Salmon Creek Drainage Basin Conceptual Hydrologic Model

Prepared for:

URS Corp and
Thurston County Water and Waste Management

Prepared by:

Pacific Groundwater Group
2377 Eastlake Ave. East
Seattle Washington 98102

June 2001

Table of Contents

Tables

Figures

Appendices

Executive Summary

The objective of this report is to describe factors influencing groundwater and surface-water flow in the Salmon Creek drainage basin in Thurston County, Washington and to provide data for quantitative model development. The models will be used to evaluate flood mitigation alternatives.

A preliminary conceptual model of the groundwater system in the Salmon Creek and adjoining basins was published in February 2000 using information from prior hydrologic studies, particularly studies by the U.S. Geological Survey (Pacific Groundwater Group, 2000). It considered factors that influence the groundwater system—climate, geologic features, and the distribution of aquifers (geologic units that produce significant amounts of water) and aquitards (units that do not produce significant amounts of water). It also considered hydrologic processes, such as groundwater circulation and recharge, surface-water flow, and the interactions between groundwater and surface water. The report recognized the need for additional field data to supplement the publications. Therefore, groundwater levels and surface-water discharge were measured throughout 2000.

An updated conceptual model, described in Section 2 of this report, uses the new field data to complement the published information. It will be used to develop mathematical models of groundwater and surface-water flow. These mathematical models will be used to predict the efficacy of structural solutions to flooding.

The Salmon Creek basin encompasses 11.4 square miles of northern Thurston County, Washington. It features a remarkably flat glacial *outwash* plain with depressed areas that are prone to flooding during periods of prolonged or heavy precipitation. The surface soils and uppermost *aquifer* in this outwash plain consist of highly permeable materials that are recharged mostly by precipitation. Very little precipitation leaves the area as surface runoff because it is so effectively accepted by the soils and the stream channel network is not well developed.

Precipitation was exceptionally high in Western Washington during three of the four years preceding 2000. The average precipitation over the 50-year period of record is 51 inches, whereas, precipitation during calendar years 1996, 1997, 1998, and 1999 was 62.6, 68.2, 46.0, and 72.8 inches, respectively. Most groundwater recharge in the project area originates as precipitation. Other minor sources include seepage from septic drain fields, leakage from water and sewer lines, and infiltration of irrigation returns. Seasonal variations in recharge are pronounced, with most recharge occurring during the wet winters when *evapotranspiration* is lowest. Estimated average annual recharge on the outwash plain averages about 35 in/yr, whereas recent recharge during the latter half of the 1990's was above average because of the high precipitation.

Hydrographs (groundwater-level trends over time) for wells monitored for this study show that recharge during December through March resulted in increases in groundwater elevation of 3 to 11 feet during the winters of 1998-99 and 1999-2000. The hydrographs also show that the recharge season is followed by a more-lengthy period of drainage each year. Recharge, and changes in groundwater elevation are greatest in the eastern portion of the basin and smallest in the west.

Much of the land surface in the basin is nearly flat, and the topographic boundaries of the basin in some areas have shifted in places because of filling for road construction, particularly along Littlerock Road. Topography, including man-made alterations, affects the distribution and depth of flood waters.

The *hydrostratigraphy* of the region is characterized by a series of aquifers occupying glacial sediments, and aquitards occupying both glacial and non-glacial sediments. *Vashon recessional outwash (**Qvr**)* mantles the land surface in most of the basin. The unit consists primarily of moderately well-sorted, loose sand and gravel. This unit contains the uppermost aquifer in the central basin, which is unconfined, and supplies water to shallow wells. It is particularly important to this project, because it readily absorbs precipitation, allowing little to leave the project area as surface runoff.

All twelve new wells installed for this project encountered the ***Qvr*** unit**,** and all except one were *screened* within it. Total thickness of the ***Qvr*** unit ranges from 8 feet to greater than 50 feet at the new borings. Of the new boring locations, the greatest thickness of ***Qvr*** was encountered on Port property (Olympia Airport), where the bottom of the ***Qvr*** unit was not encountered in any of the three borings, and south of the airport where the bottom was encountered at 50 feet depth.

Vashon Till (***Qvt)*** underlies the ***Qvr*** aquifer and forms the uppermost regional aquitard. It consists of variably compacted, but often dense, sand and gravel in a silt and clay matrix. Well drillers commonly describe the till as "hardpan" or "cemented gravel."

Vashon Advance outwash (***Qva)*** underlies the ***Qvt*** aquitard. It was deposited by glacial meltwater issuing from the front of the Vashon ice sheet as it advanced. It consists of coarse, sandy gravel in its upper portion and grades downward to fine sand with silty interbeds at its base. The ***Qva*** aquifer is the uppermost confined aquifer and primary water-supply aquifer in the area, supplying many domestic and public supply wells. The ***Qva*** unit varies from 50 to 100 feet thick.

Although older unlithified sedimentary deposits and volcanic bedrock lie beneath the Qva unit in the central basin and, therefore, play a secondary role in flood occurrence, they are exposed at land surface in the hills that form the southeastern boundary of the basin. Groundwater from the southeast uplands appears to play an important role in maintaining baseflow in the creeks during the summer.

