Ground-Water Elevations and Flow Directions

Ground water flows from areas of high hydraulic head (high water-level elevation) to areas of low head (low water-level elevation). Because hydraulic heads vary laterally and vertically in a ground-water system, ground-water movement will generally have a vertical as well as a horizontal component. Contour maps of heads in aquifers are constructed to determine the horizontal direction of flow. The vertical component of flow can be determined by comparing water levels in nearby wells completed at different depths in the same aquifer or in different aquifers.

A contour map of the water table represents the elevation of the top of the saturated part of the uppermost unconfined aquifer. The horizontal direction of ground-water flow is generally perpendicular to the contour lines and water flows down the slope of the contours in a manner analogous to the flow of water down the slope of the land surface. An accurate map of the water table is constructed from water levels measured in wells that are open to a small interval at the water table. In practice, water-table maps are constructed from water levels measured in wells open over a range of intervals at or below the water table that represent a mixture of heads that are close to, but not at, the elevation of the water-table surface.

If a well is completed in an aquifer confined by overlying materials of low permeability, ground water in the aquifer may be under sufficient pressure to cause the water level in the well to rise above the top of the aquifer. A contour map of heads in a confined aquifer defines a water-level surface that shows the horizontal direction of flow in the confined aquifer. Because hydraulic heads can vary with depth, water-level maps based on measurements from wells completed at different depths or completed in different confined aquifers will reflect some mixture of horizontal and vertical gradients.

Horizontal Ground-Water Flow

Two water-level contour maps were constructed to determine horizontal ground-water flow directions in the Willamette Basin: a water-table map for the basin-fill sediments, and a generalized water-level map for the Columbia River basalt unit. Because water levels vary over time, the maps were largely constructed using measurements from more than 400 wells made during a 2-week period in mid-November 1996, a time of year during which ground-water levels generally approximated average annual water levels. Water levels in many wells were measured prior to heavy rains that fell during the second week of the measurement period. Water levels in most areas rose less than 10 ft in response to the rain event. Therefore, water-level maps based on these measurements are considered to be representative of average annual conditions. Water-level contours were not constructed for most of the Portland Basin because few wells were measured and detailed water-level maps are available in a previous study (McFarland and Morgan, 1996).

Shallow Basin-Fill Sediments

A water-table map for the basin-fill sediments (pl. 1) was constructed using water levels measured in shallow wells, typically less than 150 ft deep, open to the Willamette silt and upper, middle, and lower sedimentary units. Contours were also constrained by water levels from other shallow wells if measurements were made during late October through early December in any year from 1986 to 2000, and if long-term observation wells in an area showed consistent water levels over that same time interval. Stream-stage elevations were used to determine where water-level contours crossed streams.

Where water-level information was not available, the water-table elevation was estimated relative to land surface. The water table is found within 5 to 20 ft of the land surface in the upper sedimentary and Willamette silt units in most areas of the central and southern Willamette Basin, and in the lower sedimentary unit in the Tualatin Basin based on monitoring wells for water-quality assessments and wells measured as part of this study. Because few measured wells are open to the Willamette silt unit, water-table elevations in this unit were estimated using water levels from shallow wells completed in the underlying sedimentary units. The water table will be higher than water levels measured in these shallow wells because, according to drillers' reports and well data, hydraulic heads decrease with depth in the lowland. In the southern Willamette Basin, where the Willamette silt unit is generally less than 20 ft thick, average annual water levels in shallow wells completed in the underlying middle sedimentary unit are generally within 10 ft of land surface, which closely approximates the water table in the silt. In the central Willamette Basin, where the silt unit is up to 120 ft thick, water levels in the silt can be 10 to 25 ft higher than those in shallow wells completed in the underlying sediments (Iverson, 2002). This difference is consistent with the low vertical permeability of the Willamette silt unit, which provides a resistance to vertical flow that results in high water-table elevations relative to water levels in underlying units. Consequently, where the silt is thick, water levels in shallow wells completed in underlying sedimentary units will underestimate the elevation of the water table, but errors will generally be less than 25 ft.

Although Piper (1942) recognized that the water table occurred in the Willamette Silt in the central Willamette Basin, he described shallow ground water in the silt as "semi-perched," which suggests that an unsaturated zone occurs below the water table. However, piezometer and monitoring well data from ground-water quality assessments indicate that the regional water table generally occurs at shallow depths in the silt and that all sediments are fully saturated below this surface.

