions of shallow depths to water may represent areas of concern with regard to existing or planned stormwater injection systems.

The surface representing the water-table elevation is similar to land surface; the highest elevations are in the Tualatin Mountains, Boring Hills, and foothills of the Cascade Range, and the lowest elevations are along major rivers and streams and in the terrace deposits in the northern, eastern, and northeastern parts of the city of Portland. Regional ground-water flow is toward the major ground-water discharge areas, consisting of the Columbia, Willamette, and Clackamas Rivers. Locally, shallow ground-water flow direction derived from the water-table elevation map generally is toward adjacent streams and rivers. A notable exception is in the middle and upper parts of the Johnson Creek drainage basin, where much of the shallow ground water flows toward the Sandy, Columbia, or Willamette Rivers.

The range of seasonal water-table fluctuations in shallow wells used for analysis with water-level measurements distributed throughout the year ranged from 1 to 22 feet with a mean of 7 feet. Results of the analysis indicated that differences in the spatial distribution of seasonal fluctuations of the water table in the Portland area largely were a function of the effective porosity of the hydrogeologic unit in the range of fluctuation of the water table and, therefore, were categorized by hydrogeologic unit. Small seasonal water-table fluctuations occur throughout the study area but are more heavily concentrated in the terraced areas between the Willamette and Columbia Rivers north and west of the Boring Hills. Seasonal fluctuations generally are largest in the Sandy, Boring, and Damascus areas with few exceptions.

Introduction

There has always been a need for reliable information on the configuration of the water table in the Portland, Oregon area (fig. 1), for a multitude of purposes. This information typically is used in construction of buildings, roads, and infrastructure; well drilling; evaluation of aquifer susceptibility; and the design of monitoring programs to determine the extent and severity of possible aquifer contamination. However, recent and planned construction of new infrastructures for diverting stormwater runoff have raised concerns regarding the protection of ground-water resources in the Portland area and have emphasized the need for information about the configuration of the water table. Presently (2008), large numbers of underground injection control (UIC) systems (for example, stormwater injection systems, sumps, and drywells) are used to divert stormwater runoff into the subsurface. Additional UIC systems are expected to be constructed, and stormwater runoff also will be diverted to other types of stormwater drainage systems such as vegetated swales, pervious pavement, disconnected downspouts, and other diversion methods that are designed to allow for the infiltration of stormwater. The goals are to manage surface runoff and to protect the quality of water entering rivers, streams, and the ground-water flow system. However, information is needed regarding the configuration of the water table to help determine the appropriate use of these diversion methods to meet regulatory requirements and to minimize the effect on ground-water quality and ground-water levels. To help provide this information, the U.S. Geological Survey (USGS), in cooperation with the City of Portland, City of Gresham, Clackamas County's Water Environment Services, and Multnomah County began a study in 2003 to determine the configuration of the water table in the Portland area.

Purpose and Scope

The purpose of this report is to present estimated depth-to-water and water-table elevation maps for the Portland metropolitan area, along with estimates of the relative uncertainty, and seasonal water-table fluctuations. The study area comprises most of the Portland metropolitan area, where an increasing need for information on the position of the water table and issues pertaining to UIC systems have come to the forefront. The area previously was the focus of an extensive USGS regional ground-water study providing a foundation for the current investigation.

The method of analysis used to determine the configuration of the water table in the Portland area relied on water-level data collected from shallow wells as part of the current study or used in previous USGS investigations and on surface-water features that are representative of the water table, including major rivers, streams, lakes, wetlands, and springs. Depth to water and water-table elevation were interpolated independently based on kriging methods and then combined into a single representation of the water-table position. Kriging methods also were used to develop a map of relative uncertainty associated with the values of the water-table position. Range of seasonal water-table fluctuations was evaluated based on wells with multiple water-level measurements distributed throughout the seasons and then categorized by hydrogeologic unit.

Background

Hydrologic Definitions and Principles

This section contains a short introduction to some ground-water terms and principles to help the reader better understand concepts discussed in the main body of the report.

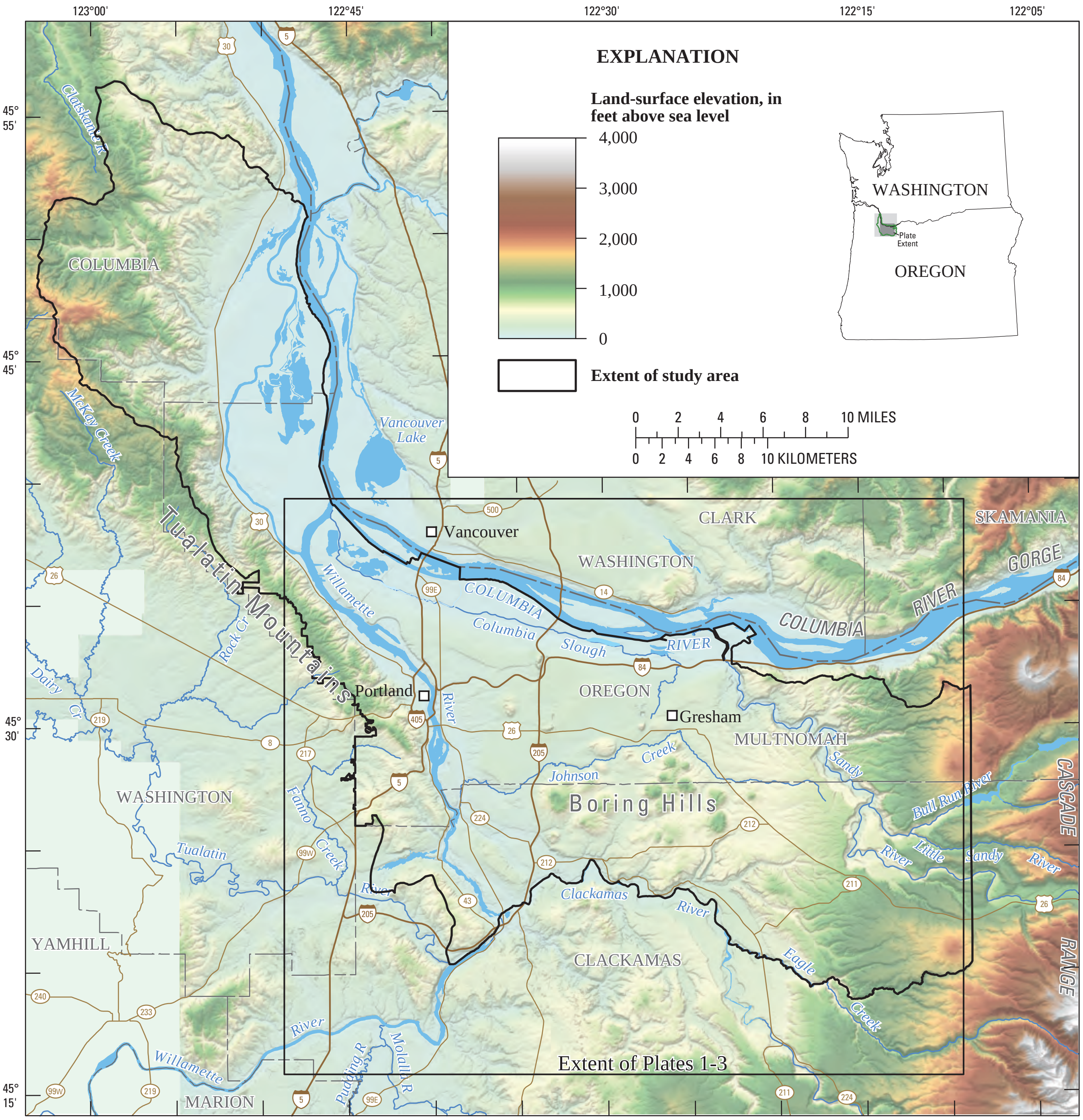


Figure 1. Location of the study area in the Portland Basin in northwestern Oregon.

Definition of the Water Table

Technical definition of the water table is the imaginary surface in an unconfined aquifer at which the pressure is atmospheric (Lohman, 1972b, p. 1). The water table is thought of as the surface representing the top of the saturated zone, below which all pores in the rock matrix are filled with water (fig. 2). The water table is defined by the levels at which water stands in wells that just penetrate the top of the water body (Lohman, 1972a, p. 14). Additional information on the position of the water table is provided by the locations of surface-water features that interact with the water table, which can include rivers, streams, lakes, wetlands, and springs (Fetter, 1994, p. 114-115).

The above definition of the water table excludes

- Capillary fringe water—water in the unsaturated zone that is held by capillary forces and may be under tension (negative pressure);
- Confined water—water in the saturated zone between two impermeable rock layers, which may result in the water being under pressure; and
- Perched water—water that is unconfined ground water separated from an underlying body of ground water by an unsaturated zone (Lohman, 1972a, p. 7) (fig. 2).

Perched ground water typically is isolated from the regional water table by low-permeability beds.

The two conventions typically used to define the position of the water table (fig. 2) are depth and elevation: (1) depth to the water table below land surface is referred to as "depth to water" in this study and also referred to as the "unsaturated zone thickness;" and (2) the elevation of the water table above a datum (NAVD 88, a representation of mean sea level is used in this study; see section "Datums" for more information), which will be referred to as "water-table elevation." The two conventions are related and can be equated as follows:

water-table elevation = land-surface elevation – depth to water below land surface (elevations are in feet NAVD 88; depth is in feet).

Depth-to-water values can be transformed (converted) to values of water-table elevation based on this equation, if the land-surface elevation is known and, conversely, the water-table elevation can be transformed to depth to water. The terms "water-table position" or "water-table level" will be used to refer to the vertical location of the water table independent of the convention used to define it.

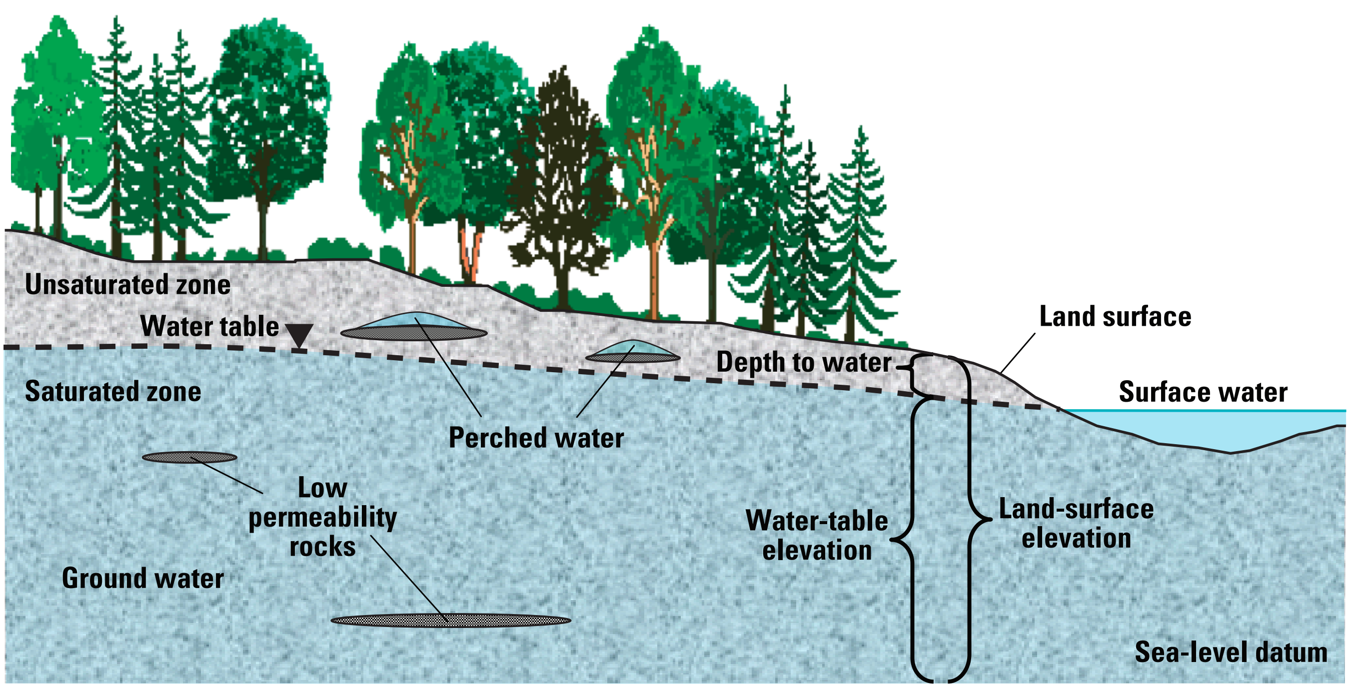


Figure 2. Occurrence of ground water, the position of the water table, and the relation between depth-to-water table and water-table elevation.

Configuration of Water Table and Water-Table Fluctuations

The water table generally is a subdued replica of land surface (Latham, 1878, p. 207-208; King, 1892, p. 15 and 18; King, 1899, p. 99; Russell, 1963, p. 10). This condition more commonly is observed in humid areas with relatively thin unsaturated zones. The configuration (shape or form of the surface) of the water table is a function of the geometry of the land surface, rate and location of ground-water recharge and discharge, aquifer properties, and extent, thickness, and shape of the aquifer and adjacent confining units (Haitjema and Mitchell-Bruker, 2005, p. 784). These factors generally do not change with time, with the exception of recharge and discharge and, therefore, variations in the water-table configuration represent changes in recharge, discharge, or both. Changes in the rates of recharge or discharge cause changes in ground-water storage, which are represented by water-table fluctuations. The water table rises due to increased ground-water storage when the rate of recharge exceeds the rate of discharge and declines when these conditions are reversed (Veeger and Johnston, 1996, p. 28). Fluctuations can be the result of any influence that can change the amount of or location of recharge or discharge. Changes in recharge can result from variations in natural factors, such as in precipitation patterns or rates, or from human-induced modifications such as changes in impervious area, irrigation, septic systems, stream withdrawals, or stormwater runoff into UIC systems. Changes in discharge occur primarily as a result of variations in pumping rates, evapotranspiration, or changes in ground-water storage.

The quantity and timing of precipitation typically are the greatest influences on water-table fluctuations in the Portland Basin. Ground-water levels rise following precipitation of sufficient intensity and duration to satisfy surface runoff, evapotranspiration, and soil moisture deficits, with the residual resulting in recharge. Water levels decline after extensive periods of little or no precipitation as ground water discharges to rivers, streams, springs, or is utilized by pumping or evapotranspiration. Water-table fluctuations can occur on a wide range of time scales, from hours, as in the response to high intensity precipitation events or in response to changes in stream stage, to decades, as in response to long-term changes in climate or land use (Hogenson and Foxworthy, 1965, p. 12; McFarland and Morgan, 1996, p. 38; Conlon and others, 2005, p. 61). As a result, the water-table position is dynamic and constantly changing in response to changes in natural and human-induced stresses acting over a wide range of time scales.

Ground-Water Flow Direction

The direction of ground-water flow in an unconfined aquifer is dependent on the hydraulic head, an indicator of the total energy available to move ground water through an aquifer; the hydraulic head at the water table is equal to the water-table elevation (Freeze and Cherry, 1979, p. 39; Taylor, and Alley, 2002, p. 3). Ground water in an unconfined aquifer flows downgradient from areas of high hydraulic head to areas of low hydraulic head. Therefore, a map depicting the configuration of the water-table elevation can be used to infer the direction of ground-water flow. However, ground-water flow is three dimensional and consists of vertical as well as horizontal components of flow. Water-table elevation maps are useful in determining the approximate horizontal direction of ground-water flow at the water table but should be used with caution and the knowledge that a vertical component of flow also is present and that the direction of lateral flow may vary with depth below the water table. A helpful description of ground-water level maps and how the maps may be used is provided by Bexfield (2002, p. 48-49).

Water-table elevation maps also are useful for identifying ground-water flow systems. A flow system consists of water within a bounded area that enters an aquifer at a recharge area, moves through the aquifer along pathways (flowpaths), and exits at a discharge area. Ridges in the water table usually represent ground-water flow divides from which ground water moves away in both directions normal to the ridgeline (U.S. Water Resources Council, 1980) and form boundaries between flow systems. A common classification scheme divides flow systems by relative size into local, intermediate, and regional systems that are differentiated primarily based on the distance between the recharge and discharge areas (Tóth, 1963, p. 4806). Local-flow systems are characterized by relatively short and shallow flowpaths that extend from a topographic high in the water-table elevation (recharge area) to an adjacent topographic low (discharge area). Intermediate flow systems include one or more local flow systems between respective points of recharge and discharge, and contain flowpaths that are longer and deeper than local flowpaths. Regional (or deep) flow systems may include multiple intermediate and local systems and have the longest and deepest flowpaths that begin at major ground-water divides and terminate at regional discharge areas, such as the Columbia and Willamette Rivers. Recognition of ground-water divides from water-table elevation maps can be useful in helping to identify and differentiate recharge and discharge areas, as well as the presence of local, intermediate, and regional ground-water flow systems.