Groundwater in the ***Qvr*** aquifer discharges laterally to surface-water features, vertically downward to underlying units, and upward to plant roots. Head (groundwater elevation) contours for the ***Qvr*** aquifer indicate the flow directions and the approximate location of the groundwater divide that separates groundwater discharging to Salmon Creek from groundwater flowing to adjacent streams. In the wet season, this groundwater-basin boundary coincides approximately with the Salmon Creek watershed, the surface-water boundary. Groundwater along the divide had a maximum head of greater than 190 feet above sea level (NGVD29) on March 20, 2000. Westward-flowing groundwater to the north of the Salmon Creek groundwater basin flows towards Black Lake and Black River and some of their tributaries, including Fish Trap Creek. Groundwater to the northeast, east, and southeast of the Salmon Creek basin discharges to the Deschutes River and some of its tributaries. The eastern limit of the groundwater basin appears to shift westward during the dry season, when Salmon Creek gains groundwater mostly from the southeastern hills and a limited area north of Salmon Creek.

Comparison of groundwater flow directions in the ***Qvr*** and ***Qva*** aquifers suggests differences in the groundwater drainage patterns. The divide separating westward flowing groundwater from eastward flowing groundwater in the ***Qva*** aquifer is substantially west of the wet-season divide in the ***Qvr*** aquifer. Whereas Salmon Creek itself and the Salmon Creek groundwater basin (as defined based on wet season ***Qvr*** groundwater flow) extend east to within a mile of the Deschutes River, the boundary in the ***Qva*** aquifer is about half-way between the Deschutes and Black Rivers. This suggests that the ***Qva*** is not influenced greatly by Salmon Creek but is instead controlled by the elevation of the Deschutes and Black Rivers. In the eastern portion of the basin it is therefore possible for groundwater moving horizontally in the ***Qvr*** aquifer to discharge to Salmon Creek, whereas nearby shallow groundwater that moves vertically down through the till to discharge to the Deschutes River. In general, downward flow from the ***Qvr*** aquifer to the ***Qva*** aquifer increases with increasing distance from drainage features and increasing hydraulic conductivity of the till.

As part of this project, discharge in Salmon Creek, Blooms Ditch, and Fish Trap Creek was monitored between mid-November 1999 and November 30, 2000. Salmon Creek's average discharge during the 13-month study period was 18.2 cfs near the creek's mouth, where it crosses Littlerock Road, and 2.1 cfs in the upper basin, where it crosses Tilley Road. The average discharge in Blooms Ditch was 16.9 cfs at Littlerock Road, only slightly less than in Salmon Creek. This reflects the slightly smaller watershed area and similar geologic units. The average discharge of the much smaller Fish Trap Creek watershed was 3.6 cfs at the railroad crossing.

The maximum discharge near the mouth of Salmon Creek was approximately 204 cfs on December 15, 1999. The minimum flow of about 0.5 cfs at that location occurred over several days near the end of August, 2000.

Both Salmon Creek and Blooms Ditch occupy relatively flat, low-gradient watersheds. The central reach of Salmon Creek drops only 30 ft over 4 miles. The low gradient and high infiltration capacity of the outwash plain, combined with extensive wetlands and open pasture, results in an efficient storage of groundwater. Over the study period, the upper watershed (above I-5) produced about 5.3 cfs/channel mile, while the lower basin produced about 2.8 cfs/channel mile. During the baseflow period, the upper basin produced even a greater portion of the flow. That finding is consistent with groundwater-level data indicating that areas where head is above the stream bed are extensive during the wet season but limited to a small portion of the upper basin, and probably the southeastern hills, during the dry season.

The variation of flow in Salmon Creek and Blooms Ditch are similar. The Salmon Creek basin, however, appears slightly better than the Blooms Ditch watershed at storing water. Although high flows are similar, Salmon Creek maintains a greater low flow for a longer period than does Blooms Ditch. Fish Trap Creek, although a smaller watershed, is the most efficient at water storage. Although the peak flow of Fish Trap Creek was only slightly greater than 20 cfs, the lowest flow never dropped below one cfs. Fish Trap Creek is gauged at the outflow of a series of wetlands that receive groundwater from the basin immediately north of Salmon Creek.

The stream channels on the outwash plain are not deeply incised and therefore they do not effectively drain the basin. Consequently, much groundwater must flow relatively long distances to the Black River and Black Lake before it can discharge to the surface. Some of the unconfined groundwater percolates down through the underlying till aquitard to the confined outwash aquifer, but this is also a slow process because of the lower hydraulic conductivity of the till. For these reasons, drainage of groundwater from the unconfined aquifer is slow, causing the water table to rise above ground surface during extended periods of heavy precipitation and to linger there for weeks after the rains cease. Groundwater flooding in the project area recedes by a combination of (1) shallow groundwater flow that discharges to the nearest stream channel or ditch, (2) deeper flow that discharges to successively more distant downstream reaches of the creek, and (3) leakage to underlying units.