The regional pattern of ground-water flow is from the margins of the lowland towards the major streams (pl. 1). Ground-water discharge to streams is indicated where contours bend upstream. The change in hydraulic head per unit horizontal distance, referred to as the horizontal hydraulic gradient, is represented by the slope of the water table. Closely spaced contours of equal interval indicate a steep hydraulic gradient (steep slope), whereas widely-spaced contours indicate a flat hydraulic gradient. The velocity of ground-water flow is proportional to the hydraulic gradient if the hydraulic conductivity and effective porosity are constant.

In the southern Willamette Basin, shallow ground water flows from the southeast to the northwest in much of the basin and from east to west in the Stayton Basin. Hydraulic gradients are relatively flat, generally less than 15 ft/mi (feet per mile), because of the gently sloping land surface and relatively high permeability of the upper and middle sedimentary units near land surface. Contours are generally perpendicular to streams, indicating that most ground-water flow is nearly parallel to streams. Although ground water discharges to streams throughout the southern basin, focused ground-water discharge is expected where the Willamette River is constricted to a narrow trench cut into low permeability materials of the basement confining unit near Albany. This is consistent with water-table contours in the 12-mile reach between the Marys River and the gap at Albany, where the contours bend upstream and are nearly parallel to the Willamette River, indicating flow toward, and discharge to, the river. Focused ground-water discharge is expected in a similar gap at the confluence of the North and South Santiam Rivers.

Chlorofluorocarbon (CFC) age dates of shallow ground water (Appendix B) are consistent with flow directions indicated by the water-table contours in the southern Willamette Basin. Samples were collected from shallow wells in the upper and middle sedimentary units along a flow path from the east edge of the valley floor to the floodplain of the Willamette River near Corvallis (fig. B1). Young water (25 years old or less) was found at the eastern edge of the lowland where local recharge is the principal source of inflow to the shallow ground-water system. Older ground water was generally found to the west, consistent with longer flow paths although ages were variable (16 to more than 57 years old) suggesting mixing with younger water. This is to be expected since recharge from precipitation occurs throughout the valley floor. Young ground water (26 years old), found in the upper sedimentary unit at the end of the flow path, may represent the influx of precipitation and surface water into the highly permeable floodplain deposits adjacent to the Willamette River.

Shallow ground-water flow patterns are more complex in the central Willamette Basin because small streams incised up to 50 ft into the Willamette silt unit have a greater effect on shallow water levels than the less incised streams in the southern basin. Most small streams in the central basin, such as the Pudding River and Champoeg Creek, occupy deep, narrow, linear trenches cut into the Willamette silt unit. These stream trenches are separated by relatively flat surfaces that form the typical valley floor at the top of the Willamette silt unit. In general, the trenches do not fully penetrate the silt except near their confluence with the Willamette or Mollala Rivers.

In the areas between streams, the water table generally occurs at depths of less than 15 ft within the silt, and hydraulic gradients are typically between 20 to 40 ft/mi. Gradients steepen adjacent to the steep cutbanks that form the walls of entrenched stream drainages (Iverson, 2002) and near the steep-walled erosional margins of the unit adjacent to the Willamette River floodplain as the water table drops to the level of the streams. The steep hydraulic gradients adjacent to most small streams in the central basin are probably 500 ft/mi within 200 ft of the stream, which is not depicted on the water-table map in plate 1.

The configuration of the water table in the central Willamette Basin produces a number of local flow systems in the Willamette silt unit in which ground water flows from local topographic highs between stream drainages towards adjacent streams. This pattern indicates local recharge in the silts, a component of horizontal flow within the silts towards local streams, and discharge to local streams. Discharge to these smaller streams is limited by the low permeability of the silt. Because there is little resistance to flow in the more permeable sediments of the upper sedimentary unit, hydraulic gradients are relatively flat in the floodplain of the Willamette River, typically less than 2 ft/mi.

In the basin-fill sediments in the Tualatin Basin, the water table generally occurs at depths of less than 20 ft. Ground water flows from the margins of the Tualatin Basin to the center of the basin, where it discharges to streams. Hydraulic gradients are steep because the water table is in the lower sedimentary unit, which has low permeability. Although regional discharge is to the Tualatin River, contours indicate a component of local discharge to tributaries of the Tualatin River.