Need for Water-Table Position Information

Information describing the water-table position is useful for many applications, including understanding aquifer susceptibility, ground-water flow direction, contributing areas to wells, depth to water, or at what level ground water may affect construction activities. Representations of the water-table position include depth to water (equivalent to the thickness of the unsaturated zone) and water-table elevation. The primary focus of this study was to determine the water-table position in order to better understand the susceptibility of ground-water resources in the Portland area. The thickness of the unsaturated zone often is used as one of the components to evaluate aquifer susceptibility to contamination by estimating travel time or the potential for natural remediation in the unsaturated materials. This type of analysis commonly is used for point source contamination such as spills at point of use or transportation corridors, or for evaluating features such as leaking underground storage tanks and stormwater injection systems including UIC systems (Oregon Department of Environmental Quality, 2005a, p. 3, 7, 11, 36-37; 2005b, p. 3-4, 8-10, 20, 22-23, 27-31). Current estimates of the number of UIC systems in the Portland metropolitan area include about 11,000 publicly owned and an estimated 25,000 to 35,000 privately owned UIC systems. The distribution of UIC systems owned and maintained by Multnomah and Clackamas Counties and the cities of Portland, Gresham, Milwaukie, and Troutdale is shown in figure 3.

Information describing the depth to water has various other possible uses, such as well drilling or construction design (for example, roads, buildings, and sewers). Depth-to-water information also can be useful for nonpoint source issues such as the residential or agricultural application of pesticides and fertilizers. Information on water-table elevations is useful for determining the direction of shallow ground-water flow, which can be used for monitoring possible nearby downgradient effects from an area of concern or identifying nearby upgradient sources from areas of interest. Information on water-table fluctuations helps to describe the range of possible seasonal variation that might be expected. Results of the study also can be used (1) as a baseline to identify changes in water levels resulting from changes in natural or human-induced causes, (2) as a tool to help identify areas where more detailed studies and supplemental data are needed to provide for greater resolution, or (3) to constrain the water-table position and reduce the uncertainty in the estimate of the water-table position.

Previous Investigations

Ground-water hydrology of the Portland area has been the focus of numerous studies, although many of these studies are limited in scope. The most notable early investigations were those by Hogenson and Foxworthy (1965), who studied the ground-water resources for much of western Multnomah County; and Leonard and Collins (1983), who studied ground water in northern Clackamas County. A regional ground-water study by the USGS in the late 1980s and early 1990s represents the most recent extensive work done in the Portland Basin. Many reports resulted from this work, including:

- Ground-water data: McCarthy and Anderson (1990)
- Description of hydrogeologic units: Swanson and others (1993)
- Estimated average annual ground-water pumping: Collins and Broad (1993)
- Estimation of ground-water recharge: Snyder and others (1994)
- Description of the ground-water flow system: McFarland and Morgan (1996)
- Simulation of the ground-water flow system: Morgan and McFarland (1996)

The interested reader is referred to these reports for more detailed information on the hydrogeology of the Portland Basin.

Description of Study Area

The primary study area, consisting of the Oregon part of the Portland Basin in northwestern Oregon (fig. 1), covers about 615 mi^2 and includes parts of Multnomah, Clackamas, Columbia, and Washington Counties. The Oregon part of the Portland Basin is defined here as the area bounded by the Tualatin Mountains to the west, the Columbia River to the north, the foothills of the Cascade Range to the east, and the Clackamas River to the south. The final boundary used for the presentation of the results is based on an uncertainty analysis and is limited to areas where the relative uncertainty of the water-table position was deemed to be acceptable. The final area of analysis excludes some parts of the primary study area, especially to the northwest in Columbia County, and extends beyond the bounds of the primary study area in other areas, depending on the quantity and distribution of available water-level data. The study area, which includes Portland, the largest city in Oregon, currently (2008) has a population of about 1 million. However, many of the suburban areas in Portland are rapidly growing, especially in Clackamas, Multnomah, and Washington Counties, contributing to an increasing population.

The Columbia River is the major drainage for the Portland Basin and flows westward out of the Columbia River Gorge until it reaches the confluence with the Willamette River, then flows northward. Topography in the study area includes flat areas, terraces, and hills. Land-surface elevations for the relatively flat areas along the floodplains of the major

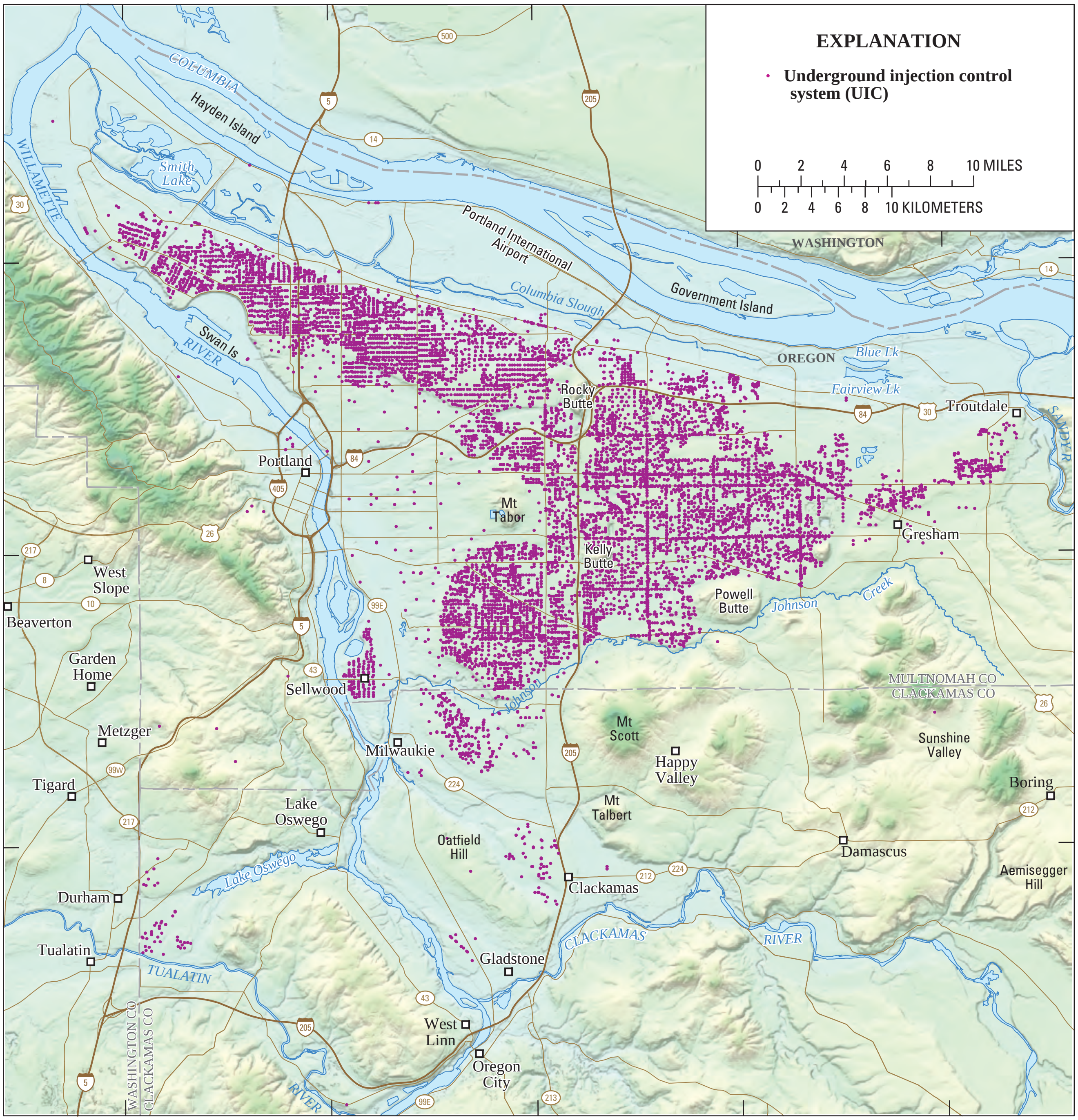


Figure 3. Location of publicly owned underground injection control systems in the Portland, Oregon area, 2008.

rivers range from 11 to 50 ft NAVD 88 (fig. 1). Rolling terraces occur above the floodplains and are remnant deposits of a series of ancient catastrophic floods (known as the Missoula Floods) (Waitt, 1985), with land-surface elevations that generally range from 50 to as high as 400 ft. Well-dissected uplands and hills are present above the terraces, with elevations more than 400 ft and sometimes exceeding several thousand feet, especially toward the foothills of the Cascade Range to the east (Trimble, 1963, p. 5 and 59).

Taylor and Hannan (1999, p. 50) describe the climate of the Portland area as relatively mild throughout the year, and characterized by cool, wet winters and warm, dry summers. Annual precipitation at the Portland International Airport (National Climatic Data Center Coop ID 356751) averages 37.1 in. (30-year normal for 1971–2000); however, precipitation generally is greater throughout most of the study area. About 50 percent of the precipitation occurs from December through February, with lesser amounts in spring and autumn, and very little during summer (Taylor and Hannan, 1999, p. 50). The Cascade Range is an orographic barrier to ocean weather systems moving across Oregon from west to east. As a result, precipitation generally increases eastward in the study area toward the foothills of the Cascade Range.

Hydrogeologic Setting

Overviews of the geology and hydrology of the Portland Basin presented in the following sections summarize more detailed descriptions in reports by (1) Swanson and others (1993), who discuss the thickness, extent, and lithology of hydrogeologic units in the basin; (2) McFarland and Morgan (1996), who describe the ground-water flow system of the basin, including its boundaries, hydraulic characteristics, and components of recharge and discharge; and (3) Morgan and McFarland (1996), who discuss the geology and hydrology related to the simulation of the ground-water flow system based on numerical modeling.

Hydrogeology

The northwest-trending Portland Basin was formed by structural deformation of the underlying Eocene and Miocene volcanic and marine sedimentary rocks. Late Miocene and younger fluvial and lacustrine sediments are overlain by unconsolidated Pleistocene Missoula Flood deposits and Holocene Columbia River alluvium (Swanson and others, 1993, p. 9; McFarland and Morgan, 1996, p. 6). The consolidated and unconsolidated basin-fill sediments are thickest adjacent to the Columbia and Willamette Rivers, where the thickness of the sediments may be as much as 1,800 ft. Hydrogeologic units in the Portland Basin, as defined by McFarland and Morgan (1996, p. 9), include, from youngest to oldest, the unconsolidated sedimentary aquifer, Troutdale gravel aquifer, confining unit 1, Troutdale sandstone aquifer, confining unit 2, sand and gravel aquifer, and older rocks. An additional unit, the undifferentiated fine-grained sediments, is mapped where the Troutdale sandstone aquifer is missing and confining units 1 and 2 cannot be differentiated. Results from several hydrogeologic units were combined as modified by Snyder and others (1998, p. 5) for the purpose of simplifying discussion and analysis. References to the undifferentiated fine-grained sediments in the remainder of the report will include confining units 1 and 2 (fig. 4).

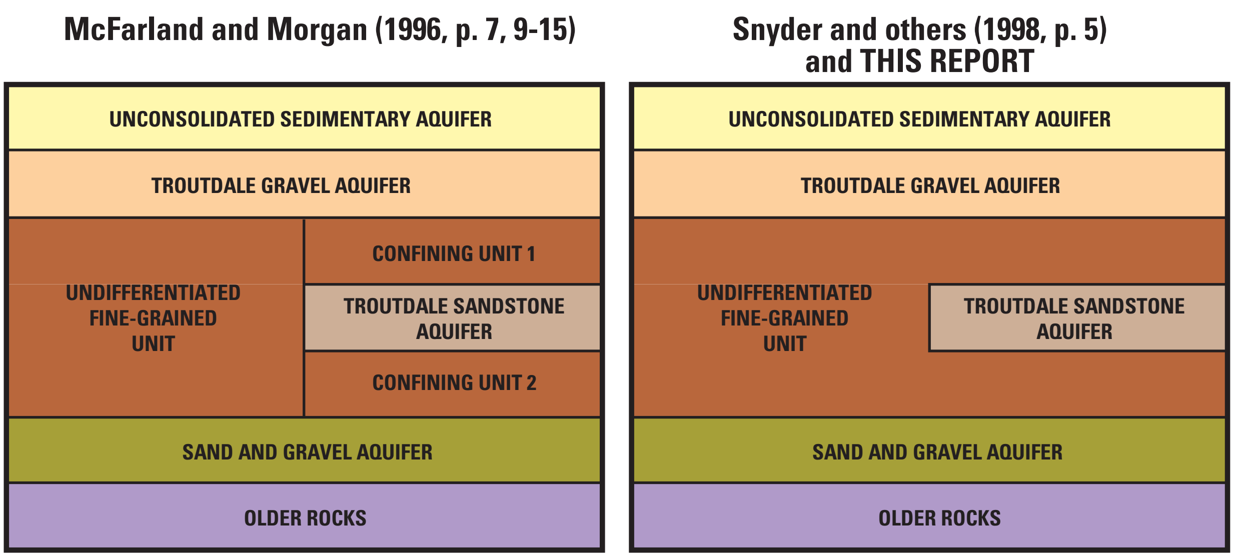


Figure 4. Comparison of hydrogeologic unit terminology for the Portland Basin, Oregon.

Low-lying areas between the cities of Portland and Gresham, consisting of the floodplains of the Columbia and Willamette Rivers and the terraced areas above the floodplains, are of particular interest because of the large population and the great number and density of existing and proposed UIC systems. Primary surficial aquifers in this area consist of the unconsolidated sedimentary aquifer and the Troutdale gravel aquifer where the Troutdale aquifer is exposed at the surface or where it underlies the unconsolidated sedimentary aquifer in areas where that aquifer is nearly or completely unsaturated (Morgan and McFarland, 1996, p. 1, 57–58). These aquifers supplied more than 80 percent of the pumpage in 1987–88 (Collins and Broad, 1993, p. 8). The extent, thickness, distribution, size, and sorting of the materials composing these aquifers exert a strong influence on the position and character of the water table across the Portland area.

Throughout much of the low-lying areas in Portland (particularly to the north and west), the water table lies within the unconsolidated sedimentary aquifer (Hogenson and Foxworthy, 1965, p. 42). Materials in this part of the unconsolidated sedimentary aquifer consist of recent alluvium and repeated cycles of sediments grading upward from boulders, cobbles, and gravels to sands and silts. The degree of sorting of these cycles of layered materials is variable and though bedding (planes separating distinct sediments or rocks) is present there are many unconformities as the layers can be vertically and laterally discontinuous (Trimble, 1963, p. 58-62; Hogenson and Foxworthy, 1965, p. 26; Waitt and O'Connor, 2000, p. 7). These materials are a result of deposits from a minimum of 40 prodigious floods (collectively referred to as the Missoula Floods) (Bretz, 1969; Waitt, 1985, p. 1284). The Missoula Floods occurred about 12,700–15,300 years ago and were caused by the periodic catastrophic failure of the ice damming glacial Lake Missoula in western Montana releasing scores of colossal jökulhlaups (glacier-outburst floods) (Waitt, 1985, p. 1284). Floodwaters traveled hundreds of miles westward, carrying large quantities of rock material, which subsequently was deposited as layers of silt, sand, gravel, cobbles, and boulders in the Portland Basin after rapid loss in transporting power as the floodwaters moved from the high energy environment of the narrow Columbia River Gorge into the relatively low energy environment of the Portland Basin, where the area widens. Peak discharge for some floods exceeded 700 million ft^3/s (Minervini and others, 2003) or about 3,600 times the mean daily discharge of the present day Columbia River at Vancouver, Washington. A hydraulic constriction of the Columbia River downstream of Portland prevented the rapid draining of the basin, resulting in a large lake extending about 115 mi down the Willamette Valley with a width exceeding 25 mi in places, and inundating the Portland area to depths as great as 400 ft (Trimble, 1963, p. 64–66; Minervini and others, 2003). Many of the familiar geomorphic features of the Portland area were either created or influenced by erosion or deposition associated with the episodes of flooding and are exhibited as ridges, terraces, channels, or depressions. These include well-known features such as Sullivan Gulch (west terminus of Interstate Highway 84) and Alameda Ridge (Allison, 1978a, p. 182). The thickness of the unconsolidated sedimentary aquifer typically is between 50 and 100 ft, with local accumulations of greater than 250 ft. The unconsolidated sedimentary aquifer is the most permeable of the aquifers in the Portland Basin; however, permeability varies substantially due to the high degree of heterogeneity of the aquifer materials, which can result in some local areas of perched ground water (McFarland and Morgan, 1996, p. 16 and 20).