Discharge data indicate that all reaches of the streams in the project area appear to be fed by groundwater in the wet season, in addition to periodic stormwater runoff. During late winter, the water table is so high in parts of the basin that every depression—*kettles*, borrow pits, and innumerable swales—fill to some level with groundwater. The groundwater and surface-water hydrographs developed for this project indicate that streamflow correlates closely with the rise and fall of the water table. When the water table is high, the streamflow is about bank-full in all channels. The water table drops to an elevation at or below the stream level during the late dry season and those low baseflows of Salmon Creek are supported by groundwater from limited areas, largely in the eastern basin.

To evaluate the historical frequency of groundwater flooding and simulate possible future flooding, a correlation between the long precipitation record and the shorter groundwater elevation (*head*) record was developed. The resulting "Antecedent Precipitation Index for Head" (APIH) is a mathematical predictor of groundwater elevations based on historical (antecedent) precipitation. The influence of precipitation decreases with its age; therefore, precipitation that is more recent was given greater weight by use of a decay coefficient. APIH is applicable to regions where heads are dominated by the effects of direct precipitation, rather than by surface-water or tidal interactions, or by infiltration of snow melt.

For example, based on the APIH analysis of a monitoring well at Pederson Place, flooding probably occurred to some extent there during water years[1] 1951, 1956, 1961, 1972, 1974, 1997, 1998, and 1999. Furthermore, flooding may have occurred there on about 3 percent of the days during the 50-year record and on a least 1 day during 16 percent of the years of record. More frequent flooding was indicated at the intersection of 93rd and I-5 (Restover).

The APIH analysis was used to identify that the late winter of 1999 probably experienced the most severe flooding during the period of record. Groundwater-level data from late winter 1999 were interpreted to provide an estimated worst-case depth-to-water map for the basin. Interpretations indicate that 23 percent of the basin had water levels at or above ground surface, and that groundwater was within 6 feet of ground surface over 68 percent of the basin at that time.

---

[1] Water year is October 1 through September 30.

1. Introduction

This report presents groundwater and surface water data (a conceptual model) for the Salmon Creek Basin in Thurston County Washington. The conceptual model is necessary to understand groundwater flooding that occurs in the basin. The conceptual model will serve as the foundation for quantitative surface-water and groundwater models. The quantitative models will simulate the behavior of *groundwater* and *surface water* in the project area and further aid in understanding groundwater-induced flooding. The conceptual model is based on studies of geology, hydrology, climate, drainage works, and on maps of topography and hydrography.

Figure 1 shows the extent of the project area, which includes approximately 25 square miles in parts of Township 17 North, Ranges 2 and 3 West, in Thurston County, Washington. The project area extends north to Trosper Lake, south to Bloom's Ditch, west to the Black River, and east to the Deschutes River. It includes all of the Salmon Creek drainage basin, as well parts of adjoining drainages.

1.1 Report Organization

This report is organized as follows:

- Section 1 contains background information, including a discussion of data sources used for the analyses completed for the project.
- Section 2 presents the conceptual model of the basin and is divided into subsections on climate, *hydrography, hydrostratigraphy*, *groundwater recharge, groundwater circulation*, earth properties, surface water, groundwater-surface-water interactions, and analysis of historical flooding. Appendices are used to present the details of groundwater and surface-water measurements collected throughout 2000 by this project, and analysis of historical groundwater flooding frequency and severity.
- Section 3 is a description of statistical and mapping work done for this project to describe the history of groundwater flooding and the likely maximum extent of flooding in 1999.
- Section 4 includes a glossary of technical terms to help the lay reader understand the concepts presented in this report. Terms that are included in the glossary are italicized the first time they are used in the text. Section 3 also includes a list of the acronyms and abbreviations used throughout this report.
- Finally, Section 5 is a list of references used for this study.

1.2 Data Sources

This report was developed using information from several sources, including two Water Resource Inventory Area (WRIA) studies (Pacific Groundwater Group, 1995; Wildrick and others, 1995).

The boundary between these two WRIAs—the Deschutes River WRIA 13 and the Upper Chehalis River WRIA 23—runs northwest to southeast across the project area. Salmon Creek and Blooms Ditch lie within WRIA 23 and drain to the Chehalis River via the Black River, while the areas to the north and east lie within WRIA 13 and drain to the Deschutes River.