The elevation and direction of flow indicated by the water table in the sediments of the central and southern Willamette Basins has not changed appreciably since it was first mapped in 1935 (Piper, 1942). This indicates that average annual water levels have generally remained constant in this area since 1935 in spite of the large increase in annual ground-water pumpage over that same span of time. Graphs showing a general absence of long-term decline of water levels discussed in the next section further illustrate this point. Near Woodburn, long-term graphs of water levels indicate a possible decline of less than 10 ft in the water table.

Deep Basin-Fill Sediments—Central Willamette Basin

In the central Willamette Basin, where the Willamette silt unit is thick and confines the underlying permeable deposits of upper sedimentary unit, water levels in the middle sedimentary and lower sedimentary units differ from those of the water table. The change in water levels with depth is gradual, that is, water levels in the upper part of the upper sedimentary unit are similar to the water table, and water levels in the lower part of the upper sedimentary unit and upper part of the lower sedimentary unit represent the water levels of a confined aquifer. Ground water in the confined basin-fill aquifer in the central Willamette Basin likely flows to the Willamette River and the lower reaches of the Pudding and Molalla Rivers, where the confining Willamette silt unit has been removed by stream incision. Because few wells are selectively open to the lower part of the upper sedimentary unit, a water-level map of the confined basin-fill aquifer is not available.

The aquifer consisting of the middle sedimentary unit is confined by the Willamette silt unit and has a poor connection to smaller streams. This pattern of flow was recognized by Piper (1942, p. 35) who described the deeper confined unit as “deep pervious beds that pass below the floors of the stream trenches.” Aquifer tests and the response of water levels to precipitation and pumping also suggest that the middle sedimentary unit is confined where the Willamette silt unit is present. Although other studies (Price, 1967a; Woodward and others, 1998) suggest that ground water in the middle sedimentary unit in the central Willamette Basin is unconfined and discharges to small streams underlain by Willamette silt unit, hydrologic data collected during this study indicate ground water in the middle sedimentary unit in this area is generally confined and discharges to the Willamette River.

Columbia River Basalt Unit

Water-level data in the Columbia River basalt unit were collected in the Portland, Tualatin, and central Willamette Basins. Constructing a map of water levels in the Columbia River basalt unit presents several problems: (1) measured water levels in the Columbia River basalt unit are not evenly distributed, with many wells open to Columbia River basalt unit at the margins of the basins and relatively few wells in the center of the basin, (2) multiple permeable interflow zones separated by the less permeable flow interiors result in potentially large variations in water levels with depth, and (3) water levels in many wells represent composite heads because the wells have uncased boreholes that are open to multiple permeable interflow zones. Therefore, although water-level maps based on composite heads in the basalts must be interpreted with some caution, some general conclusions about ground-water flow in the basalt unit can be made based on the water-level map shown in figure 19.

The water-level map for the Columbia River basalt unit indicates that ground water in the basalt unit generally moves from upland areas at the basin margins, where the unit is exposed at land surface, towards the basin interiors, where the unit is buried by sediments. The general contour patterns suggest that regional discharge from the unit is to the Tualatin and Willamette Rivers. However, the rate of regional discharge to these streams from the basalt unit is probably low because of the low vertical permeability of the basalts and the great thickness of fine-grained sediments above the basalts (fig. 8). Stream-seepage data (Appendix C) and the occurrence of springs indicate that some ground water in the basalt unit discharges to small streams, such as Drift Creek, that are incised into the basalt unit in upland outcrop areas.

Although the direction of ground-water flow inferred from the contours is reasonable, the close spacing of water-level contours where the unit crops out in upland hills suggest unrealistically high horizontal hydraulic gradients. The contours are based on wells completed at different depths and open to different permeable interflow zones. These unrealistically steep gradients reflect vertical gradients between permeable interflow zones rather than horizontal gradients within an interflow zone or within the basalt unit as a whole. Based on water levels in a small number of wells open to similar basalt interflow zones in the Parrett Mountain (Miller and others, 1994) and Silverton (Marc Norton, OWRD, oral commun., 2004) areas, horizontal gradients in the upland areas are expected to be low, less than 10 ft/mi.