The Troutdale gravel aquifer has been assigned by Swanson and others (1993, p. 27–29) to include several geologic formations—poorly to moderately cemented conglomerates of the Troutdale Formation, the volcaniclastic conglomerate of the Springwater, Walters Hill, and Gresham Formations, as well as locally thick accumulations of the Boring Lava. Conglomerates of the Troutdale Formation that extend over most of the study area were deposited by the ancestral Columbia River. The volcaniclastic conglomerate was derived from the Cascade Range and is present throughout much of the southeastern part of the study area. Finally, many of the isolated hills in the central and southern parts of the study area, including Mount Sylvania, Mount Tabor, Rocky Butte, Kelly Butte, Powell Butte, Mount Scott, and the Boring Hills, consist entirely of or contain a core of the Boring Lava, which can interlayer with the other units that form the Troutdale gravel aquifer (Trimble, 1963, p. 37; Swanson and others, 1993, p. 27). Thickness of the Troutdale gravel aquifer ranges from 100 to 400 ft throughout much of the basin (Swanson and others, 1993, p. 28). The Troutdale gravel aquifer has a relatively high permeability, although it also exhibits a large range in values (McFarland and Morgan, 1996, p. 16 and 20). Perched ground water occurs in some parts of the Troutdale gravel aquifer, particularly those associated with the Boring Lavas or the volcaniclastic conglomerates; however, the perched ground-water bodies are discontinuous and irregularly distributed (Hogenson and Foxworthy, 1965, p. 23, 25, 36, and 39).

Occurrence and Movement of Ground Water

Recharge to the Portland Basin from precipitation, runoff into UIC systems, and on-site waste-disposal systems (septic systems) was estimated by Snyder and others (1994, p. 30) over the entire Portland Basin and ranged from 0 to 49 in/yr with a mean of 22 in/yr. Recharge primarily is through the infiltration of precipitation, although in areas of urban development, recharge from runoff into UIC systems and on-site waste-disposal systems contributed about 38 and 17 percent of the total, respectively. However, the number of UIC systems has increased substantially since 1994, although many on-site waste-disposal systems have since been removed as part of an extensive sewer project in mid-Multnomah County. Irrigation-return flow and losing streams may constitute locally important sources of seasonal recharge, but are believed to be insignificant on a regional scale. Ground-water recharge typically moves downward through the unsaturated zone to the water table (however, the unsaturated zone may be missing in areas where the water table is present at land surface). Ground water then may flow into unconfined, perched, or confined aquifers depending on the permeability of the aquifer and the overlying and underlying layers.

Ground-water movement primarily is controlled by the topography of the basin, which creates regional, intermediate, and local ground-water flow systems. The Columbia, Willamette, and Clackamas Rivers represent the regional discharge areas for the ground-water flow system in the study area (McFarland and Morgan, 1996, p. 20–23). Much of the ground water discharging to the rivers enters the ground-water system in upland recharge areas along the western Cascade Range, the Boring Hills, or the Tualatin Mountains; moves downward and horizontally toward the rivers; and finally moves upward to discharge to the rivers (Morgan and McFarland, 1996, p. 8; Hinkle and Snyder, 1997, p. 19–20, pl. 1; Snyder and others, 1998, p. 13–23 and unpub. data, 1998). An example of a discharge area for an intermediate ground-water flow system includes much of the Sandy River. Local ground-water flow systems are much smaller, with distances of only hundreds of feet between recharge and discharge areas (Morgan and McFarland, 1996, p. 9). Directions of ground-water flow can vary between each type of flow system and even within a flow system due to complexities in the flow system. This can present situations where the direction of ground-water flow at or near the water table may not be representative of the directions of ground-water flow at greater depths. These conditions have been illustrated in particle-tracking examples in the ground-water system of the Portland Basin (Hinkle and Snyder, 1997, p. 20, pl. 1).

Ground-water discharge in the Portland Basin is primarily to gaining streams and rivers, wells, and springs (McFarland and Morgan, 1996, p. 23). The largest component of ground-water discharge in the Portland Basin is to streams and rivers. Ground-water withdrawals from wells in the study area primarily are used for industry and public supply, with smaller amounts used for irrigation and domestic purposes (Collins and Broad, 1993, p. 7). Major springs in the study area are near Crystal Springs Creek and along the southern side of the Columbia River between the cities of Troutdale and Wood Village.

Study Methods

The preferred way to map the water-table configuration is to obtain one or more synoptic (collected simultaneously) sets of measurements of the depth to water in wells that encompass the entire area of interest with sufficient density to minimize uncertainty between measurement locations. However, to conduct such an intensive collection of measurements was beyond the scope of this study. Instead, the method of analysis used to determine the configuration of the water table in the Portland area relied primarily on three sources of readily available information: (1) existing water-level data from shallow wells; (2) locations of surface-water features that are directly hydraulically connected to and, thereby, representative of the water table; and (3) land-surface elevation. These sources of information were then combined and used with statistical methods to estimate the water-table configuration. Many methods have been developed for the analysis of these types of data to determine the water-table configuration. Data often are manually contoured, enabling additional hydrologic knowledge to be incorporated; however, this method is potentially prone to bias and error, especially where hydrologic knowledge is limited. The fundamental observation that the water table is a subdued replica of the land surface indicates that topographic data can be used to guide and constrain the mapping of the water-table configuration. A number of studies have used a regression analysis to define the relation between water-table and land-surface elevations (Williams and Williamson, 1989; Sepúlveda, 2002; Peck and Payne, 2003). The regression analysis appears to work well for areas where the topography and precipitation are consistent over a region and the hydraulic properties of the aquifers generally are homogeneous. However, Sepúlveda (2002, p. 18) noted that regression generally fails to provide reliable estimates in upland areas of low recharge or high permeability where land-surface elevation and water levels may not be correlated. Most importantly, regression ignores local variations, possibly resulting in large errors for areas where the features are not typical of the region or that are subject to additional hydrologic stresses (Rouhani, 1986, p. 213 and 215). Supplemental explanatory variables can be included in the regression that can improve the results but require additional data that may not be readily available. Therefore, regression has limitations for the determination of the water-table configuration for specific areas. In addition, neither manual contouring nor regression methods readily provide an objective measure of the reliability of the water-table position estimate at specific locations. Manual contouring and regression methods were not adopted for the purposes of this study for these reasons.

Kriging was the method of interpolation selected for use in this study. Kriging is based on a geostatistical theory predicated on the observation that values of spatially distributed data commonly are correlated—values at nearby locations are more highly correlated than values at distant locations (Alley, 1993, p. 87). Kriging produces a grid of regularly spaced estimates from irregularly spaced data (like well locations) from which contour maps and other depictions of the water table can be made. Kriging is particularly well suited to problems in the hydrosciences (Delhomme, 1978, p. 251) and has been widely used to map ground-water surfaces (Alley, 1993, p. 87). Kriging estimates have statistically optimal properties such as producing the minimum possible error variances of any linear-estimation method (Davis, 2002, p. 418). The kriging method also maximizes the use of available data, helps to compensate for the effects of clustered data, provides a map of uncertainty of the kriging estimates, and is an objective analysis (Davis, 1986, p. 383 and 386; Bossong and others, 1999, p. 17). Because the kriging method is not based on the physics of the ground-water flow system, the results should be scrutinized to ensure that the interpolation is reasonable and consistent with available hydrogeologic information.

A flow chart of the simplified development of the depth-to-water and water-table elevation maps is presented in figure 5. A depth-to-water dataset was derived from locations and depths to water measured at wells and the locations of surface-water features where the depth to the water table is zero. A water-table elevation dataset was derived by subtracting depth-to-water values from land-surface elevation that was determined by the use of a Digital Elevation Model (DEM). A semivariogram (a special type of graph) was determined for each dataset to obtain the parameters for the kriging analysis. Each dataset was interpolated separately using kriging that resulted in preliminary maps of depth to water and water-table elevation. Values from the preliminary water-table elevation map were subtracted from the land-surface elevation to create another version of a preliminary depth-to-water map. The two versions of the depth-to-water maps were averaged to create a final depth-to-water map. Values from the final depth-to-water map were subtracted from the land-surface elevation at each location to create a final map of the water-table elevation.

Seasonal water-table fluctuations were analyzed using summary statistics of data from shallow wells that had multiple water-level measurements. Care was taken to ensure that only wells with water-level measurements collected throughout the year were used and to remove measurements that may not have been representative of the static water level of the aquifer. Careful selection of wells and measurements ensured that the complete range of seasonal variation was observed and that spurious measurements did not interfere with the analysis. Spatial distribution of seasonal fluctuations was determined to be largely influenced by the effective porosity and was classified based on the hydrogeology in the range of fluctuation of the water table.

Sources and Descriptions of Data

Water Levels in Wells

Three sources of water-level information from wells were used in the analysis of the water table. Information on water levels reported by well constructors at the time of new well installation is the largest source of available data for the Portland area. Data also are available for ground-water levels reported in previous USGS studies of the ground-water hydrology in the Portland area. Finally, additional wells were located and water levels were measured as part of this study. The unsaturated zone thickness in the Portland area generally is less than 300 ft; therefore, only water levels from wells with completed depths of 300 ft or less were considered for use in the analysis of the water table. Water levels in these shallow wells were assumed to represent the water table, although the open interval of the well is usually substantially below the water table.

Measurements Documented in Well-Construction Records

Since 1955, well drillers in Oregon have been required by the State to file a well report (log) documenting the well installation with information describing the well location, type of subsurface materials encountered, well depth, construction, and the depth to water. These records are available from the Oregon Water Resources Department (OWRD) at http://www.wrd.state.or.us. OWRD has more than 20,000 wells on file that have completed depths of less than 300 ft in the Portland area; this extensive dataset was first investigated as a source of depth-to-water information for interpolation of the water table. Locations of many wells (especially older wells) generally are not accurately known. Commonly, the locations are reported only to the nearest mile or quarter mile. This large number of wells was initially assumed to provide a robust dataset for estimating the water-table position even though the locations are not always accurate. Wells in the same geographic area were grouped and a measure of the central value of the depth to water was used to represent the position of the water table for that location.

The values of depth to water recorded in well logs were grouped by sections (1 mi^2). The median value (the central value of the distribution of all water-level measurements when the data are ranked in order of magnitude, also known as the 50th percentile) of depth to water for each section was then calculated. The median was selected as the summary value instead of the mean because, unlike the mean, the median is a “resistant measure” that is not strongly influenced by a few extreme measurements (Helsel and Hirsch, 2002, p. 5). This resistance to the presence of outlying measurements was considered a desirable property for characterizing depth to water.

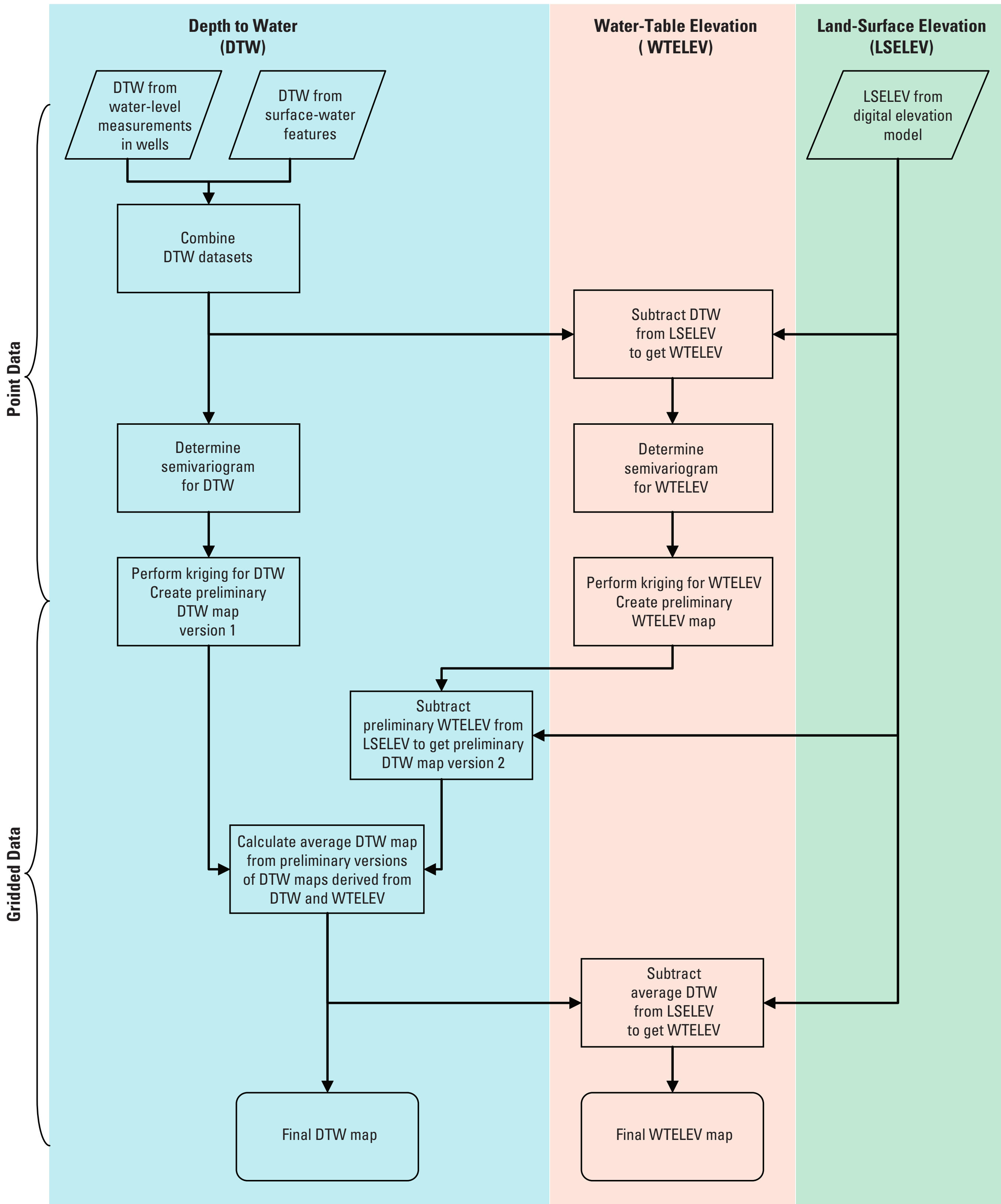
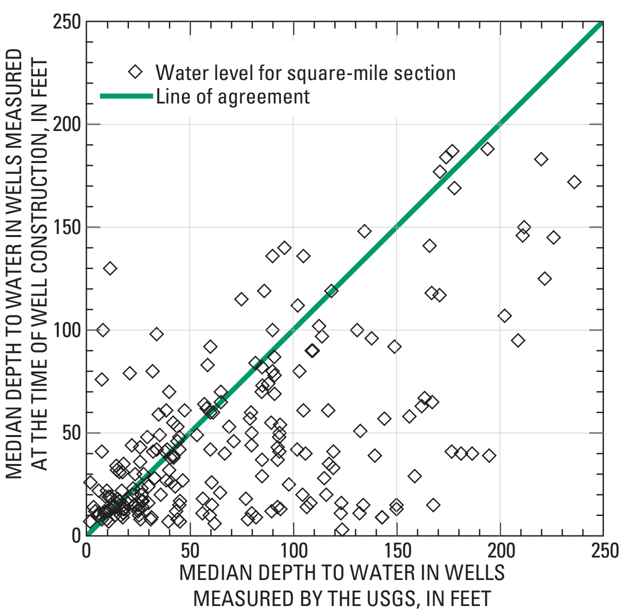


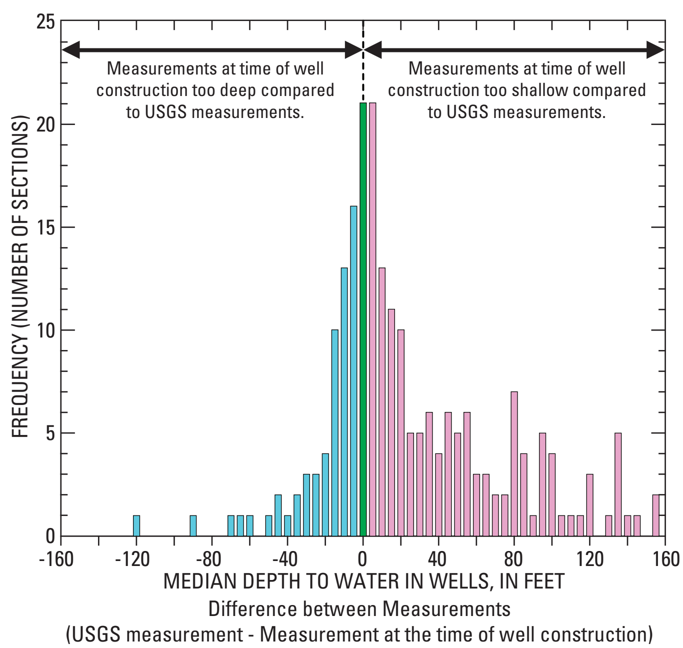
Figure 5. Procedures used to develop depth-to-water and water-table elevation maps.