Several important studies of geology and groundwater in northern Thurston County were published by the State of Washington (Wallace and Molenaar, 1961; Noble and Wallace, 1966) and the U.S. Geological Survey (USGS; Drost and others, 1998 and 1999). In addition, several other studies by consultants have provided valuable information for this present study:

- A wellhead protection study for City of Tumwater (Economic and Engineering Services and others, 1997)
- Drainage studies (Woodward-Clyde, 1997a and 19997b; J.W. Morrisette & Associates, 1999)
- A groundwater-flooding study (Pacific Groundwater Group, 1997)
- A surface-water modeling study (Christensen, 1995)
- Monitoring reports (Applied Hydrogeologic Research, 1999; Groundwater Science Services, 1999)

Finally, new data were generated for this project. Twelve new shallow groundwater monitoring wells were installed in January 2000 to complement the five ("LRS") wells installed by Thurston County in 1998. Six of the new wells were funded under this project directly ("SCDP" wells), and six were funded by the City of Tumwater (three "Tumwater" wells) and the Port of Olympia (three "POA" wells) in a coordinated effort. **Figure 1** shows the location of the wells and **Appendix A** contains well logs for the new wells. Water levels have been monitored automatically in the five LRS wells since October 1998 and the six SCDP wells since February 2000. The transducers and data loggers remain in these wells and data continue to be collected.

Manual water level measurements were collected in 51 wells and eight stream locations on March 20, 2000 to provide a "snap shot" of hydrologic conditions at that time. Thurston County, the City of Tumwater, and the Port of Olympia all provided data and personnel to support this effort. This *synoptic* measurement has provided the first basin-wide assessment of shallow groundwater flow direction and allowed the delineation of areas where groundwater is tributary to Salmon Creek (the "groundwater basin"). The boundaries of the Salmon Creek Basin presented in this report differ from those presented in the Preliminary Conceptual Model and Work Plan (Pacific Groundwater Group, 2000) based on that groundwater flow direction analysis, and based on additional interpretation of land topography.

Twelve stream monitoring locations were also established. Four gaging stations with continuous water level recorders were established and additional 8 stations were measured manually twice a month throughout 2000. In-stream flow measurements were made at the four stations with continuous recorders and four additional stations to establish *rating curves*. **Figure 1** shows the gaging station locations ("SC" sites) and **Appendix B** presents details of the surface water monitoring work.

2. Conceptual Model of the Hydrologic System

A hydrologic system encompasses all the elements that influence how groundwater and surface water accumulate, flow, and interact within a specified area. These elements, as described by Toth (1970) include:

- Topography
- Geology, specifically the distribution and hydraulic properties of soils and subsurface materials
- Climate, which controls the amount of recharge reaching these materials, along with other factors such as the types of soil and vegetation at the surface

In addition, human activity may affect the quantity and quality of water in the system.

Hydrologic systems occur within drainage basins. Surface-water drainage basins, more commonly known as "*watersheds*," are defined by topographic boundaries. Groundwater drainage basins are delineated using the line of highest groundwater elevation and/or groundwater flow paths. Groundwater and surface-water basins are assumed to coincide unless information indicates otherwise. Groundwater-basin boundaries may shift in response to changes in recharge distribution, drainage, or pumping. For this study, the "drainage basin" is defined by the combination of a watershed, a groundwater basin that drains to the same stream, and an area where groundwater recharge flows into the watershed. The project area includes the Salmon Creek drainage basin and parts of adjacent basins, which are included in this study because they influence the hydrologic processes of interest.

The behavior of a hydrologic system can be described by two types of models—conceptual and mathematical. A conceptual model is qualitative rather than quantitative. If based on sufficient data, it can provide a framework for a mathematical model, which is quantitative and can be used as a predictive tool once it is calibrated to observed field conditions.

2.1 Climate

Northern Thurston County has a marine warm-temperate climate, with relatively warm, dry summers and typically mild, rainy winters.

Precipitation averaged 51 inches per calendar year (in/yr) between 1951 and 1980 at the Olympia Airport (Drost and others, 1999). About 70 percent of this precipitation occured during the 6 months from October through March, when monthly totals exceeded 4 inches. Annual precipitation can vary substantially. For example, annual precipitation at the Olympia airport between 1950 and 1961 varied between 38 and 67 in/yr.

Precipitation has been exceptionally high in Western Washington over the few years preceding 2000. Precipitation during calendar years 1996, 1997, 1998, and 1999 was 62.6, 68.2, 46.0, and 72.8 inches, respectively.

2.2 Topography

The topography of the region is characterized by low hills on the northwest and southeast, separated by a broad, flat, plain that trends northeast-to-southwest. The hills generally lie at elevations of 300 to 400 feet above sea level (the North American Vertical Datum of 1929, or NAVD29; **Figure 1**). The plain lies at elevations between about 180 and 200 feet. Some areas will not support tree growth because of coarse, droughty soils and other factors. The plain is cut by the Deschutes River Valley, which runs along the eastern portion of the project area at an elevation of about 100 feet. Black Lake and Black River form the western margin of the project area; Black Lake drains mostly northward to Capital Lake, which drains to southern Puget Sound. The Black River drains southward from Black Lake but it is not incised as deeply as the Deschutes River. Consequently, it has a much lower gradient and a very slow velocity in the reach along the project area. The Salmon Creek basin slopes gently to the west, toward the Black River. Near the confluence of Salmon Creek and the Black River, the terrain drops slightly more steeply down to the river's floodplain.

The topographic boundaries in relatively flat areas have shifted in places because of filling for road construction, particularly along Littlerock Road. Topography, including man-made alterations, effects the distribution and depth of flood waters.