Horizontal gradients beneath the valley floors in the central Willamette Basin near Wilsonville are less than 6 ft/mi based on water-level differences of less than 25 ft in wells that are more than 4 mi apart (fig. 20). Gradients between these wells have decreased by about 50 percent since the City of Wilsonville stopped pumping from the basalt aquifers in late April 2002. This suggests that a significant fraction of the horizontal gradient in the basalts in this area was induced by withdrawals from the City’s wells completed in the basalt unit.

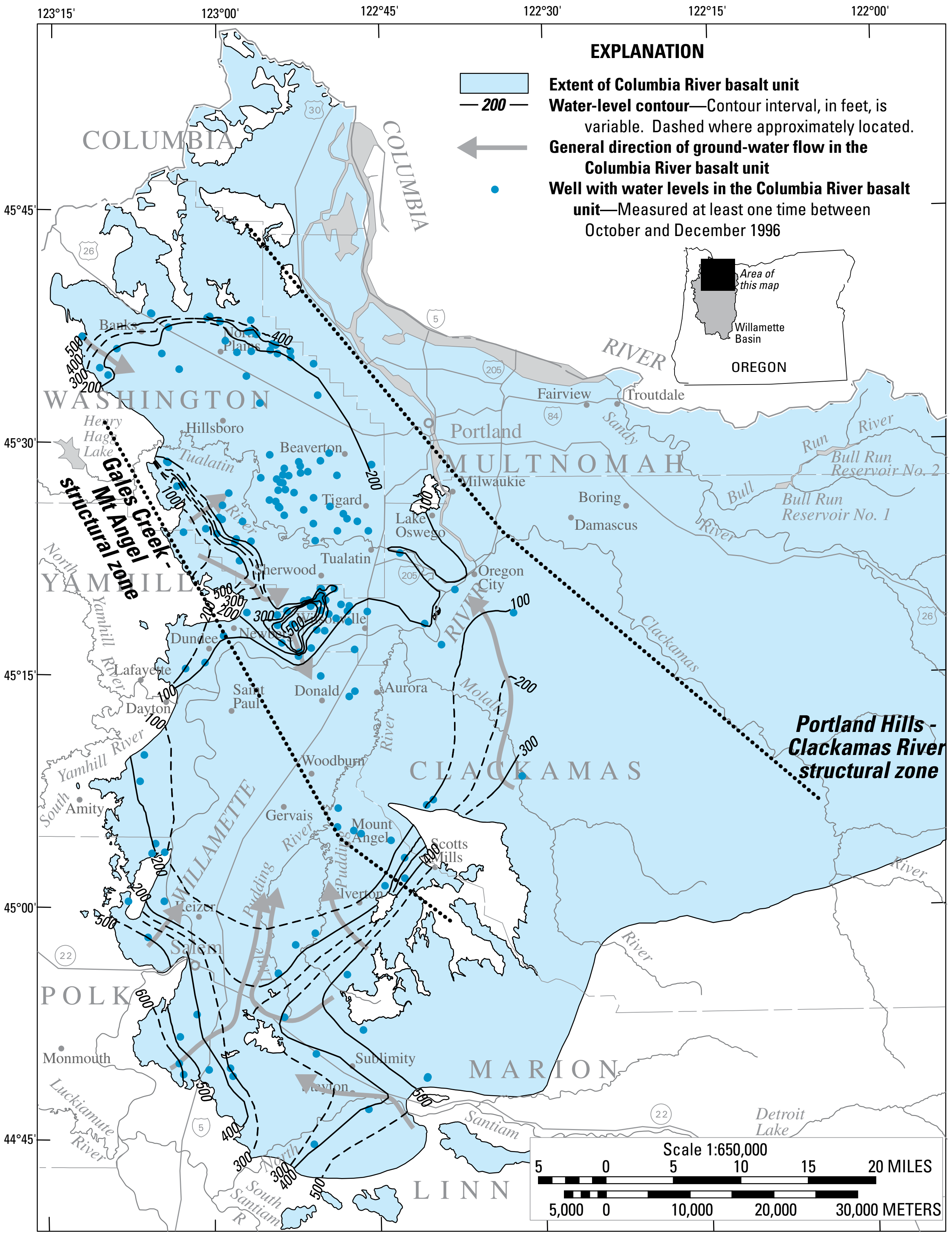

Figure 19. Generalized lines of equal hydraulic head and ground-water flow direction in the Columbia River basalt unit, November 1996, northern Willamette Basin, Oregon.