Each of the 220 points in figure 6A represents a single 1 mi^2 section in the study area where depth-to-water measurements have been documented from well-construction records and the USGS for one or more wells with depths less than or equal to 300 ft (although the measurements were not necessarily from the same wells in the section). If the water levels measured at the time of well construction are good representations of the depth to the water table, then there should be a close correspondence with the water levels measured in wells by the USGS in the same section, and the values would be expected to plot along a straight line with a slope of 1, referred to as the “line of agreement” in figure 6A. However, the plot reveals a cloud of points, rather than a line indicating only a modest relation between water levels measured at the time of well construction and water levels measured by the USGS over the last several decades in the same 1 mi^2 section. The points in figures 6A and the histogram in figure 6B are skewed toward shallow values of depth to water as reported in the well logs, indicating that the measurements at the time of construction generally appear to be shallower than the measurements by the USGS. Magnitudes of differences in depth to water from the two sources of data range from -119 to 156 ft with a mean of the absolute value of the differences of 36 ft. The magnitude of the differences far exceeded what might be expected due to seasonal fluctuations or long-term trends as a result of measurements at the time of construction and those measured by the USGS on different dates. The large scatter and skew in depth-to-water data from the well reports indicated that the data would be unsuitable for the purpose of estimating depth to the water table in the present study.

Differences between median values for depths to water reported in well-construction records and those measured by the USGS could be a result of variations in land-surface relief in the 1-mi^2 sections if different sets of wells were used. To determine if bias exists in the measurements reported at the time of well construction, a direct comparison was made for those wells with measurements subsequently made by the USGS. More than 4,400 water levels measured or recorded by the USGS were analyzed for 145 wells that had 10 or more measurements, including the measurement in the well-construction record to examine whether the measurements at the time of well construction were representative of the typical measurements for individual wells. The probability that the measurement at the time of construction represents an end-member observation (either the minimum or maximum depth to water) for an individual well, assuming a typical and unbiased measurement, is 2/n, where n is the number of measurements for the well. Using n equal to 20 measurements (the median value of the number of measurements for the 145 wells), the probability that a measurement at the time of construction represents an end-member observation is 2/20 or 10 percent. The number of wells that would be expected to have the measurement at the time of construction represent an end-member observation is N * 2/n where N is the number of wells. Therefore, if the measurements reported in well logs are



***A.* Relation of water-level measurements reported at time of well construction and by USGS for wells in the same square-mile section**



***B.* Residuals calculated as USGS measured depth to water minus depth to water reported in well-construction records for wells in the same section**

Figure 6. Water-level measurements reported in well-construction records and by the U.S. Geological Survey.

typical and unbiased those measurements would be expected to represent an end-member observation in 145 * 2/20, or about 15 of the 145 wells. However, measurements reported in well logs represented an end-member observation for 62 of the 145 wells (43 percent of the wells). The probability of this occurring by chance alone is extremely unlikely, less than 1 in 1 billion. For these 62 wells, 65 percent of the measurements at the time of construction represented the shallowest depth to water recorded and 35 percent represented the deepest depth to water recorded. This is a clear indication that the measurements at the time of construction frequently are not representative of the static water-level conditions in a well and more likely are to be shallower than the actual depth to water.

Many factors can cause these departures from agreement; and may be related particularly to the differences in timing of when the well was constructed and measured and when the USGS made measurements, and may include short-term effects, seasonal variations, or long-term trends. However, the timing of the measurement reported in a well-construction record is important, especially if the measurements were made when water levels in the wells were not at equilibrium. Measurements at the time of well construction that appear to be shallow relative to measurements by the USGS may be the result of measurements that were made soon after well construction, when water levels in the wells were temporarily shallower as a result of incorporation of drilling fluids or well completion activities (development of well by surging and pumping of water). Other causes could include misidentification of a wetting front as the water table, or the encountering of perched aquifers due to the presence of local confining layers. Departures from agreement also may result from measurements at the time of well construction that generally appear to be deeper than measurements by the USGS. These may be a consequence of measurements that were taken soon after well construction while a well was undergoing recovery following heavy pumping during well completion activities in aquifers with lower permeabilities. Finally, strong vertical gradients, wrongly located wells, database errors, and variations in topographic relief also could contribute to discrepancies between water-level measurements from the well reports and USGS datasets. Therefore, water levels measured at the time of well construction should be used with caution, especially for wells that have locations that are not precisely known and have little information regarding their topographic position. Water-level measurements reported on well construction records as a result of these findings were deemed unsuitable for the purposes of determining the depth to the water table to the accuracy required for this study without the use of additional information regarding the well location or the measurement conditions.

Archived USGS Measurements

Because of problems associated with the use of the water-level measurements reported in well-construction records, the use of these data was discontinued in favor of water-level data published in USGS reports, archived in the USGS National Water Information System (NWIS) database, or other USGS files (Piper, 1942; Griffin and others, 1956; Brown, 1963; Hart and Newcomb, 1965; Hogenson and Foxworthy, 1965; Leonard and Collins, 1983; McCarthy and Anderson, 1990; Hinkle, 1997; Woodward and others, 1998; Orzol and others, 2000; Lee, 2002; Conlon and others, 2005). This dataset has far fewer wells than the dataset of water levels recorded in well logs but contains verified well information and water-level measurements that are more substantiated. Wells that had artesian water levels (above land surface) or that were flowing, possibly indicating confined conditions, or that had completed depths greater than 300 ft were eliminated from the analysis. Otherwise, wells were assumed to be open to the water-table zone. When one or more wells were located within 100 ft of each other, a single well was selected for use in the analysis. The well selected generally was the shallowest well or the well with the greatest number of water-level measurements unless information was available to indicate that water levels in the well were not representative of the water table.

The period of record for the archived water-level data used extended from 1929 to 2004. The longest period of record for water-level measurements at an individual well was 67 years. The median water level calculated from all reliable water-level measurements was used to represent the water level for wells with multiple measurements. Individual measurements that indicated the well was dry, obstructed, or influenced by pumping were removed from consideration. Initial water-level measurements that were signified as “reported” or “by driller” were removed from the calculation of the median with the exception of wells with only a single water-level measurement. These single measurements that were probably obtained from well-construction reports were retained because much of the well information had been previously reviewed and evaluated for use; locations and land-surface elevations of these wells generally are more precisely known; and use of these measurements helped to constrain the position of the water table in areas of limited information.

Minimum elevation of the water table throughout the study area, referred to as the base water-table elevation, is expected to be equal to the elevation of the water table at the regional discharge areas unless the water level is being influenced by some type of local stress, such as pumping. The mean stage of the Columbia River at Vancouver, Washington (USGS site number 14144700), for the 5-year period from 1998 through 2002 was about 11 ft NAVD 88, which was selected to represent the base elevation of the water table. Median water-table elevations in wells that were lower than the base water-table elevation were evaluated. Most of these 66 wells are adjacent to the Columbia or Willamette Rivers. Stage in these rivers can vary widely as a result of seasonal fluctuations, tidal influences, or flow regulation by dams. The minimum stage at the Columbia River during the 5-year period used to establish the base water-table elevation was about 4 ft NAVD 88. Shallow wells adjacent to either of these rivers with median water-table elevations between 4 and 11 ft NAVD

88 were assumed to be strongly influenced by the river at the time of measurement. The 47 wells that met these criteria were retained in the analysis; however, the median water-table elevation at each well was set to 11 ft NAVD 88 and the depth to water adjusted accordingly. Wells with water levels between 4 and 11 ft NAVD 88 that were not adjacent to the rivers or that had median water-table elevations less than 4 ft NAVD 88 were assumed to have been influenced by pumping or to have been assigned inaccurate land-surface elevations for the determination of water-table elevation. There were 19 wells in this category that subsequently were eliminated from the analysis.

Median water levels used at each well, the USGS site number (a unique identifier), the USGS Portland Basin well-identification number, the station name, the location of the well, and other useful information are shown in appendix A, table A1. Figure 7 shows the location of wells used in previous USGS studies. Water-level and well-construction data for most wells can be retrieved from the USGS NWIS database through NWISWeb at http://waterdata.usgs.gov/or/nwis/gw using the USGS site number. Data for the remainder of the wells may be obtained online from the USGS Portland Basin Ground-Water Study data archive (U.S. Geological Survey, 2006) using the USGS Portland Basin well-identification number to access specific well information.

Available data from the USGS indicated that several areas in the study area were underrepresented by wells having useful information. The gaps in the distribution of available data would produce areas with high uncertainty. Some of these areas were located in regions where a substantial need exists to refine the position of the water table for use with regard to UIC systems and other ground-water resource issues. Additional ground-water level data were collected in these areas for use in the analysis.

Water-Level Measurements

Existing water-level information from wells was supplemented in areas of sparse data by identifying candidate wells in the OWRD database that were situated in areas of interest and conducting a field effort to locate and measure these wells. The criteria for selection included permanent water wells with characteristics that would indicate that the well was completed in the water table and water levels were representative of unconfined or water-table conditions. Wells with completed depths greater than 300 ft, wells with a substantial thickness of potential confining layers such as silt or clay above the open interval, or wells with water-level measurements above land surface (indicating artesian conditions) were not used to avoid water levels that could represent confined conditions. Wells that were relatively shallow (300 feet or less) and recently constructed, and that had complete location information were given priority during the field effort to locate and measure wells.

More than 75 wells were visited, but after on-site evaluation, only 20 wells met the criteria for inclusion in the current study (fig. 7). Well locations were determined by use of a Global Positioning System (GPS), well-construction details were documented, and water levels were measured based on standard USGS methods (U.S. Geological Survey, 1980, p. 2-8). Well information including location, construction, and depth to water were entered into the USGS NWIS database.

The resulting dataset of wells used in previous USGS investigations and wells located and measured for this study consisted of 582 wells. However, some areas remained where no suitable wells could be located or measured. The location of surface-water features representative of the water table was used to supplement information on the water-table position for these areas.

Surface-Water Features

Locations of surface-water features such as major rivers, streams, lakes, wetlands, and springs that are in direct hydraulic contact and interact with ground water can be used to constrain the estimate of the water-table position in these areas. These features indicate where the water table is at land surface, and the elevations of these features represent the elevation of the water table.

All reaches of the Columbia, Willamette, and Clackamas Rivers in the study area were assumed to be representative of the water table throughout the lengths and widths of the rivers. Other rivers and streams were selected on the basis of a previous USGS study (McFarland and Morgan, 1996, p. 8 and 27) in which streamflow measurements were made in downstream order during low-flow conditions following an extended dry period. Streams that showed gains in flow of greater than 0.5 ft^3/s per river mile, after accounting for inflows from tributaries and outflows to diversions, were assumed to be gaining water from ground-water discharge and thus, representative of the water table. The following gaining reaches were identified and used in determining the water-table position (fig. 7): Clackamas River basin: Kellogg Creek, Rock Creek, parts of Deep Creek and Tickle Creek; Columbia River basin: Columbia Slough, Fairview Creek, Sandy River, Bull Run River; Willamette River basin: parts of Johnson Creek (pl. 1).

The elevations of 22 springs with discharges generally greater than 0.1 ft^3/s reported by McFarland and Morgan (1996, p. 8, and 24-27) and McCarthy and Anderson (1990, p. 31) provide additional constraints of the water-table position (appendix A, table A2). The two primary areas of spring discharge are at Crystal Springs in southeast Portland and near the cities Troutdale and Wood Village (pl. 1). Other surface-water features, such as major lakes and wetlands, were reviewed and included if judged to be hydraulically connected to the ground-water flow system.

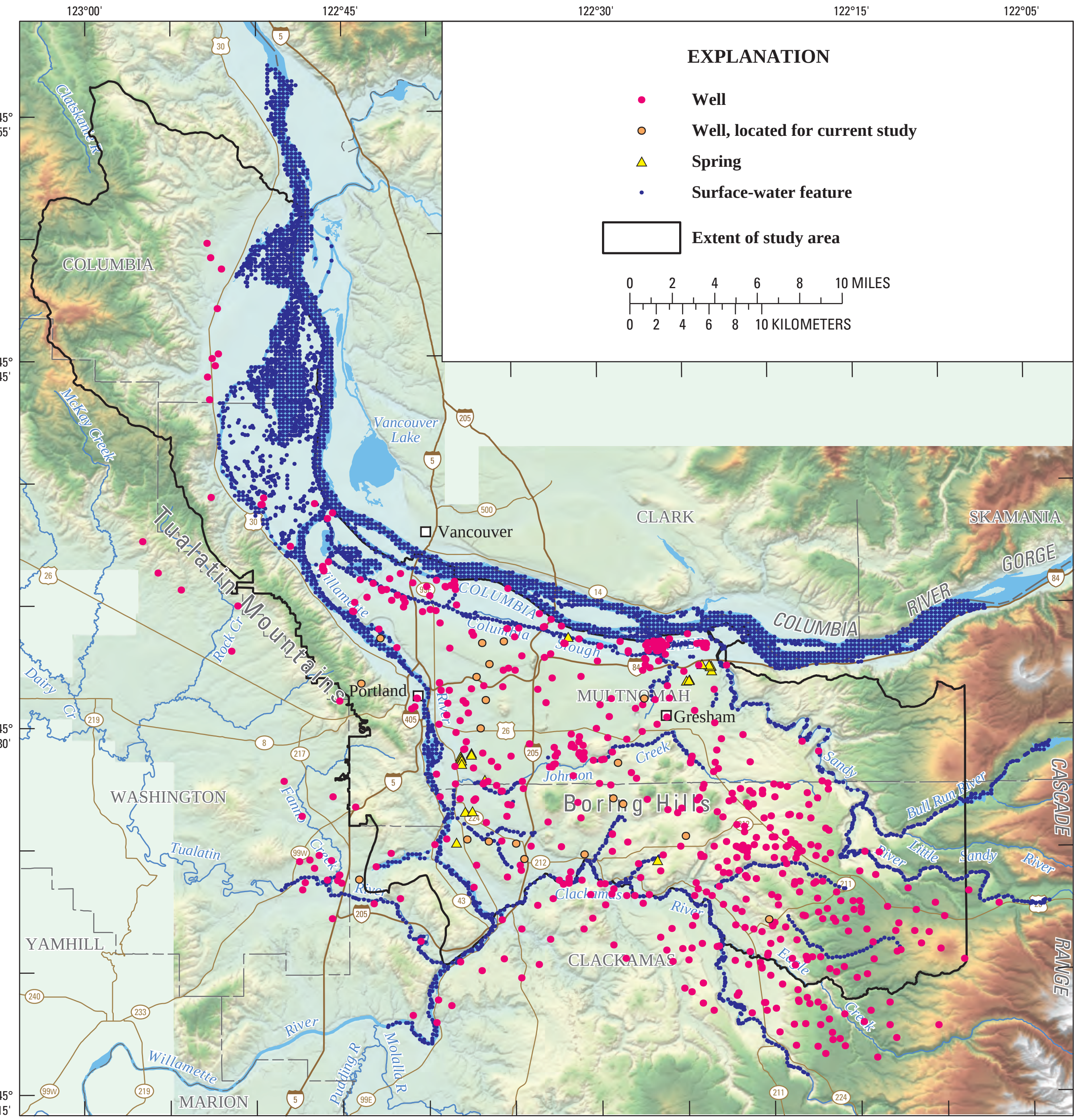


Figure 7. Location of wells, springs, and surface-water features used in the interpolation of the water-table position in the Portland, Oregon area.

Land-Surface and Surface-Water Elevations

Information on land-surface and surface-water elevations is needed to determine the accurate elevations of wells and surface-water features so that the water-table elevation can be calculated from depth-to-water information. A 2-meter lateral resolution Digital Elevation Model (DEM) was obtained from Metro, a regional government agency serving the Portland metropolitan area. The 2-meter DEM covers most of the Portland metropolitan area and was developed from 5-foot-interval contours interpreted with the use of aerial orthophotography from 2001 (Metro, 2002). A 10-meter lateral resolution DEM from the USGS was used for areas not covered by the 2-meter DEM (U.S. Geological Survey, 1999). The 10-meter DEM was resampled at a 2-meter lateral spacing by use of a bilinear interpolation to match the spacing of the 2-meter DEM from Metro. These two DEMs were combined into a single 2-meter DEM for the entire study area. River reaches for the Columbia and Willamette Rivers were smoothed to remove structures such as bridges and to ensure that the river reaches remained lower than adjacent land-surface areas. The mean stage of the Columbia River, calculated as 11 ft NAVD 88, was used to represent the lowest river elevation throughout the study area. The vertical resolution of the 2-meter and 10-meter DEMs is reported as about 0.3 and 21 ft, respectively (U.S. Geological Survey, 2000; Metro, 2002). The land-surface elevations for wells and springs used in the study were estimated by using the revised 2-meter DEM and calculated as the median land-surface elevation within a 100-foot radius of the reported locations. The 100-foot buffer for determination of land-surface elevation was used because the locations of wells and springs often are known only to an accuracy of 100 ft, depending on the method of determination.