2.3 Hydrostratigraphy

The *hydrostratigraphy* of the region is characterized by a series of glacially derived aquifers, and both glacial and non-glacial *aquitards*, including the following hydrogeologic units (from youngest to oldest):

- Vashon recessional outwash (***Qvr***) – aquifer
- Vashon till (***Qvt***) – aquitard
- Vashon advance outwash (***Qva***) – aquifer
- Kitsap Formation (***Qf***) – aquitard
- Penultimate glacial deposits (***Qc***) – aquifers and aquitards
- Undifferentiated Tertiary and Quaternary deposits (***TQu***) – aquifers and aquitards
- Tertiary bedrock, sedimentary and volcanic (***Tb***) – aquitard

This project focuses on the ***Qvr, Qvt,*** and ***Qva*** units because they lie at shallow depths and play a strong role in the drainage problem addressed herein. Older, deeper aquifers and aquitards generally have less effect on shallow drainage and they are not discussed in detail. However, older deposits are exposed at ground surface in the hills that define the southern Salmon Creek drainage basin and at that location these deposits appear to be important in supplying groundwater perennially to Salmon Creek. Additional data on deeper layers is available in Drost (1998 and 1999).

Figure 2 is a geologic map that shows surface outcrop patterns for the hydrogeologic units in the project area. **Figures 3 and 4** are hydrogeologic cross sections A-A′ and B-B′, which show the subsurface distribution of these units through the project area.

2.3.1 Installation of New Borings

Twelve new shallow groundwater monitoring wells were installed in January 2000 to complement the five ("LRS") wells installed by Thurston County in 1998. Six of the new wells were funded under this project directly ("SCDP" wells), and six were funded by the City of Tumwater (three "Tumwater" wells) and the Port of Olympia (three "POA" wells) in a coordinated effort. **Figure 1** shows the location of the wells, **Table 1** contains survey data, and **Appendix A** contains well logs.

The wells were installed using a hollow-stem auger drill rig operated by Tacoma Pump and Drill Inc. Split-spoon soil samples were collected every five feet of depth or at a change of soil type. The target horizon for all but one boring was the ***Qvr***; however, in most cases the top of the upper-most aquitard (typically the ***Qvt***) was encountered and then the borehole was backfilled to an appropriate depth for construction of a ***Qvr*** monitoring well. Two-inch diameter PVC monitoring wells were constructed in each borehole. The six SCDP wells were completed at land surface by protective steel casings and the remaining wells were completed with flush-mount monuments. Survey data were provided by Southwest Survey, Inc.

2.3.2 Vashon Recessional Outwash (*Qvr*)

Qvr mantles the land surface in the project area between the Deschutes and Black Rivers **(Figures 2, 3, and 4)**. The unit consists primarily of moderately well sorted, loose sand and gravel. It originated as glacial outwash that was deposited by streams that drained the front of a rapidly retreating lobe of the Vashon glacier, approximately 14,000 to 15,000 years ago. The unit contains the uppermost aquifer in the project area and supplies water to shallow wells. It is particularly important to this project because it is highly effective at receiving recharge from precipitation, allowing little to leave the project area as surface runoff.

Also included in this unit is a glacial lake deposit that is composed of fine sand and silt. Within the project area, the uppermost ***Qvr*** layer is composed of these lake sediments only on the Port of Olympia property as evidenced by borings POA-MW1, POA-MW2, and POA-MW3 (**Figure 1 and Appendix A**). The lake deposits are underlain by the more typical, coarser ***Qvr*** sediments. Vertical drainage of water in areas of substantial silt will be slower than in other areas.

The ***Qvr*** contains little gravel at the surface but coarsens downward, grading to gravelly, medium-grained sand. Silty laminae are present throughout but occur more often near the surface. The portions of the ***Qvr*** that were deposited by a system of braided, high-energy streams contain zones of relatively clean gravel. The *Holocene* floodplain deposits that occur along the rivers, creeks, and streams in the project area have been included in the ***Qvr***. These deposits usually are designated ***Qal*** but their hydraulic properties are similar to those of the ***Qvr***.

Figure 5 is a map showing the thickness of the ***Qvr*** as presented by Drost and others (1999). Thickness ranges between 25 and 50 feet over most of the project area. The ***Qvr*** thickness map of **Figure 5** has not been modified from the original authors' work based on the new borings drilled for this project.

The aquifer is subject to contamination from septic drainfields and other human sources. Consequently, relatively few wells in the project area are completed in the ***Qvr***; and most of those lie near the Deschutes River Valley. The aquifer is in direct hydraulic continuity with the numerous wetlands of the basin shown on **Figure 1**.

All twelve new wells installed for this project encountered the ***Qvr*** and all except one were *screened* within it. Total thickness of the ***Qvr*** was interpreted to range from 8 to greater than 50 feet at the new borings. These thicknesses are in general agreement with the contours on **Figure 5**. Of the new boring locations, the greatest thickness of ***Qvr*** was encountered on Port property (Olympia Airport) where the bottom of the ***Qvr*** was not encountered in any of the three borings. At SCDP-MW5 south of the airport the upper aquifer was 50 feet thick. **Appendix A** presents the boring logs.