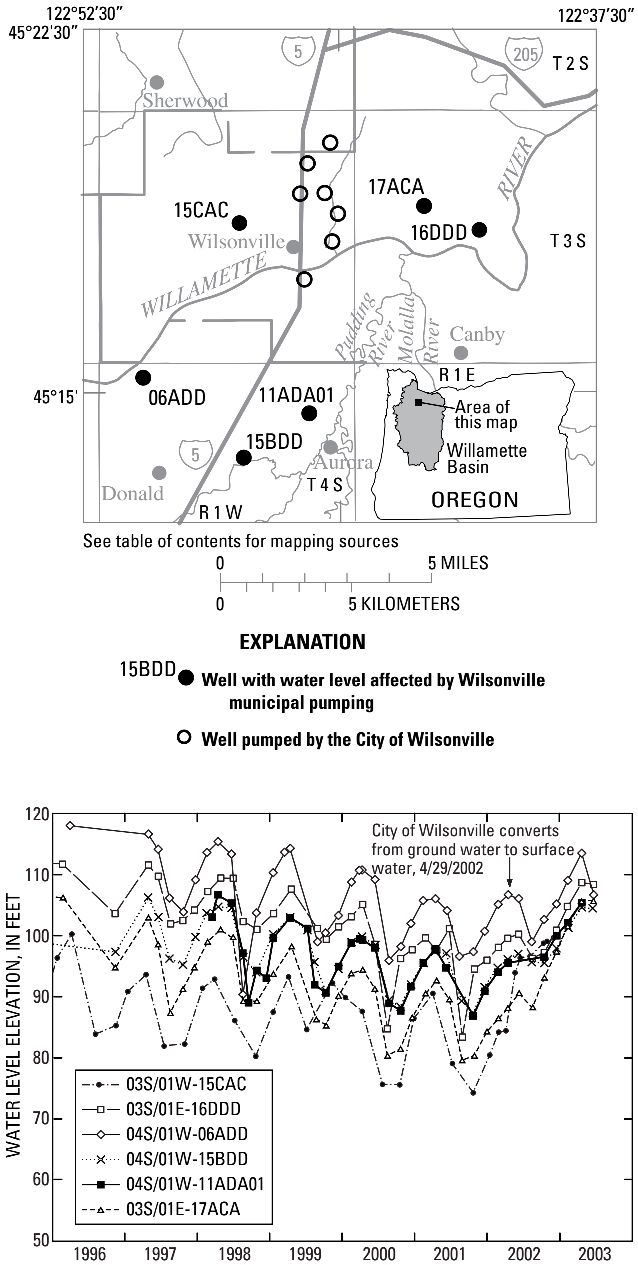

Figure 20. Water levels in wells open to the Columbia River basalt unit near Wilsonville, Oregon, 1996–2003.

These observations indicate that horizontal gradients in the basalt unit were probably no greater than 1 ft/mi under natural conditions. Vertical gradients in the basalt unit appear to be low on the valley floor and most ground-water flow in the unit is essentially horizontal in this part of the system.

Water-level fluctuations and elevations in the deeper zones of the Columbia River basalt unit beneath upland areas are similar to fluctuations and elevations in the basalt unit in the basin. For example, the seasonal fluctuations and long-term decline in water levels in a deep upland well (07S/01W-02CAA01) are similar to those in a well open to the basalt unit in the basin lowland (06S/01W-21CDC02) (pl. 1). Water-level elevations in the two wells differ by less than 15 ft. This similarity suggests a direct connection between deep interflow zones in the uplands and the basin flow system beneath the valley floor.

Various studies suggest that faults can impede horizontal ground-water flow in the Columbia River basalt unit (Newcomb, 1959; Bauer and Hansen, 2000; Reidel and others, 2002) by juxtaposing the thinner, permeable interflow zones against thicker, low-permeable flow interiors or by the formation of a low permeability gouge zones along the fault. It is unclear whether faulting in the Columbia River basalt unit affects horizontal flow on a regional scale in the Willamette Basin. Observations from an aquifer test near Mount Angel indicate that the Gales Creek-Mount Angel structural zone acts as a local flow barrier over short time intervals. Conversely, the regional response of water levels in wells near Wilsonville to changes in pumping suggests that faults, which are likely over this large area, may not act as flow barriers. If faults create barriers to horizontal flow in the basalt unit, they will probably have a large impact on the dynamics of ground-water flow when the unit is stressed by pumping since the propagation of pumping impacts will be limited across these boundaries.