Representation of Surface-Water Features

The method of depiction of surface-water features considered characteristic of the water table at land surface was dependent on the form of the feature represented: point, linear, or areal. Single points were used to represent individual features such as springs or small water bodies including small wetlands or lakes. Linear features such as streams and small or narrow rivers were represented by points spaced every 1,000 ft along the length of the reaches that were considered to be in connection with the ground-water system. Areal features, such as large rivers with substantial width or lakes having large areas, were discretized by placing points in each 1,000 × 1,000-ft^2 area. Depth to water for all points representing surface-water features was set to zero. The water-table elevation was set equal to the lowest land-surface or surface-water elevation near the point on the basis of the 2-meter DEM developed for the study area. About 4,000 points were used to represent surface-water features representative of the water table at land surface (fig. 7).

Data Limitations

Limitations in the dataset used for analysis can lead to increased errors and, therefore, larger uncertainty in the results. These include uncertainty in the spatial distribution of the data points (lateral and vertical), bias introduced as a result of the temporal distribution of the measurements, and errors resulting from the presence of perched or confined aquifers. Uncertainty resulting from the lateral spatial distribution of available data is a function of the number and location of data consisting of available wells and surface-water features used for analysis, and is discussed further in section, “Assumptions and Assessment of Errors.” The vertical spatial distribution is dependent on the construction characteristics of available wells. Water-level measurements used in this study are from wells with various open intervals in the saturated and unsaturated zones. Although these wells may have different open intervals, the measured water levels were assumed to reasonably represent the water-table depth. The criteria to use only wells less than 300 ft in depth may result in greater error in areas where the actual depth to water may be greater than 300 ft, although for the Portland Basin, this is restricted to a limited number of relatively well-defined areas. The accuracy of the land-surface elevation associated with each well and surface-water feature is dependent on the precision and accuracy of the lateral position of the well or surface-water feature and the accuracy of the 2-meter DEM used to represent the land-surface elevation. Use of the median land-surface elevation within a 100-foot radius of the reported position of the well or spring and the lowest elevation near the remaining surface-water features helped to provide a robust estimate of the land-surface elevation.

The temporal distribution of the available water-level data used in the study covered the period from 1929 to 2004, with measurements collected during different months, seasons, and years. A synoptic dataset, which would have removed influences of long-term, seasonal, or short-term fluctuations, was impossible to obtain. Long-term fluctuations can result from climatic changes in temperature or the quantity and timing of precipitation, or may be due to anthropogenic influences such as the use of water resources or land-use changes that affect the quantity or timing of discharge including pumping, stream withdrawals, or recharge due to irrigation or changes in impervious areas. Seasonal fluctuations can result from precipitation, evapotranspiration, streamflow, and irrigation patterns. Short-term fluctuations can occur as a result of high intensity rainfall events, floods, or localized pumping. However, many of the wells have multiple measurements covering long periods of time, and the use of the median values of these measurements is intended to help reduce the uncertainty of the water-table position estimate. Additional discussion on temporal variations in water-level measurement is presented in the section, “Seasonal Water-Table Fluctuations.”

Perched ground-water zones may be present in the shallowest parts of surficial aquifers, though water wells rarely are open to these zones, as the source of water often is unreliable due to large seasonal variations (McFarland and Morgan, 1996, p. 20). Hogenson and Foxworthy (1965, p. 36 and 42) noted that in the eastern and northern parts of the city of Portland, area water levels in wells generally are representative of the regional water table. However, they also noted that perched conditions are more common in the more eastern and southeastern parts of the study area, especially in the area between the cities of Gresham and Sandy (pl. 1), in the aquifers of the Boring Lava in the Boring Hills area, or in areas covered by alluvial deposits adjacent to the Sandy and Clackamas Rivers (Hogenson and Foxworthy, 1965, p. 25, 29, 36, and 39). Some of the water-level measurements used in this study possibly could represent perched zones. Nonetheless, in most places, the measurements of depth to water are believed to reflect the depth to the water table. The use of water-level measurements representative of perched zones rather than the regional water table could result in estimating the water table to be shallower than the actual elevation.

Interpolation of the Water Table

Each water-level measurement from a well or location of a surface-water feature that was deemed to represent the water table at land surface was represented by a point (or set of points for some surface-water features) (fig. 7). These points represent the water table at these locations and can be used to interpolate the position of the water table between these points.

Depth to Water versus Water-Table Elevation

Two conventions typically are used to define the position of the water table, depth to water and water-table elevation (fig. 8). The choice of which convention to use (depth to water or water-table elevation) may not be obvious when interpolating the water table. The interpolation of the water table is unlike the interpolation of the potentiometric surface of a confined aquifer where only the elevation of the potentiometric surface above some datum such as sea level typically would be used. This is because the potentiometric surface generally is not influenced by surface topography

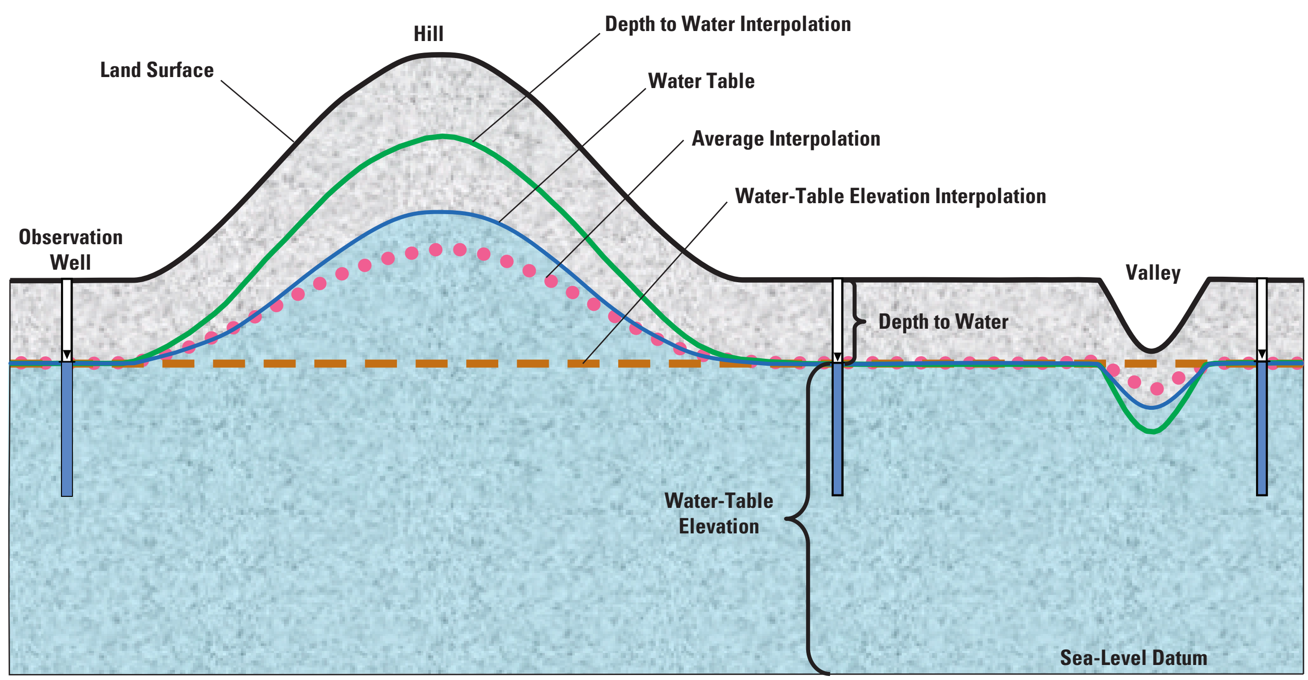


Figure 8. Averaged interpolation of the water-table position based on interpolations of depth to water table and water-table elevation.

and can be either above or below land surface (Fetter, 1994, p. 115). However, the water tables for some ground-water systems are expected to be related to land surface in that the water table is commonly a subdued replica of the land surface (Latham, 1878, p. 207-208; King, 1892, p. 15 and 18; Meinzer, 1923, p. 31; Heath, 1983, p. 20; Haitjema and Mitchell-Bruker, 2005, p. 781). This is particularly true for most parts of the Portland area, where much of the surficial aquifer consists of unconsolidated materials and the depth to water is relatively shallow. As a result, the influence of the land surface should be considered during the interpolation of the water table; however, the degree to which the land surface influences the water table depends on several factors. These factors have been discussed by many authors (Tóth, 1963; Freeze and Witherspoon, 1967, p. 634; Haitjema and Mitchell-Bruker, 2005, p. 784) and include wavelength of topographic features (steep versus gentle slopes), amplitude (magnitude) of topographic features (water levels generally are shallowest beneath valleys and deepest beneath hilltops [Low and others, 2002, p. 204]), hydraulic conductivity and storage of the surficial aquifer (aquifers with low hydraulic conductivity and storage more closely resemble topography than aquifers with high hydraulic conductivity and storage [Low and others, 2002, p. 204]); hydraulic conductivity of the underlying aquifer or confining unit (controls vertical flow), and spatial distribution and quantity of recharge and discharge.

The interpolation of the depth-to-water and water-table elevation datasets can produce substantially different results. The interpolations are expected to be exactly identical at the control points, such as observation wells or surface-water features representative of the water table, which act to constrain the interpolations (fig. 8). However, the interpolations may greatly diverge with increased distance from control points. For the hypothetical example presented in figure 8, the interpolation of the water table based on depth to water is too shallow under hills compared to the hypothetical water table, and under valleys the depth-to-water interpolation is too deep compared to the hypothetical water table. In contrast, the interpolation of the water table based on water-table elevation is too low under hills compared to the hypothetical water table, and under valleys the water-table elevation interpolation is too high compared to the hypothetical water table. Neither interpolation is entirely satisfactory for this hypothetical example; however, if the two interpolations are averaged by taking the mean of the values at each spatial position, the resulting surface (fig. 8) appears to be an improvement in the representation of the water table. This averaged interpolation retains many of the strengths of each interpolation with fewer of the weaknesses of either for the particular hypothetical example presented.

Averaging the interpolations of depth to water and water-table elevation incorporates the land-surface information into the interpolation. The interpolations of the water-table elevation and the depth to water represent the end members of a spectrum of possible interpolations depending on the conditions controlling the position of the water table previously described. These conditions change spatially across an area of interest as topography and hydrogeology change from place to place.

Both conventions of defining the water table initially were used to interpolate the water table for the Portland area. However, the conditions described for the hypothetical example were observed in each of the interpolations. As a result, the two interpolations were averaged by taking the mean of the values at each spatial position. This produced a water-table map that was realistic and reasonable based on our conceptualization of the ground-water flow system in the Portland area.

Kriging Interpolation

A brief description of kriging is presented here—the method of interpolation used for this study. Davis (1986), Deutsch and Journel (1998), and Bossong and others (1999) provide a more complete discussion on geostatistical methods. Kriging can be described as a type of spatial moving average, where the value at an unsampled location is estimated as a weighted average of the known observations. The weights assigned to the known values are based on spatial trends and correlations that may be present (Bossong and others, 1999, p. 4). The weights are a function of distance, where nearby observations are given more influential weights than more distant observations (Davis, 1986, p. 384). Kriging automatically adjusts the weights for the effects of data clustering, reducing the overall weight of a group of observations that contain much of the same information (Bossong and others, 1999, p. 17).

Kriging weights are assigned through the use of semivariograms. A semivariogram is a graph of the semivariance, which is a measure of the average difference of the observed values for points a given distance apart. As the distance increases, the semivariance (or dissimilarity) in the water-table level increases. The interaction of distance and semivariance is represented graphically on the semivariogram. Separation distances between all possible pairings of the observed data in a semivariogram are computed and the results divided into bins (lags) of generally equal intervals of separation distance (Holtschlag and Koschik, 2004, p. 7). Squared differences between all measured water-table levels are computed in each lag, and one-half the mean squared differenced value, the semivariance, is plotted at the center of each lag. This graph is called the empirical semivariogram (also referred to as the experimental or sample semivariogram), and is based on the actual water-level data. The empirical semivariogram consists of a set of points from the observed data and is used to develop a theoretical semivariogram for use in the kriging analysis.

The theoretical semivariogram generally consists of a smooth curve representing a mathematical expression or function that needs to be fit through the scattered empirical semivariogram points. A number of possible theoretical semivariograms (or models) can be tested through a trial-and-error process to determine the model that bests fits the measured data of the empirical semivariogram (Bossong and others, 1999, p. 5). The selected theoretical semivariogram model then is used in the kriging analysis to assign the optimal set of weights to the observations of the water-table level when interpolating a value of the water table between existing observation locations (Davis, 1986, p. 383).

Two types of kriging methods were used to analyze the data. One consideration in the selection of the kriging method is the absence or presence of a detectable spatial trend or “drift” in the data. Drift is often associated with land-surface or water-table elevation data that have a regional dip or trend (Bossong and others, 1999, p. 4 and 27; Desbarats and others, 2002, p. 25). The method of ordinary kriging is used for data with no drift; universal kriging should be considered for data when drift is present (Bossong and others, 1999, p. 6). The presence of spatial trends in the data is indicated by a parabolic empirical semivariogram shape (Bossong and others, 1999, p. 29, 42). Drift in the analysis of the empirical semivariogram typically is handled by estimating the spatial trend in the data by using a polynomial representation and then subtracting this from the data (Bossong and others, 1999, p. 29; Davis, 2002, p. 428-429 and 259-260). The residuals then are used to determine a new empirical semivariogram for the selection of a theoretical semivariogram model. The parameters of the model are used by universal kriging, the method subsequently used for the interpolation of the data.

Kriging can be used to interpolate values at points or over blocks. Point kriging is an exact interpolator, returning the value of the measurements at the observation locations. Block kriging is not an exact interpolator and returns the linear average of an attribute over some subarea (Alley, 1993, p. 99). Desbarats and others (2002, p. 33) describe block kriging as a compromise between spatial resolution and accuracy in measured water-table levels because water levels averaged over blocks of area can be estimated with less uncertainty than levels at a single point and can serve to mitigate the influence of erratic samples. Block kriging was used for the interpolation because of these considerations, and as a result estimates at observation locations may vary slightly from the measured values.

Kriging analysis was performed separately for the two conventions of depicting the water table, depth to water and water-table elevation. Semivariograms were developed individually for each convention and were used to determine the parameters for block kriging of each dataset. The interpolated values of water-table elevation then were subtracted from a DEM simulation of the land-surface elevation at each spatial position to transform the interpolated values of water-table elevation into values representing depth to water. The land-surface elevation DEM used was a resampled version of the 2-meter DEM developed for the study based on bilinear interpolation at a cell spacing of 250 ft to match the orientation, position, and spacing of the interpolation grid. The two interpolations of depth to water (direct and through transformation) then were averaged to produce a final interpolation of depth to water. A final interpolation of the water-table elevation then was created by subtracting the averaged depth-to-water interpolated values from the resampled DEM of the land-surface elevation. The maps and discussion of depth to water and water-table elevation use the average of the two interpolations.

Semivariogram Development

Empirical and model semivariograms were determined for each kriging analysis (depth to water and water-table elevation). The semivariograms developed for this study were determined with the use of only the information from wells and springs to prevent the large number of data points representing the other types of surface-water features from overwhelming the well and spring data, which more directly represent the water table over land areas. The kriging method accounts for clustering of data, and, therefore, the surface-water data were used in addition to the well and spring data. The development of the semivariograms was accomplished through the use of several programs designed to aid in the display and selection of parameters. These programs facilitate identifying which of the many theoretical semivariogram models best fit the empirical semivariogram and help to optimize the parameters for the best fit. Empirical semivariogram analysis and modeling of theoretical semivariograms were performed by using VARIOWIN software (Pannatier, 1996). The theoretical semivariogram models were fitted manually to the empirical semivariograms and the fit assessed with the “Indicative Goodness of Fit” statistic, which provides a measure of how well a model matches the measured data (Pannatier, 1996, p. 56).

Analysis of the empirical semivariogram for depth to water indicated that the data exhibited no discernible drift as determined from the shape of the empirical semivariogram (fig. 9*A*). Therefore, the parameters resulting from the semivariogram analysis could be used directly with ordinary kriging to interpolate the data. Parameters used for the theoretical semivariogram model for the kriging methods are listed in table 1.