2.3.3 Vashon Till (*Qvt*)

The ***Qvt*** typically underlies the ***Qvr*** and where it occurs it forms the uppermost regional aquitard. It consists of variably compacted, but often dense, sand and gravel in a silt and clay matrix. Sand usually predominates. Well drillers commonly describe the till as "hardpan" or "cemented gravel". The contact between the ***Qvr*** and ***Qvt*** is sharp; the contact with the underlying ***Qva***, however, usually is gradational over several feet.

The role of the ***Qvt*** as an aquitard in the hydrogeologic system is very important. It generally has relative low permeability and impedes the percolation of groundwater from the overlying ***Qvr***. However, its thickness and permeability vary substantially, and it may be absent in some areas. In addition, sometimes the unit is so poorly described in driller's logs that it may not be recognizable. In areas where the ***Qvt*** is not present, the ***Qvr*** and ***Qvr*** contact each other and function as a single aquifer.

Figure 6 is a map showing the thickness of the ***Qvt***. The thickness of the till typically ranges from 5 to 50 feet, although it is absent along the Deschutes River Valley, where it was eroded away. It is also absent north of Trosper Road, at least as far west as Barnes Lake. Two authors' interpretations of till thickness are presented on **Figure 6**. The interpretations by Drost and others (1998 and 1999) differ somewhat from those by AESI (1997). The differences may result from different interpretations of well logs or different assumptions in areas where there are no data. The interpretation by Drost is the basis for the USGS groundwater model of Northern Thurston County and will be adopted for this project unless specific data are disclosed to the contrary. The till thickness map of **Figure 6** has not been modified from the original authors' work based on the new borings drilled for this project.

The ***Qvt*** was encountered in nearly all of the new wells except for those drilled on Port property where the till is either absent, or below the depth of the borings at 25, 30, and 50 feet. Where encountered elsewhere in the basin, the top of the till was at depths ranging from 8 to 50 feet below ground surface. Only one of the borings penetrated the till and therefore substantial new information on till thickness was not generated.

Based on the geologic map of **Figure 2**, the ***Qvt*** mantles land surface in the hills that form the southeastern edge of the basin and therefore in that area the ***Qvr*** is missing. The till in that area appears to overlie older glacial deposits (***Qc***) and bedrock (***Tb***).

2.3.4 Vashon Advance Outwash (*Qva*)

The ***Qva*** aquifer underlies the ***Qvt*** aquitard. Like the most of the ***Qvr*** aquifer, it was deposited by glacial meltwater issuing from the front of the Vashon ice sheet as it advanced. It consists of coarse, sandy gravel in its upper portion and grades downward to fine sand with silty interbeds at its base. Silt content typically varies from less then 1 to greater than 5 percent. Because the ***Qva*** unit was deposited by a system of braided, high-energy streams, it also contains zones of relatively clean gravels, with interbeds of cobbles and boulders.

The ***Qva*** is the primary aquifer in the area, supplying many domestic and public supply wells. The ***Qva*** varies from 50 to 100 feet thick.

New well SCDP-MW1 was drilled through a substantial silt, clay, and gravel aquitard from eight to 15 feet depth that is interpreted to be the ***Qvt***. ***Qva*** sediments below the ***Qvt*** were described as sandy gravel with a clay lens. The well was screened in the ***Qva*** aquifer from 18 to 28 feet depth. New well SCDP-MW2 was installed adjacent to SCDP-MW1 and is screened in the ***Qvr*** aquifer overlying the till. Water levels in these tandem wells provide information on vertical groundwater movement in the area near the mouth of Salmon Creek.

2.4 Groundwater Recharge

The replenishment of groundwater is called groundwater recharge. In the project area, recharge originates as a portion of precipitation falling on the area and from other smaller sources. Humans may reduce or increase the recharge rate by affecting hydrologic processes.

2.4.1 Distribution of Recharge

Figure 7 shows the average annual quantity and distribution of groundwater recharge estimated in the project area. Drost and others (1999) estimated annual average recharge with a method based on long-term average precipitation and temperature, as well as on the approximate hydraulic properties of soils and human influences. Two precipitation-recharge relationships were used to estimate recharge throughout the County. The relationships were developed in two previous studies for parts of western King County (Woodward and others, 1995) and parts of Thurston County (Berris, 1995). They take the form of simple linear equations that relate average annual recharge to precipitation for a given type of soil.

Most recharge in the project area originates as precipitation. Estimated average annual recharge for the project area ranges from about 10 to 35 in/yr, and recharge on the outwash plain averages about 35 in/yr. Seasonal variations are pronounced, with most recharge occurring during the wet winters when evapotranspiration is lowest. Other minor sources include seepage from septic drain fields, leakage from water and sewer lines (quantity unknown), and infiltration of irrigation returns (quantity unknown).