Vertical Ground-Water Flow

Vertical flow in the ground-water system of the Willamette Basin shows a pattern that is generally downward, consistent with recharge areas. Upward flow components are generally limited to narrow zones adjacent to the major stream drainages, indicating ground-water discharge to streams.

The general pattern of downward flow in the basin can be evaluated by comparing water levels in pairs of adjacent wells completed at different depths (fig. 21, table 7). Downward flow, indicated by negative hydraulic gradients, occurs within the basin-fill sediment, between the basin-fill sediments and the Columbia River basalt unit, and within the Columbia River basalt unit in the lowlands.

Within the basin-fill sediments, a downward component of flow is common, with the largest downward gradient, -2.3 ft/ft, found between the less permeable Willamette silt unit and the middle sedimentary unit. An upward component of flow occurs in the narrow drainages of small streams that are deeply entrenched into the Willamette Silt. Upward components of flow in these areas are consistent with flowing wells that are limited to narrow zones coincident with these drainages. However, ground-water discharge to these streams is limited by the low hydraulic conductivity of the Willamette silt unit. Upward ground-water flow also occurs in the basin-fill sediments near the Willamette River, which is a regional discharge area, and where ground-water discharge occurs through the permeable upper sedimentary unit.

The vertical component of ground-water flow between the basin-fill sediments and the Columbia River basalt unit is downward throughout most of the extent of the basalt unit in