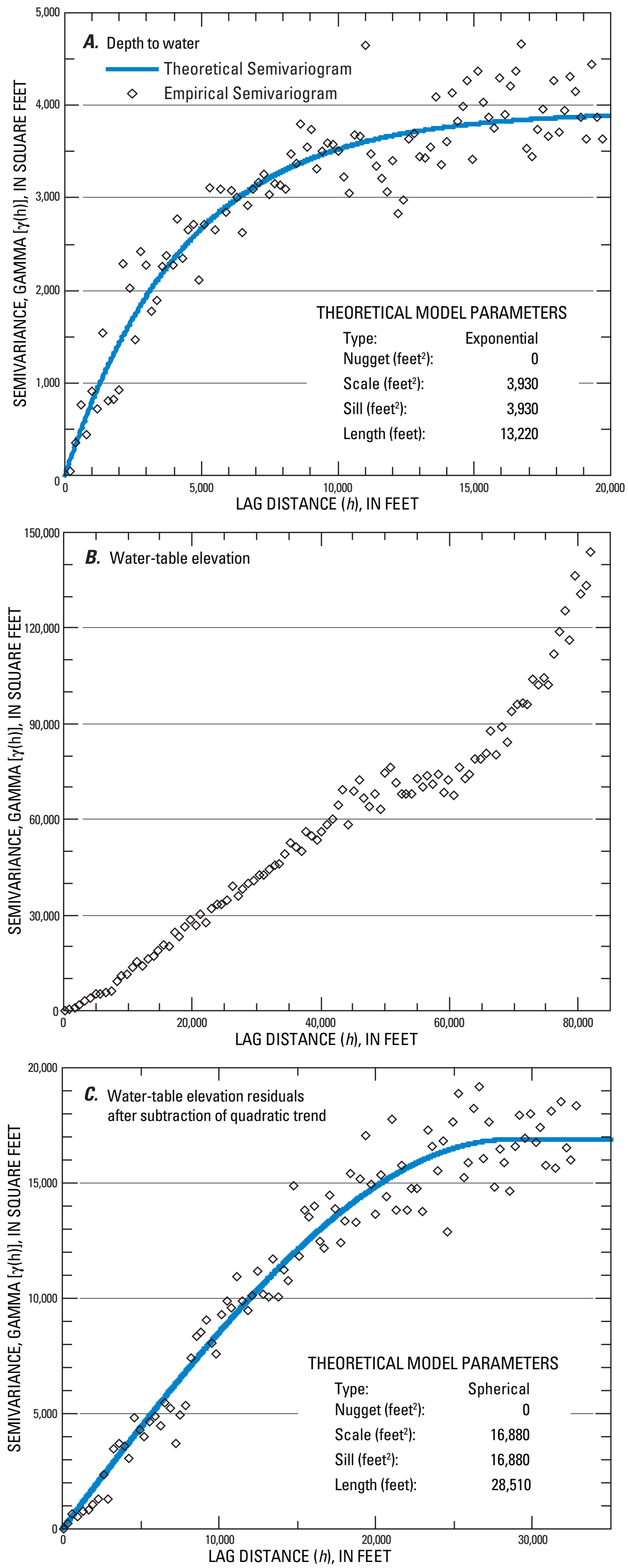


Figure 9. Semivariogram analysis for depth to water, water-table elevation, and water-table elevation residuals after subtraction of quadratic trend.

Table 1. Semivariogram and kriging parameters used for interpolation of depth to water and water-table elevation.

[ft, foot; ft^2, square foot; mi, mile]

	Semivariogram parameters					
	Model	Nugget (ft^2)	Scale (ft^2)	Sill (ft^2)	Length (range) (ft)	Polynomial drift
Depth to water	Exponential	0	3,930	3,930	13,220	None
Water-table elevation	Spherical	0	16,880	16,880	28,510	Quadratic

	Kriging parameters								
	Kriging type	X Spacing (ft)	Y Spacing (ft)	Number of data points	Number of search sectors	Maximum number of data points used in each sector	Maximum number of data points used in all sectors	Minimum number of data points used in all sectors	Search radius (mi)
Depth to water	Block	250	250	4,605	4	16	64	8	39
Water-table elevation	Block	250	250	4,605	4	16	64	8	39

The water-table elevation data exhibit drift, as determined from the parabolic shape of the empirical semivariogram (fig. 9*B*). The drift in the water-table elevation was estimated by using a quadratic least-squares regression, which was subtracted from the water-table elevation. The residuals were then used in a new semivariogram analysis to determine the parameters of the theoretical semivariogram model to be used in interpolation by using universal kriging (fig. 9*C* and table 1). For the water-table elevation dataset, the subtraction of the estimated drift, kriging of the residual values, and subsequent transformation back to water-table elevations by adding the estimated drift was carried out by the kriging software.

Kriging Implementation

Kriging analysis was performed with the use of Surfer software (Golden Software, Inc., 2002) by using a rectangular grid oriented north-south/east-west with square blocks 250 ft on each side. The area of analysis was extended about 4 mi beyond the geographic extremes of the data to maximize the information made available by the data. The semivariogram and kriging parameters used for the depth-to-water and water-table elevation interpolations are listed in table 1.

A small number of blocks in the analysis of depth to water were interpolated to be negative (above land surface), especially in low-lying areas, where many surface-water features were used to represent the water table with a depth to water of 0 ft. These values were corrected to represent a depth to water of 0 ft for these blocks to be consistent with the definition of the water table based on hydrogeologic reasoning by using existing knowledge of these areas. Similarly, a small number of blocks in the analysis of the water-table elevation were interpolated with values less than 11 ft. These values were corrected to 11 ft, which is the elevation used to represent the base water-table elevation as determined by the mean stage of the Columbia River, which is the regional discharge area and lowest water-table elevation. Water-table elevations less than 11 ft are hydrogeologically unlikely unless the levels were being influenced by some type of local stress such as pumping or evapotranspiration. The averaged interpolations of depth to water and water-table elevation also were evaluated and modified as needed to ensure that the depth to water equals or exceeds 0 feet below land surface and that the water-table elevation equals or exceeds 11 ft.

Relative Uncertainty

The formation of maps of the standard deviations of the estimates of the water-table position is a product of the kriging analysis. These maps largely are based on the semivariogram model used and the geometric configuration of the available data (Delhomme, 1978, p. 257, 262; Bossong and others, 1999, p. 5 and 43). The maps provide a method to evaluate the reliability associated with the values of the water-table position and can be used as a measure of the uncertainty. However, the standard deviation values should be considered relative to one another and not in any absolute sense (Alley, 1993, p. 97).

Standard deviation maps were generated for the analyses of depth-to-water and water-table elevation. These maps are similar and were averaged to produce a single standard deviation map for the water-table position. The resulting standard deviation map was used to limit the extent of the analysis. Areas where the averaged standard deviation exceeded 100 ft were excluded from the results. These areas are on the perimeter of the study area, where few data are available to constrain the interpolation analysis and as such have unacceptably high uncertainty. The areas with standard deviation values less than 100 ft were rescaled to a dimensionless value that will be referred to as the "relative uncertainty." The values of the relative uncertainty range between 0 and 1 where 0 represents a low relative uncertainty and 1 represents a high relative uncertainty. The resulting map (pl. 3) is intended to be used to determine relative uncertainty when evaluating the water-table configuration maps or estimating a value at a site-specific location. Locations with more nearby data sites that are less redundant (values on multiple sides are more useful than values on the same side) will exhibit a smaller relative uncertainty than locations with few or distant data sites, or with data sites that are less than optimally positioned (Davis, 1986, p. 388-389; Alley, 1993, p. 96). Note that the relative uncertainty map is a result of the statistical properties of the dataset and does not incorporate knowledge or uncertainty with regard to the hydrogeology of the study area.

Assumptions and Assessment of Errors

The accuracy of the depth-to-water and water-table elevation maps depends on various factors pertaining to the data, the method of interpolation, and the hydrogeologic conditions of the surficial aquifers in the study area. Some of these factors have been discussed in the sections, "Data Limitations" and "Relative Uncertainty." The following assumptions are made with regard to the well data used for interpolation:

- Water levels in wells are representative of water-table conditions in unconfined aquifers;
- Individual water-level measurements are representative of static conditions not influenced by transient stresses such as pumping;
- The median value of all water-level measurements for each well is representative of the long-term position of the water table;
- Spatial positions of the wells are accurately known;
- Land-surface elevations of the wells are accurately assessed; and
- The surface-water features that were used for interpolation were assumed to be the features that represent the long-term position of the water table as being present at land surface; spatial positions of the features are accurately known; and land-surface elevations of the features are accurately assessed.

The method of interpolation has a large influence on the accuracy of the water-table maps, which is influenced by the spatial distribution of data points, semivariogram modeling, the appropriate selection of the kriging parameters, the level of discretization (spatial resolution) used, and basic assumptions about the hydrogeology. The latter includes the assumption that the hydrogeologic conditions in the surficial aquifers were homogeneous and isotropic. The spatial discretization used in the interpolation can lead to errors when comparing to site-specific measurements of the water-table position, especially in areas of abrupt local change in hydrogeologic properties, steep land-surface relief, or steep water-table gradients, as the estimate from interpolation represents the water-table position for a 250-foot square block and also relied on the resampled DEM of land-surface elevation.

Some of the assumptions cannot be completely evaluated and may not have been fully met. The water-table configuration maps, however, generally are representative of the conditions in the study area. Nonetheless, the actual position of the water table may differ from the estimated position at site-specific locations, and short-term, seasonal, and long-term variations in the differences also should be expected. A measure of the accuracy of the estimation of the water-table configuration can be determined by evaluating the magnitude and the variability in the differences between measured and estimated values of the water-table position. The difference between the measured depth to water and the estimated depth to water based on the interpolation for the 582 wells and 22 springs ranged from -49 to 50 ft, with a median value of less than 1 ft and 95 percent of the estimated values within 18 ft of the measured value.

A possible consequence of interpolation is that if features are used in the analysis (wells and (or) surface-water features representative of the water table) that are within close proximity to each other and have substantially different water levels, the resulting estimate of the water-table position will be intermediate to all values. This can result in a large difference between the measured and estimated water-table position. Differing water levels in adjacent features can result from the use of wells with dissimilar open-intervals, steep hydraulic gradients due to changes in lithology or structure of the aquifer, areas of high land-surface relief, proximity to recharge or discharge stresses, the use of wells with water-level measurements representative of different time periods, or the use of wells or surface-water features that are not representative of the water table (such as wells influenced by perched ground water or streams that are not gaining).

The relative uncertainty map (pl. 3) addresses some but not all possible errors associated with the analysis of the water-table position. For example, areas with estimated depths to water greater than 300 ft will have a high uncertainty because data for the analysis of the water table were restricted to wells with a maximum depth of 300 ft. Therefore, the relative uncertainty map is intended to be used as a guide with the understanding that all sources of uncertainty are not depicted.

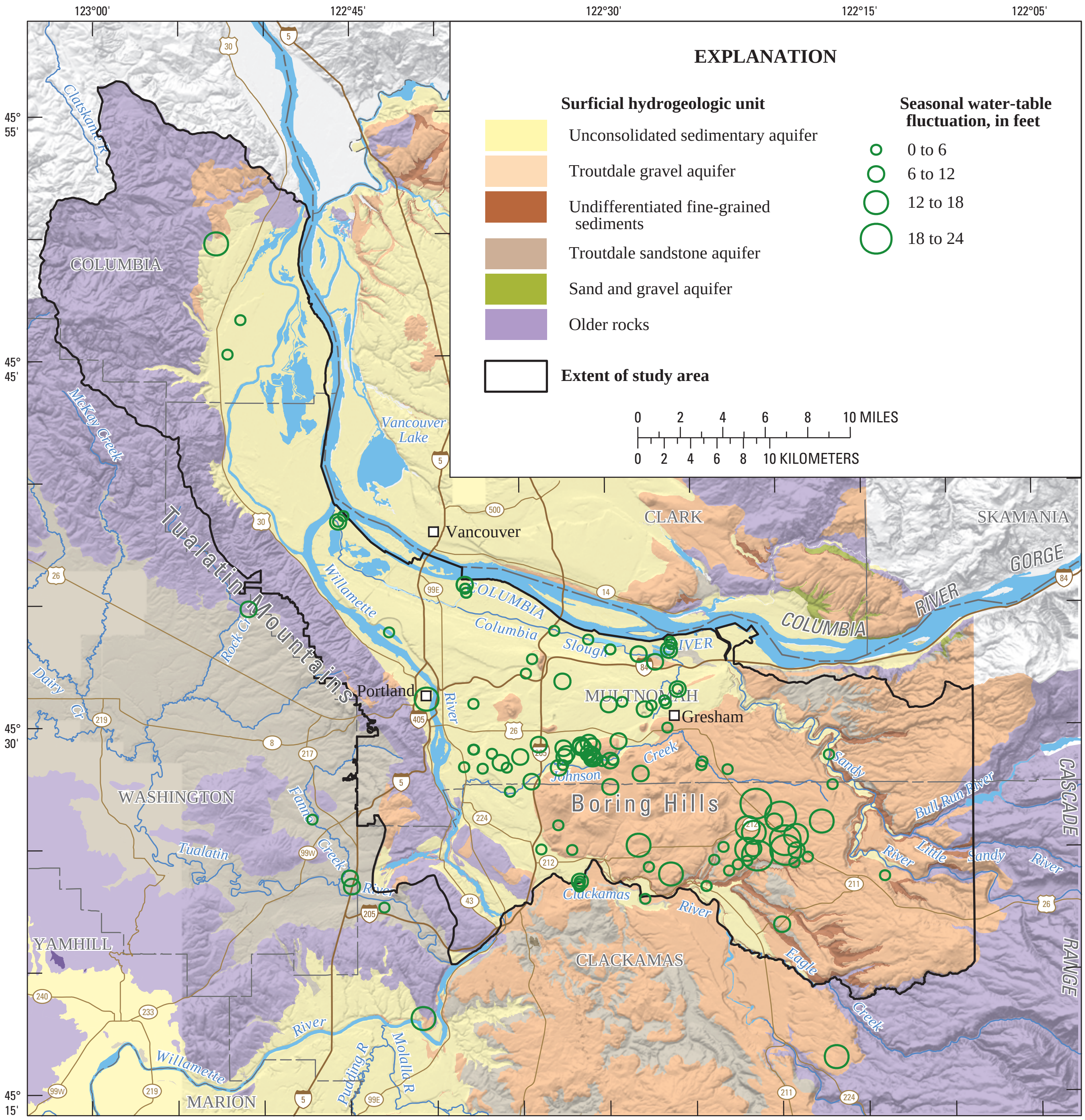
Seasonal Water-Table Fluctuations

The water table is not a stationary surface and is continually fluctuating in response to changes in recharge to or discharge from the aquifer. Seasonal fluctuations of the water table in the Portland area are related to seasonal changes in ground-water recharge from precipitation, losing streams, irrigation, or runoff to UIC systems, or from seasonal changes in discharge due to evapotranspiration or the pumping of wells (McFarland and Morgan, 1996, p. 30). Ground-water levels in the Portland area normally are highest during the spring following the winter period of high precipitation and low evapotranspiration. Water levels recede during the summer in response to less precipitation and high evapotranspiration and are lowest in the autumn. The position of the water table also can change as a result of long-term changes in precipitation; changes in the location, timing, or quantity of irrigation or pumping; creation of impervious surfaces from urban development; or installation or removal of UIC systems or on-site waste disposal systems (septic systems). However, the present analysis did not differentiate between seasonal fluctuations and long-term changes except for the exclusion of a small number of wells with hydrographs that exhibited obvious long-term influences. These changes, especially from pumping, can be severe in areas such as the Sandy-Boring or Damascus areas, where large declines in ground-water levels led to declaration of ground-water limited areas by the Oregon Water Resources Department (2006, p. 12-13). Limitations on withdrawals instituted by the OWRD have subsequently resulted in the substantial recovery of ground-water levels in these areas. These fluctuations may influence the analysis of seasonal water-table fluctuations but should have limited influence on the median water level used in the depth-to-water analysis.

The magnitude of seasonal water-table fluctuations depends on the quantity of recharge or discharge added or removed from the aquifer as well as on the effective porosity of the aquifer. The greater the effective porosity, the greater the storage available in the aquifer. An aquifer with a greater effective porosity will experience a smaller change in the water-table position due to a change in a given volume of water compared to an aquifer with a lesser effective porosity.

The 582 wells used in the analysis of the water-table position were evaluated for use in the analysis of seasonal water-table fluctuations. In addition, 20 wells not used in the analysis of the water-table position, primarily because of the proximity to other wells, were added to the pool of candidate wells for analysis of seasonal water-table fluctuations. Of these wells, 394 wells had 2 or more water-level measurements and had no depths to water above land-surface (depth to water less than 0 ft below land surface) that might indicate artesian or confined conditions. Water-level fluctuations for wells in this group for the period of record ranged from 0 to 138 ft, with a median of 7.5 ft.