Figure 8 shows groundwater *hydrographs* for 11 shallow wells installed for this project. The hydrographs show the seasons and locations of groundwater recharge (increasing water levels) and discharge (decreasing water levels). Starting in December 1999, water levels were monitored in the five "LRS" wells using automated pressure transducers and dataloggers. During February 2000, another six wells were added to the monitoring network (the "SCDP" wells).

The hydrographs show that recharge in December through March resulted in increases in groundwater elevation of 3 to 11 feet in the last two winters. The hydrographs also show that the recharge season is followed by a more-lengthy period of drainage each year. Recharge, and changes in groundwater elevation, are greatest in the eastern portion of the basin and smallest on the west.

In the four highest wells in the basin (LRS-008, LRS-011, SCDP-MW4, and SCDP-MW5), the water table follows a similar pattern, with rising head from December through March, then gradually declining head from April through October. Well SCDP-MW6, located at City of Tumwater's Bush Middle School well field, may respond to pumping of the City wells in addition to natural recharge and discharge.

The water table in LRS-006 at Fish Trap Creek was at its maximum when monitoring started in December 1999 and changed very little until mid-June, then declined slowly until early October 2000. It is less than ten feet deep. The head at 165 feet is approximately at ground surface so it cannot rise further.

The water table in LRS-007 reached its maximum in mid-December 1999, then fluctuated within a range of about a foot thorough March 2000. This well may be affected by Department of Natural Resources' pit lake, located about 200 feet south of the well, on the opposite side of 99th Ave. This lake appears to receive stormwater runoff and may focus groundwater recharge. The well also is located just upgradient of the wedge-shaped frequently-flooded area at the northeast corner of the intersection between 99th Ave. and Littlerock Road. Floodwater outflow from this area appears to be restricted by the Littlerock road grade and the area receives additional runoff from a constructed ditch.

2.4.2 Factors Influencing Recharge

In addition to precipitation, the amount of recharge depends on the soil's moisture-holding capacity and its infiltration capacity, which in turn depend on compaction, organic content of the uppermost soil, and particle-size distribution. The amount of recharge depends also on temperature and vegetation. Soils that have relatively low percentages of clay, silt, and organic matter allow precipitation to infiltrate readily and are less subject to compaction. Most soils in the project area, including the Cagey, Norma, Mukilteo, and Nisqually soils, have high infiltration rates because they originate largely from sand and gravel outwash. Less permeable soils, such as those derived from glacial till, contain higher concentrations of dense, fine-grained materials, allowing less infiltration. Accumulations of organic matter over the soil, such as forest duff, may reduce overland runoff from finer-grained soils by absorbing precipitation until it can slowly infiltrate the (largely) inorganic soil below. Conversely, low-lying areas that have accumulated organic materials and fine sediment tend to have lower infiltration rates. Areas that feature these soil types have a higher runoff potential but are rare in the project area. Vegetation also catches some precipitation on its leaves, from which the water may later evaporate. Areas with intense traffic on soils sensitive to compaction have reduced infiltration capacity. Such conditions are primarily present on Port parcels used for log sorting and milling.

Recharge rates tend to be significantly lower in areas covered by concrete, pavement, or other man-made structures. However, if runoff from impervious surfaces drains to areas where the water can infiltrate, only local redistribution of recharge occurs, and the broader-scale total is unchanged. Removal of vegetation, especially trees, may increase total recharge if the soil is not compacted or paved over. If stormwater from impervious surfaces flows away in pipes or ditches to streams, groundwater recharge will be reduced.

2.5 Groundwater Circulation and Hydraulic Properties of Hydrogeologic Units

After infiltrating into the soil and percolating to the water table, groundwater flows from its point of recharge and eventually discharges to pumping wells, springs, or surface-water bodies. Flow is controlled by the rate of recharge, *hydraulic gradient*, and by the hydraulic properties of the hydrogeologic units.

Water seeks the path of least resistance as it flows from higher to lower elevations along the hydraulic gradient, a term that refers to the difference between groundwater elevations over a given distance. Because horizontal hydraulic conductivity tends to be much higher than vertical hydraulic conductivity in layered sediments, horizontal flow tends to predominate over vertical flow. The presence of an aquitard accentuates this tendency. Even so, some water will flow downward to underlying units. Within an aquitard, water tends to flow vertically rather than horizontally because that is the shortest path between the two aquifers. Accordingly, in the project area, groundwater flow is predominantly horizontal in the ***Qvr*** and ***Qva*** aquifers and vertical in the ***Qvt*** aquitard. Throughout most of the project area, vertical flow is downward through the ***Qvt***.

Groundwater in the project area occurs under either *unconfined* ("*water-table*") or *confined* conditions. For unconfined conditions, such as in the ***Qvr***, water is at atmospheric pressure, and groundwater levels in wells completed in the aquifer are at or below the top of the aquifer. When water is pumped from an unconfined aquifer, it is released to the well by dewatering of the aquifer. That is, water drains from pores in the geologic materials, leaving a film of water and air. For confined conditions, such as in the ***Qva*** unit, water is at pressures greater than atmospheric, and groundwater levels in wells completed in the aquifer are above the top of the aquifer. A confined aquifer, such as the ***Qva***, is overlain by one or more aquitards (confining beds), such as the ***Qvt***.