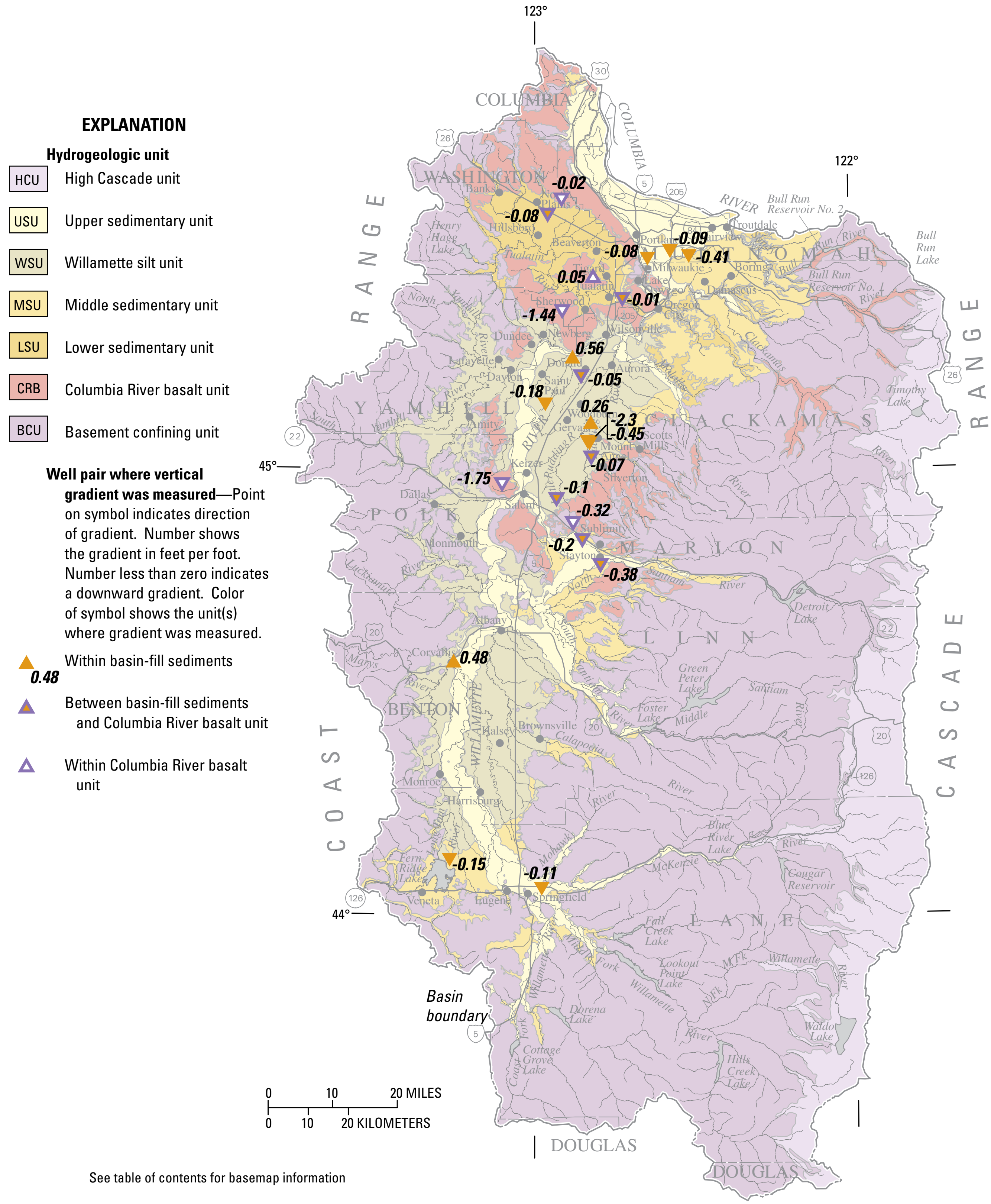

Figure 21. Vertical hydraulic gradients measured in well pairs, Willamette Basin, Oregon.

Table 7. Average vertical hydraulic gradient within and between hydrogeologic units of the Willamette Basin, Oregon, determined by water levels in well pairs.

[OWRD, Oregon Water Resource Department; USGS, U. S. Geological Survey; ft, feet]

Location	OWRD number	USGS site number	Elevation of mid-point of opening (ft above or below (-) NGVD29)	Horizontal distance between wells (ft)	Average vertical hydraulic gradient (ft/ft)
		Basin Fill (downward)			
01S/01E-24BBC01	MULT 63238	452827122382401	30.5		
01S/01E-24BBC02	MULT 63239	452827122382402	-33	10	-0.08
01S/02E-13CDA1	None	452840122302202	227.75		
01S/02E-13CDA2	None	452840122302201	190.8	3	-0.41
01S/02E-16BAA01	MULT 63388	452921122340401	144		
01S/02E-16BDA01	MULT 50871	452912122340401	-155	700	-0.09
05S/02W-08CCA2	MARI 52504	450851122575801	57.5		
05S/02W-08CCB1	MARI 52597	450851122580101	-39.5	1,800	-0.18
06S/01W-08DAD06	MARI 55017	450340122493404	119.95		
06S/01W-08DAD03	MARI 54952	450340122493402	94.2	3	-0.45
06S/01W-08DAD04	MARI 54953	450339122492801	113.5		
06S/01W-08DAD05	MARI 55015	450339122492802	100.7	3	-2.30
17S/02W-30CAA2	LANE 10762	440341122584002	428.5		
17S/02W-30CAA1	LANE 10761	440341122584001	340.5	10	-0.11
17S/05W-02BAC2	LANE 3203	440735123154601	365		
17S/05W-02BAC1	LANE 12676	440736123154701	276	160	-0.15
		Basin Fill (upward)			
04S/02W-01CDD02	None	451444122524601	71.15		
04S/02W-01CDD01	None	451444122524701	62.45	3	0.56
05S/01W-28CCD01	None	450603122491601	112.25		
05S/01W-28CCD02	None	450603122491602	97.35	3	0.26
11S/05W-35DDD	LINN 10841	443349123150501	183.23		
12S/05W-02AAA	LINN 12120	443348123150201	161.29	300	0.48

Table 7. Average vertical hydraulic gradient within and between hydrogeologic units of the Willamette Basin, Oregon, determined by water levels in well pairs—Continued.