Only water-level measurements in wells representative of all seasons were used to evaluate the seasonal-water level fluctuations. The data were inspected through various graphical and statistical techniques, such as by plotting the calendar date of measurements based on polar coordinates to identify the center of mass (mean measurement date) and by comparing the polygonal area defined by the measurement dates plotted based on polar coordinates to identify those wells that had suitable distributions of measurements throughout the year. Wells with 10 or more measurements substantially met these criteria and were used to develop the seasonal-water level fluctuation analysis. As a result, 147 wells were analyzed with the number of measurements ranging from 10 to 306 with a median of 20 measurements. Inspection of the data revealed possible anomalous measurements likely due to clerical errors or resulting from measurement of wells when water levels were not in equilibrium such as during recovery from pumping or well development following construction. To remove possible errant measurements the measurements for each well were ranked by depth to water and only the central 90 percent of the measurements for each well were used for analysis and will be referred to as the trimmed values. Although this will remove most of the effects of measurement errors, trimming also can reduce the full range of the actual water-level fluctuations for any single well, although this effect generally is expected to be small given the number of measurements for each well. Water-levels in wells that are indicative of unusually large ranges in fluctuations were reviewed for inclusion in the analysis. The hydrographs of wells with water-level fluctuations of 20 ft or greater were visually inspected. Twenty well records, with long-term trends indicating large declines or recoveries, or with an unusually large percentage of apparently erroneous measurements likely due to recent or nearby pumping at the time of measurement, were removed from the analysis. The locations and the values of the trimmed ranges of water-table fluctuations for the remaining 127 wells are presented in figure 10 and in table A3.



Base modified from U.S. Geological Survey data and other digital sources: see table of contents of printed report for detailed information on sources. Projection: UTM, Zone 10N, North American Datum 1983, Scale factor= 0.9996, False easting = 500,000, False northing = 0.

Hydrogeology modified from Swanson and others (1993) and Conlon and others (2005).

Figure 10. Seasonal water-table fluctuations in the Portland, Oregon area. (Values of seasonal water-table fluctuation presented are the trimmed values that include the central 90 percent of the water-level measurements for the period of record for each well.)

Estimated Depth to Ground Water and Configuration of the Water Table

Estimates of depth-to-water and water-table elevation are affected by a number of variables, including the types, characteristics, timing, and errors associated with the data, as well as effects due to the interpolation method. Therefore, the maps of depth to water and water-table elevation are approximations; the values represent average conditions and have an associated uncertainty. Further, the actual water-table position will vary temporally as a result of short-term, seasonal, or long-term influences. Data files of depth to water, water-table elevation, and relative uncertainty of the water-table position are available for download as described in appendix B.

Estimated Depth to Ground Water

Depth to water ranges from 0 ft below the surface along major rivers and streams to a maximum estimated at more than 1,200 ft below land surface on the southern slopes of Larch Mountain (pl. 1). The depth to water for nearly two-thirds of the study area analyzed was less than 100 ft. Areas where the depth to water exceeds 100 ft include the Tualatin Mountains, the Boring Hills, and the foothills of the Cascade Range. Depth to water also exceeds 100 ft in the terrace deposits throughout much of northern and eastern Portland area. Depth to water greater than 300 ft is limited to a few high elevation areas and include parts of the Tualatin Mountains, the slopes of Larch Mountain, the ridge extending southeast from Lake Oswego, and the summits of Rocky Butte, Mount Tabor, Mount Scott, and several other of the Boring Hills (pl. 1). A visual inspection of the depth-to-water map reveals a significant correlation between depth to water and land-surface elevation. Depths to water were deeper in areas with high elevations such as the Tualatin Mountains, Boring Hills, and the foothills of the Cascade Range. Depths to water were shallower in low-lying areas along rivers and streams such as the Columbia, Willamette, Clackamas, and Sandy Rivers and the water table in many places is at or near land surface. The spatial correlation between the interpolated depth to water and the land-surface elevation has a correlation coefficient (R value) of 0.73 indicating a relatively high correspondence between the two; that is, as land-surface elevation increases depth to water increases. These observations are consistent with the concept that depth to water typically is greater beneath hills than valleys (Fetter, 1994, p. 114).

Areas of notably shallow depths to water in addition to the low-lying areas along major rivers and streams include much of the area adjacent to Johnson Creek, the area around Fairview Creek including several small lakes, the area extending from the west end of Lake Oswego southwest to the Tualatin River, and the area consisting of former alluvial channels (Hogenson and Foxworthy, 1965, p. 10, 11, and 28) extending from the confluence of Johnson and Crystal Springs Creeks northward to the Willamette River and southward to the Clackamas River. Another area of relatively shallow depth to water extends southwest from Fairview Creek, through the saddle area between Kelly and Powell Buttes, and intersects Johnson Creek west of Mount Scott (pl. 1). This area has been described by Allison (1978b, p. 193) as an erosional channel formed by the Missoula Floods. The area includes Beggars Tick Marsh and a small depression situated at the west end of Powell Butte, locally known as “Holgate Lake” (Lee, 2002).

The influence on the water table resulting from certain manmade features, where overlying soil and rock have been removed creating shallow depths to water, can be seen on the depth-to-water map (pl. 1). These include sand and gravel pits such as those south of the Portland International Airport, north of Kelly Butte, west of Mount Scott, and along the west side of Gresham as well as road cuts for Interstate Highway 205 in northeastern Portland area and for the railroad through northern Portland, which parallels N. Portland Road. Other influences due to manmade features can be discerned on the depth-to-water map but are actually artifacts resulting from the processing of the digital elevation model data (see section, “Assumptions and Assessment of Errors”). These features include the major elevated roadways and bridges such as those on the Interstate highways, especially near downtown Portland, which produce depths to water that are improbably greater than adjacent areas.

No published depth-to-water maps that cover an extensive part of the study area were located for comparison with the current study. However, the USGS simulated ground-water elevation based on a regional three-dimensional finite-difference ground-water flow model (Morgan and McFarland, 1996). A simulated depth-to-water map can be developed by subtracting the simulated ground-water elevations from the land-surface elevations used in the model. Output data files from the USGS model are available online (U.S. Geological Survey, 2006) and were analyzed to evaluate depth to water. Many of the wells and surface-water features used in the model also were used for the current study. The comparison is extremely good for the central part of the study area, including the areas of northern, northeastern, and southeastern Portland. Agreement also is favorable in the area of the Boring Hills. However, the ground-water model results indicate a substantial depth to water along the Willamette River; whereas, the current study uses a zero depth to water along the Willamette River. This difference may be a function of the relatively coarse horizontal discretization used for the ground-water model, which used a rectangular grid with cells 3,000 ft on a side. Other areas of disagreement between the current study and the ground-water model include the area extending from Troutdale southeast to Sandy and all areas south of Sandy, where the ground-water model appears to substantially overestimate ground-water elevation and, as a result, greatly underestimates the depth to water due to the lack of available control data in this area.

Implications of Depth to Water for Underground Injection Control Systems

The depth-to-water map (pl. 1) can be used to help identify areas where the occurrence of existing or planned UIC systems may be less suitable. Two factors commonly used to evaluate the suitability of UIC systems at a particular location are the separation distance between the water table and the bottom of a UIC system and the particle size and character of the intervening subsurface materials. Greater separation distances tend to reduce or eliminate certain types of waterborne pollution, and for the same material thickness, finer grained materials, such as clay, tend to yield greater pollution reductions than coarser grained materials, such as gravel. The typical depth of a UIC system in the Portland area is about 30 ft, although UIC systems commonly are much shallower. Assuming a 10-foot separation requirement between the water table and the bottom of a typical UIC system, the minimum depth to water needed would be 40 ft (Oregon Department of Environmental Quality, 2005a, p. 37; 2005b, p. 4, 8). Regions where the depth to water is less than or equal to 40 ft might not have a 10-foot separation distance between the water table and any stormwater injection devices that may be present. UIC systems that do not meet the separation requirements may be considered for one or more of the following actions: additional evaluation with regard to the ability of the intervening subsurface materials to adequately protect the ground water; retrofitting, possibly by adding material such as control density fill (CDF) (a blend of cement, fly ash, sand, and water) to the bottom of the UIC system to increase the separation distance; or decommissioning.

Areas with a depth to water of 40 ft or less include the area adjacent to most rivers and streams, including the Columbia, Willamette, Clackamas, Tualatin, and Sandy Rivers, and Johnson, Fairview, Beaver, Kellogg, and Mount Scott Creeks (pl. 1). Other areas of concern are the area between the Columbia Slough and the bluff to the south, the area around Fairview Creek and several small lakes in the western part of Gresham, the area consisting of a former alluvial channel extending northward from the confluence of Johnson and Crystal Springs Creek (Trimble, 1963, p. 71-72), the area consisting of a former alluvial channel extending southward from the mouth of Kellogg Creek to the Clackamas River, the areas around and between Holgate Lake and Beggars Tick Marsh, and the area immediately south of the western end of Lake Oswego. Shallow depths to water can occur at moderate to high elevations but generally are associated with incised stream channels. Seasonal fluctuation in the water table may result in additional areas where the separation distance may be inadequate for UIC systems based on the assumptions previously discussed. Users requiring information on the seasonal extremes of depth to water can add or subtract one-half the range of seasonal water-table fluctuation (selected based on the appropriate hydrogeologic unit for the area, see section "Estimated Seasonal Water-Table Fluctuations") from the estimated depth to water.

Estimated Configuration of the Water Table

The elevation of the water table ranged from 11 ft NAVD 88 along most areas of the Columbia and Willamette Rivers to more than 2,000 ft NAVD 88 on the southern slopes of Larch Mountain (pl. 2). A visual inspection of the water-table elevation map shows that the configuration of the water table is similar to that of land surface. Subtle features as well as large, obvious features of the topography are recognizable and represented. The correlation coefficient (R value) for the spatial correlation between the interpolated water-table elevation and the land-surface elevation was 0.96 indicating a high correspondence between the two; that is, as land-surface elevation increases, water-table elevation increases. Water-table elevations are high for topographic features with high elevations, such as the Tualatin Mountains, Boring Hills, and the foothills of the Cascade Range. Water-table elevations are low for areas at low elevations adjacent to the Columbia and Willamette Rivers. These observations are consistent with the concept discussed in the section "Definition of the Water Table" that the water table is often a subdued replica of the land surface.

Comparisons with previous estimates of ground-water elevation in the Portland area generally are favorable. The largest body of recent work that provides extensive maps of ground-water levels is the study of the ground-water hydrology of the Portland Basin by the USGS. Maps consisting of hand-drawn contours of ground-water elevations derived from field measurements are presented by McFarland and Morgan (1996, 20-22, pl. 2-5) for the major hydrogeologic units in the basin. Many of the wells and surface-water features used in their analysis also were used for the current study. The contour map of ground-water elevations for the unconsolidated sedimentary aquifer (McFarland and Morgan, 1996, p. 20-21, pl. 2) shows modest agreement with the estimates from the current study in the area north and west of Powell Butte, although differences can exceed 50 ft in some areas. However, the contours presented by McFarland and Morgan (1996, pl. 2) are indicated as approximate and are relatively unconstrained due to a scarcity of data in this area, making comparisons difficult. Ground-water levels for the Troutdale gravel aquifer (McFarland and Morgan, 1996, p. 22, pl. 3) show a high degree of similarity for this area as well as throughout the area bounded by the Columbia and Clackamas Rivers to the north and south and by the Willamette and Sandy Rivers to the west and east. These contours generally are more highly constrained than those for the unconsolidated sedimentary aquifer, especially in the central part of the area, due to the greater availability of well data for this aquifer. Although the Troutdale gravel aquifer underlies the unconsolidated sedimentary aquifer throughout the terraced areas in the eastern Portland area and Multnomah County, the elevation of the top of the unit generally is close to that of the water-table elevation estimated in this study. The Troutdale gravel aquifer forms the surficial aquifer in many of the areas to the southeast. Many of the wells used in the current study for estimation of the water-table elevation that have open intervals in the Troutdale gravel aquifer also were used in the development of the ground-water level maps by McFarland and Morgan (1996).

Contours of simulated ground-water elevations for the unconsolidated sedimentary aquifer (Morgan and McFarland, 1996, p. 29-30, pl. 3) developed based on a ground-water flow model are in good agreement with the water-table elevations developed in the current study for most of the area. However, in the area immediately north of Powell Butte, the current study indicates a saddle in the water table for the area between Kelly and Powell Buttes that is not represented in the work by Morgan and McFarland (1996, pl. 3), though this may be a result of the resolution of the ground-water model or of the contour interval used. Contours presented for the Troutdale gravel aquifer by Morgan and McFarland (1996, p. 29-32, pl. 4) are in good agreement with the current study for most of the area, with the exception of the area south and east of the city of Sandy. Ground-water elevations for the ground-water model are substantially higher in this area than the values derived in this study. This area has few ground-water elevation measurements, and, as a result, the ground-water flow model and the present analysis are highly unconstrained in this area.

The water-table gradients (slope of the water table) shown on the water-table elevation map are a function of the land-surface relief, permeability of the geologic materials, and variations in recharge and discharge. Steeper (higher) horizontal gradients are indicated where the water-table elevation contours are more closely spaced. Relatively steep water-table gradients occur where the geologic materials are of low to moderate permeability such as the Tualatin Mountains, Boring Hills, and foothills of the Cascade Range, which often are associated with greater topographic relief. Gentler gradients occurring in areas of higher permeability and gentler relief are most common in the low-lying areas along major rivers and streams and in the terrace deposits extending in an area approximately bounded by the Columbia River to the north, the Willamette River to the west, and the Boring Hills to the southeast.

The approximate direction of shallow horizontal ground-water flow can be implied cautiously from gradients depicted on the water-table elevation map (pl. 2). The direction of ground-water flow is indicated as the direction perpendicular to the water-table elevation contours moving from areas of high to low water-table elevations. The water-table elevation map provides an indication of the direction of flow at the surface of the saturated zone but does not provide information regarding lateral or vertical gradients in the saturated zone and how flow directions may change with depth in the flow system. Such information is needed to determine the correct ground-water flow path from a specified location. The map may provide useful indications of the possible direction of shallow ground-water flow over short distances; however, use of a ground-water flow model such as that of Morgan and McFarland (1996) developed for the Portland Basin will provide a more reasonable depiction of the actual direction of ground-water flow in three dimensions over greater distances.

The overall direction of ground-water flow is toward the major ground-water discharge areas consisting of the Columbia, Willamette, and Clackamas Rivers (pl. 2). Local directions of ground-water flow generally are toward adjacent streams and rivers and appear to follow surface drainage patterns in most instances; however, Johnson Creek is a notable exception. Directions of shallow ground-water flow indicate movement toward the Sandy River in the upper reaches of the surface-water drainage, toward the Columbia River in upper midreaches, and toward the Willamette River in some parts of the lower midreaches. Although these patterns are indicative of shallow ground-water flow only, these flow patterns may provide insights on the low unit-area discharge (stream discharge divided by the area of the drainage basin) observed for some parts of Johnson Creek (K.K. Lee, U.S. Geological Survey, written commun., 2007).

Examination of the map of the water-table elevation also reveals the presence of ground-water mounds and depressions. Ground-water mounds are areas where ground water is moving radially away from the center of the mound. The presence of the mounds may be the result of topography, less permeable aquifer materials, and (or) the presence of recharge areas either due to the infiltration of precipitation or some other source, such as losing streams, UIC systems, septic systems, irrigation, or injection wells. Ground-water mounds in the Portland Basin are usually associated with recharge areas located at the top of hills or mountains such as can be seen at the Tualatin Mountains, Mount Tabor, or the Boring Hills (pl. 2). Many of these hills receive high rates of precipitation and also may be composed of less permeable materials.

Closed ground-water depressions are areas where ground water is moving radially toward the center of the depression, indicating ground-water discharge possibly as a result of losses to gaining streams, springs, evapotranspiration, or withdrawal wells. Ground-water depressions alternatively may be the result of discharge of ground water from the surficial aquifer by the downward movement of ground water into the underlying aquifer. Several small closed depressions in the Portland area are associated with gravel pits and quarries. Other small ground-water depressions may include the area on the southwestern side of Rocky Butte and several areas located between the western side of Mount Scott and

Milwaukie (pl. 2). The two largest closed ground-water depressions are the area adjacent to the northwestern side of Powell Butte and an area near Sunshine Valley (pl. 2). The depression near Powell Butte may be the result of municipal ground-water pumping for a public-water supply which, until recently, occurred in this area. It is unknown whether the recent cessation of pumping will result in the recovery of ground-water levels in this area or whether the ground-water depression will continue to persist and can, therefore, be attributed to other causes. The depth and extent of the large depression (shown only as a nearly closed depression due to the contour interval) near Sunshine Valley is largely based on the water-level measurement of a single well. Whether this depression is a reasonable representation of the water table in this area or whether it is the result of the use of one or more wells that may be confined or have water levels that are perched is unknown. Many of the closed depressions are not well constrained by the available data and may be a result of inadequacies in the method of interpolation. Further data collection and analysis are needed to better define the depth and extent of closed ground-water depressions and to understand the causes contributing to the occurrence of these depressions.