[OWRD, Oregon Water Resource Department; USGS, U. S. Geological Survey; ft, feet]

Location	OWRD number	USGS site number	Elevation of mid-point of opening (ft above or below (-) NGVD29)	Horizontal distance between wells (ft)	Average vertical hydraulic gradient (ft/ft)
		Basin Fill/CRB (downward)			
01N/02W-17ACC	WASH 5382	453417122572901	125		
01N/02W-17DAB	WASH 5377	453414122571001	-501.5	1,000	-0.08
02S/01E-20CBD2	CLAC 3165	452249122430901	73.5		
02S/01E-20CBD1	CLAC 12346	452249122430801	-110	60	-0.01
04S/01W-19ACD01	MARI 54896	451235122510401	55		
04S/01W-19ACA01	MARI 56530	451237122510601	-411.5	300	-0.05
06S/01W-21CDC01	MARI 3280	450140122490701	-1		
06S/01W-21CDC02	MARI 51006	450141122490601	-289.5	100	-0.07
07S/02W-28ADD	MARI 7883	445606122554101	127.5		
07S/02W-28ADD01	MARI 55258	445604122554501	-54	300	-0.10
08S/01W-30DDB1	MARI 8999	445032122505001	353		
08S/01W-30DDB2	MARI 8971	445033122505101	242	140	-0.20
09S/01W-15DCB01	LINN 50629	444704122473001	344		
09S/01W-15DCB03	LINN 51763	444704122472801	145.5	160	-0.38
		CRB/CRB (downward)			
01N/02W-03AAD01	WASH 5090	453613122542901	216		
01N/02W-03ABA	WASH 14	453618122544701	10	1,350	-0.02
02S/02W-34ADB	WASH 13210	452119122544001	683		
02S/02W-34ACD	WASH 3443	452118122545001	511.5	600	-1.44
07S/03W-18BAD01	POLK 1781	445804123061201	330.5		
07S/03W-18AB1	POLK 841	445808123055601	133	1,400	-1.75
08S/02W-13BAD01	MARI 10176	445244122523701	371.5		
08S/02W-12CDB01	MARI 9917	445306122524501	302	2,200	-0.32
		CRB/CRB (upward)			
02S/01W-04ACC	WASH 11449	452534122485101	87.5		
02S/01W-04BAD	WASH 11436	452551122485801	-264	1,600	0.05

the Willamette Basin. This relation can be seen by comparing the head maps for the sediments (pl. 1) and the basalt unit (fig. 19) and by comparing adjacent pairs of wells completed in the two units (fig. 21, table 7). Upward components of flow between these units are probably limited to narrow zones in the lower elevation portions of the floodplains of the Willamette, Clackamas, Tualatin, and Columbia Rivers. Flowing basalt wells in the Tualatin and Portland Basins are generally limited to these low-lying areas (Woodward and others, 1998). Although few wells are open to the basalt unit along most stretches of the Willamette River in the central Willamette Basin, a flowing well near Wilsonville (03S/01W-24BAA01, pl. 1) indicates an upward component of flow in a narrow zone adjacent to the Willamette River in that area.

The vertical component of ground-water flow within the Columbia River basalt unit is downward throughout most of its extent in the Willamette Basin (fig. 21, table 7; Woodward and others, 1998). Upward flow in the Columbia River basalt unit is inferred from upward gradients in two wells in the Tualatin Basin and the occurrence of flowing wells (Woodward and others, 1998). Evidence of upward gradients in the central Willamette Basin is limited to a flowing well near the Willamette River (03S/01W-24-BAA01). Studies in the Willamette Basin and elsewhere (Woodward and others, 1998) suggest that enhanced upward flow and discharge may occur along major faults or sharp folds in the basalt in cases where these structural features enhance vertical permeability.

The low vertical permeability of the basalt flow interiors produces a resistance to vertical flow that can cause substantial head differences between permeable zones, such as a 340 ft head difference between 07S/03W-18BAD01 and 07S/03W-18AB1, and a 250 ft head difference between 02S/02W-34ADB and 02S/02W-34ACD. These well pairs have large downward hydraulic gradients of -1.8 and -1.4 ft/ft respectively. Large head differences are common in adjacent wells in upland outcrop areas and heads in these areas typically decrease with depth (Hampton, 1972; Price, 1967b; Foxworthy, 1970; Miller and others, 1994). Vertical head changes of 25 to 50 ft in the basalt unit over a depth interval of 100 to 200 ft are not uncommon in the uplands. An example of a 141-ft head change over a 243-ft depth interval on the northeast flank of the Stayton Basin is documented by Woodward and others (1998). Vertical head changes of up to 400 ft over a similar depth interval occur in the uplands south of Silverton.