Estimated Seasonal Water-Table Fluctuations

The 127 wells used to evaluate seasonal water-table fluctuations have trimmed ranges of water-level fluctuations that ranged from 1 to 22 ft, with a mean of 7 ft. Small seasonal water-table fluctuations occur throughout the study area but are concentrated more heavily in the terraced areas between the Willamette and Columbia Rivers north and west of the Boring Hills (fig. 10), where the wells typically obtain water from the unconsolidated sedimentary aquifer. The largest seasonal changes generally occur in the Sandy, Boring, and Damascus areas with few exceptions. These large fluctuations, which ranged as much as 22 ft, occurred in the Troutdale gravel aquifer and older rock hydrogeologic units. The magnitude of the water-table fluctuations is primarily a function of changes in recharge, discharge, and the effective porosity of the aquifer. Mean annual recharge in the Portland area (Snyder and others, 1994, p. 30) is somewhat greater in the areas of larger water-table fluctuations. Discharge due to large volumes of water pumped for agricultural usage is also greater (Collins and Broad, 1993, p. 11). However, the differences in recharge and discharge are greatly magnified in this area of large water-table fluctuations because of the lower effective porosity of the shallow aquifers.

A categorization of the seasonal water-table fluctuations by hydrogeologic unit was evaluated and developed as a result of the qualitative relation observed between seasonal water-table fluctuations and the hydrogeologic unit present. The hydrogeologic unit in the range of fluctuation of the water table (referred to as the “zone of fluctuation” and defined as the part of the aquifer between the minimum and maximum trimmed values of measured depth to water for each well) was determined. The minimum and maximum trimmed depths to water for each well used in the seasonal water-table fluctuation analysis were compared against the depth and thickness of the hydrogeologic units identified for each well (Swanson and others, 1993, p. 8) to determine the hydrogeologic unit in the zone of fluctuation. The hydrogeologic units for some wells located outside the extent of the work by Swanson and others (1993) were identified based on the hydrogeologic classifications of Conlon and others (2005, p. 7-23), and the hydrogeologic units subsequently were correlated to the hydrogeologic units defined in the current study (Conlon and others, 2005, p. 8).

Effective porosities of the hydrogeologic units in the Portland Basin were estimated by Hinkle and Snyder (1997, p. 14 and p. 39-47) based on hydraulic conductivity values calibrated for the USGS Portland Basin ground-water flow model (Morgan and McFarland, 1996, p. 17-19). The mean effective porosity for each hydrogeologic unit in the Portland Basin is shown in table 2. The mean seasonal water-table fluctuation by hydrogeologic unit can be estimated by dividing the mean recharge rate of 22.0 in/yr for the Portland Basin (Snyder and others, 1994, p. 30) by the effective porosities estimated for each hydrogeologic unit. The resulting values of estimated seasonal water-table fluctuation calculated from porosity and recharge are similar to the mean of the measured values of seasonal water-table fluctuations for each hydrogeologic unit (table 2 and fig. 11). This agreement helps to support the conceptualization that the water-table fluctuations are influenced greatly by the hydraulic properties of the hydrogeologic unit in the zone of fluctuation.

Table 2. Effective porosity and seasonal water-table fluctuations by hydrogeologic unit in the Portland, Oregon area.

[–, unknown. No wells had a zone of fluctuation within the sand and gravel aquifer]

Properties	Hydrogeologic unit						
	Unconsolidated sedimentary aquifer	Troutdale gravel aquifer	Undifferentiated fine-grained unit	Troutdale sandstone aquifer	Sand and gravel aquifer	Older rocks	All hydrogeologic units
Mean effective porosity (dimensionless)	0.31	0.28	0.21	0.29	0.26	0.15	[1]0.23
Predicted seasonal water-table fluctuation as calculated using mean effective porosity and mean average annual recharge (feet)	5.9	6.5	8.7	6.3	7.1	12.2	8.0
Mean of measured seasonal water-table fluctuations (feet)[2]	5.9	8.0	7.3	6.9	–	11.0	6.8
Number of wells used for analysis with zone of fluctuation within the hydrogeologic unit	63	39	9	14	0	2	127

[1] Weighted mean by areal extent in the Portland Basin (see Hinkle and Snyder, 1997, p. 39-47).

[2] Values of measured seasonal water-level fluctuation presented are the trimmed values that include the central 90 percent of the water-level measurements for the period of record of each well.

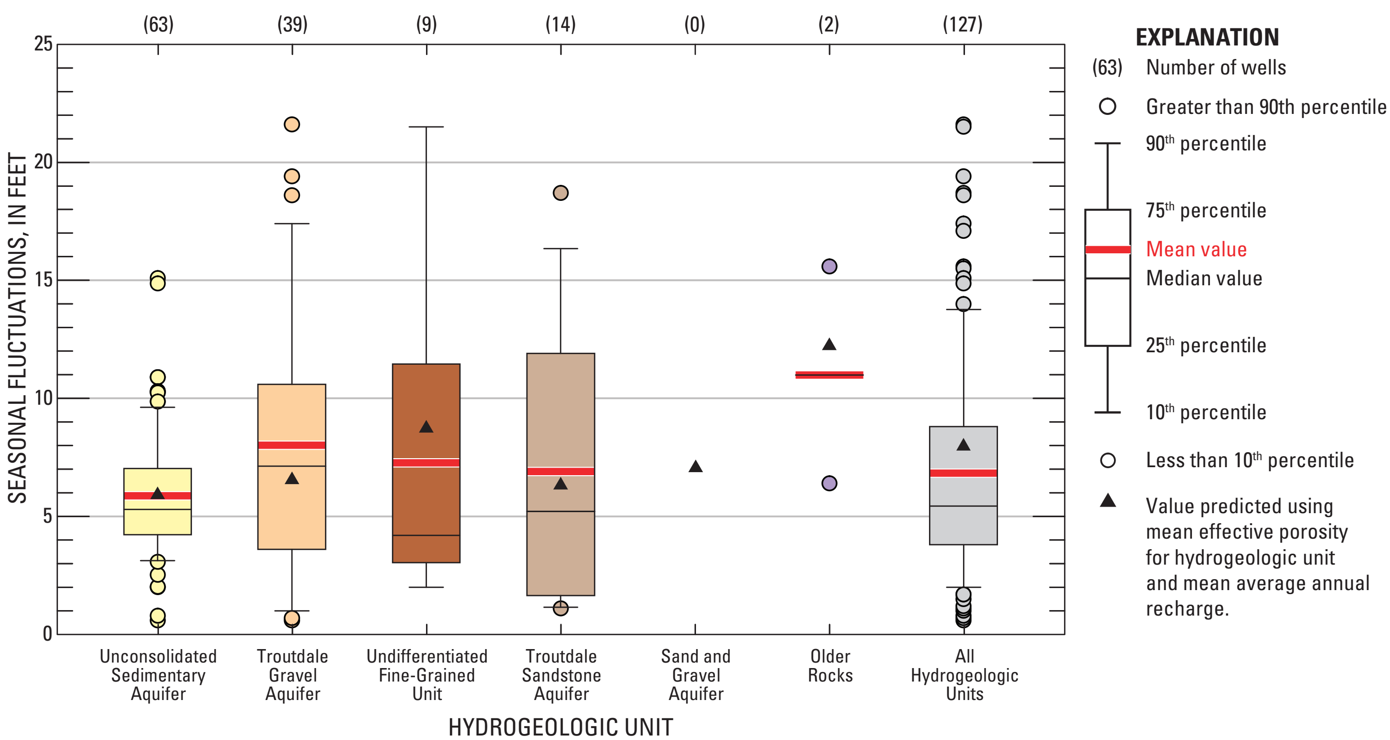


Figure 11. Estimated seasonal water-table fluctuations by hydrogeologic unit in the Portland, Oregon area. (Values of seasonal water-table fluctuation presented are the trimmed values that include the central 90 percent of the water-level measurements for the period of record for each well.)

Summary

Reliable information describing the configuration of the water table in the Portland area is needed to resolve a variety of water-resource issues including evaluation of aquifer susceptibility to contamination, effects from stormwater injection systems such as UIC systems (underground injection control systems), construction, well drilling, and monitoring, and as a baseline to identify changes in water levels resulting from natural or human-induced causes. This report presents maps of estimated depth to water and water-table elevation for the Portland metropolitan area along with estimates of the relative uncertainty and an estimate of seasonal water-table fluctuations to help answer these needs.

The method of analysis used to determine the configuration of the water table in the Portland area relied on two types of readily available information: (1) water-level data from shallow wells, and (2) surface-water features that are representative of the water table. The largest source of available data on ground-water levels in wells in the Portland area are reports filed by well constructors at the time of new well installation. However, analysis of this extensive dataset by comparison with water levels measured by the U.S. Geological Survey (USGS) in the same or nearby wells indicated a poor agreement for wells less than 300 ft deep. Further examination revealed that water-level measurements at the time of well construction frequently appear to be unrepresentative of static water-level conditions. The measurements reported in well-construction records generally were shallower than the measurements by the USGS, though many measurements were substantially deeper than USGS measurements. The magnitudes of differences in depth to water from the two data sources ranged from -119 to 156 ft with a mean of the absolute value of the differences of 36 ft. One possible cause for the differences is that the water levels in many wells at the time of construction were not at equilibrium when measured. Shallower than expected water levels could be the result of the temporary incorporation of drilling fluids or well completion activities and deeper than expected water levels could be a consequence of measurements that were taken while a well was undergoing recovery following heavy pumping during well completion in aquifers with low permeabilities.

Owing to the large disparities, water-level measurements reported on well-construction records were deemed unsuitable for use in determining the water-table position for this study without further verification. The analysis of the water-table configuration primarily relied on water levels measured by the USGS as part of the current study or used in previous USGS ground-water studies conducted in the Portland area. The median water level was used for wells with multiple measurements collected over a period of time. Supplemental water-level data were acquired by identifying candidate wells and conducting a field effort to locate and measure 20 wells in areas of sparse data. The resulting dataset of wells used from previous USGS studies and wells located and measured for this study consisted of 582 wells. Due to the scarcity of well data in some areas, surface-water features such as major rivers, streams, lakes, wetlands, and springs representative of where the water table is at land surface were used to augment the analysis. Water-table elevation for these features was set equal to land-surface elevation, which was obtained from 2- and 10-meter lateral resolution digital elevation models.

Ground-water and surface-water data were combined for use in interpolation of the water-table configuration. Two conventions typically are used to define the water-table position: (1) depth to the water table below land surface and (2) elevation of the water table above a datum. The two conventions are related and can be equated if the land-surface elevation is known. However, the interpolation of the depth-to-water and water-table elevation datasets can produce substantially different results and may represent the end members of a spectrum of possible interpolations, depending on the conditions controlling the water-table position, such as the geometry of the land surface, rate and location of ground-water recharge and discharge, aquifer properties, and extent, thickness, and shape of the aquifer and adjacent confining units. Depth-to-water and water-table elevation datasets were interpolated independently for the current study and then combined to create a single representation of the water-table configuration. The two interpolations were used to create a combined map of depth to water by taking the mean of the values at each spatial position after transforming the interpolated water-table elevation values to depth to water. A map of the combined water-table elevation was developed by subtracting the combined depth-to-water map from land-surface elevation at each spatial position in the grid. Kriging, a type of spatial moving average, was the method of interpolation used for the study. Parameters for the kriging analysis were determined through the use of semivariograms developed individually for the depth-to-water and water-table elevation datasets.

The kriging analysis also was used to evaluate the reliability or uncertainty associated with the values of the water-table position. Standard deviation maps were generated for depth-to-water and water-table elevation analyses. These maps are similar and were averaged to produce a single standard deviation map for the water-table position. The resulting standard deviation map was rescaled to determine a relative uncertainty. The values of the relative uncertainty range between 0 and 1 where 0 represents a low relative uncertainty and 1 represents a high relative uncertainty. These values can be used to determine the relative uncertainty associated with an estimate of the water-table position at any location on the map and also were used to limit the extent of the analysis where the level of relative uncertainty was deemed to be unsatisfactory.

Because the water table is not a stationary surface and continually fluctuates in response to changes in recharge to or discharge from the aquifer, an analysis was conducted to determine the range of seasonal fluctuations. The magnitude of seasonal water-table fluctuations depends on the resulting change in storage in the aquifer and the effective porosity of the aquifer. The analysis of seasonal water-table fluctuations was performed with the use of summary statistics of data from 127 shallow wells that had multiple water-level measurements distributed throughout the seasons. Results of the analysis revealed that the spatial distribution of seasonal fluctuations of the water table is largely a function of the effective porosity of the aquifer in the zone of fluctuation of the water table and can be categorized by hydrogeologic unit.

Depth to water in the study area ranges from 0 feet below the surface along major rivers and streams to a maximum estimated at more than 1,200 feet below land surface for parts of the mountains to the east. Depth to water exceeds 100 feet in the terrace deposits throughout much of northern and eastern Portland. Depth to water greater than 300 feet is limited to a few higher elevation areas and includes parts of the Tualatin Mountains, the foothills of the Cascade Range, and much of the Boring Hills. In addition to the low-lying areas along major rivers and streams, areas of notably shallow depths to water include the area consisting of former alluvial channels extending from the confluence of Johnson and Crystal Springs Creeks northward to the Willamette River and southward to the Clackamas River, much of the area adjacent to Johnson Creek, the area extending from Beggars Tick Marsh eastward to Holgate Lake at the western end of Powell Butte, the area around Fairview Creek, and the western end of Lake Oswego. These regions of shallow depths to water may represent areas of concern with regard to existing or planned stormwater injection systems.

Elevation of the water table in the study area ranges from 11 feet NAVD 88 along most areas of the Columbia and Willamette Rivers to more than 2,000 feet NAVD 88 on the western slopes of the Cascade Range. The water-table elevation is similar to land surface with the highest elevations in the Tualatin Mountains, Boring Hills, and foothills of the Cascade Range and the lowest elevations along major rivers and streams and in the terrace deposits in the area approximately bounded by the Columbia River to the north, the Willamette River to the west, and Mount Tabor and Rocky Butte to the southeast. Shallow ground-water flow directions generally are toward adjacent streams and rivers with overall flow toward the major ground-water discharge areas, consisting of the Columbia, Willamette, and Clackamas Rivers. A notable exception is in the middle and upper parts of the Johnson Creek drainage basin, where much of the shallow ground-water flows toward the Sandy, Columbia, or Willamette Rivers. Ground-water mounds are located at the top of hills or mountains such as the Tualatin Mountains, Mount Tabor, or the Boring Hills. The largest closed ground-water depression is adjacent to the northwestern side of Powell Butte.

Ground-water levels in the Portland area normally are highest during the spring following the winter period of high precipitation and low evapotranspiration. Water levels recede during the summer in response to diminished precipitation and high evapotranspiration and are lowest in the autumn. The range of seasonal water-table fluctuations observed in wells used for analysis ranged from 1 to 22 feet, with a mean of 7 feet. Small seasonal water-table fluctuations occur throughout the study area but are concentrated more heavily in the terraced areas between the Willamette and Columbia Rivers north and west of the Boring Hills, where the wells typically obtain water from the unconsolidated sedimentary aquifer. The largest seasonal changes generally occur in the Sandy, Boring, and Damascus areas with few exceptions.

The accuracy of the water-table configuration maps depends on various factors, including data limitations and errors, the method of interpolation, and assumptions made during the analysis. The water-table configuration maps generally are representative of the conditions in the study area; however, the actual position of the water table may differ from the estimated position at specific locations, and short-term, seasonal, and long-term variations in the differences can be expected.

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Appendix A. Records of Selected Wells and Springs in the Portland, Oregon Area.

Table A1. Records of selected wells in the Portland, Oregon area. Data are available at http://pubs.usgs.gov/sir/2008/5059/data/sir20085059_appendixA1.xls

Table A2. Records of selected springs in the Portland, Oregon area. Data are available at http://pubs.usgs.gov/sir/2008/5059/data/sir20085059_appendixA2.xls

Table A3. Records of selected wells used for analysis of water-table fluctuations in the Portland, Oregon area. Data are available at http://pubs.usgs.gov/sir/2008/5059/data/sir20085059_appendixA3.xls

Appendix B. Data Files of Depth to Water, Water-Table Elevation, and Relative Uncertainty of the Water-Table Position.

Data for this report, consisting of Environmental Systems Research Institute (ESRI), Inc. ArcGIS (v9.2) GRID files of the depth to water, water-table elevation, and relative uncertainty of the water-table position, including metadata information, for the Portland, Oregon area.

Depth to water, in feet below land surface: http://pubs.usgs.gov/sir/2008/5059/data/d5_masked\s/.zip

Water-table elevation, in feet above NAVD 88: http://pubs.usgs.gov/sir/2008/5059/data/w5_masked\s/.zip

Relative uncertainty of the water-table position, dimensionless units (0=low; 1=high):
http://pubs.usgs.gov/sir/2008/5059/data/s5_nrmlfxd\s/.zip

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