2.5.1 Vashon Recessional Outwash (*Qvr*)

The ***Qvr*** unit contains the unconfined aquifer in the outwash plain. Depth to water in this aquifer was measured throughout the basin during a synoptic survey on March 20, 2000. Of the 51 wells measured that day, 47 were ***Qvr*** aquifer wells. The elevation of water at stream gaging stations was also measured on March 20, 2000 as part of the synoptic measurement round. The ***Qvr*** groundwater and stream elevations are interpreted together to understand the relationship of shallow groundwater and surface water. Water levels (generally ***Qva*** water levels) were also measured during prior studies by PGG (1997), Drost and others (1998), GWSS (1999a; 1999b), and JWMA (1999). Groundwater generally lies less than 15 feet below land surface and fluctuates 3 to 11 feet seasonally. Only the lower portion of the unit is saturated during most times of the year; however, saturated thickness increases substantially during periods of heavy, prolonged rainfall. During the wettest winters, groundwater may reach the land surface in local areas, causing flooding.

The hydrographs of **Figure 8** are all for ***Qvr*** wells except SCDP-MW1 which is a ***Qva*** well. Most of the ***Qvr*** hydrographs follow the same general trend of increasing water levels in the March through December recharge season and decreasing water levels in the April through November drainage season. However, the amount of rise and fall of the water table differs between locations. The eastern-most wells (LRS-008 and SCDP-MW5) show the greatest decline in water level (10 to 11 feet) during the drainage period and the western-most wells show the least change (3 to 4 feet). Total change in surface water elevations (see Section 2.6) was typically less than 3 feet not including periods of stormwater runoff. The data indicate a change in the relationship between surface and groundwater over time and space as discussed below.

Groundwater and surface water elevation data from the synoptic measurement round were contoured to generate a map of the water table elevation in the ***Qvr*** aquifer for March 20, 2000. **Figure 9** presents the map; and **Tables 1 and 2** present the data from the synoptic measurement round. The contours on **Figure 9** were drawn by hand, using qualitative interpolation and hydrogeologic judgement. Contours were drawn consistent with a gaining stream (contours point upstream at stream crossings). Groundwater-elevation contours are equal to surface water elevation at streams and are below land surface everywhere else because groundwater flooding was not present in March 2000. In the western part of the map where field measurements are absent but the ***Qvr*** aquifer exists, groundwater elevation contours were inferred from topographic contours. In the southeast part of the surface water basin, contours were not drawn because no data are present and the ***Qvr*** aquifer may not exist. The accuracy of the map where data are scarce may be low.

The groundwater contours indicate that a groundwater divide separates westward moving groundwater from eastward-moving groundwater. The maximum elevation of the divide was greater than 190 feet above NGVD29 on March 20, 2000. The northeast portion of the divide forms part of the Salmon Creek groundwater basin boundary drawn on **Figure 9**. Groundwater within the basin boundary was flowing toward Salmon Creek at that time. Westward moving groundwater north of the Salmon Creek Basin boundary was flowing toward Fish Trap Creek and other Black Lake and Black River tributaries. Eastward moving groundwater was flowing toward the Deschutes River. In addition to these horizontal flow components, vertical flow downward into the ***Qva*** aquifer was likely occurring.

The eastern extent of the basin boundary is uncertain. Surface water data (Section 2.6) indicate that eastern Salmon Creek flows perennially, which indicates that groundwater supports stream flow year round and that groundwater levels must therefore be above stream level. The basin boundary on **Figure 9** has been drawn consistent with this concept that groundwater near the creek flows into the creek. However, the elevation of surface water at upper Salmon Creek gage SC-10 was slightly higher than groundwater elevation at upstream well SCDP-MW5 on March 20, 2000. This unusual finding may result from local ponding of surface water at SC-10 caused by constricted flow at the culvert downstream of SC-10. If that is the case, regional groundwater flow to the creek is likely in the fashion implied by **Figure 9**. If groundwater at SCDP-MW5 is indeed at lower elevation than all of the upper reach of Salmon Creek in the wet season, the basin boundary may be closer to the north side of Salmon Creek than implied on **Figure 9** and groundwater at SCDP-MW5 may be flowing towards the Deschutes River**.**

The area contributing groundwater flow to Salmon Creek appears to shrink substantially during the dry season. Groundwater and surface water elevation data from September 2000 were compiled from the surface water and groundwater hydrograph records reported herein. Although the number of control points are far fewer than during the synoptic measurement round, the limited data indicate that most of the flow in Salmon Creek was derived from two areas at that time: the hills on the southeastern portion of the basin, and the general area of well SCDP-MW-4. The documented groundwater elevation at SCDP-MW4 was above local stream level, and the groundwater elevation in the hills is presumed to be also, although no wells were monitored there. Groundwater in other areas was at or below stream level. The September 2000 data also suggest a dry-season westward shift in the divide separating groundwater that discharges to the Deschutes River, from groundwater that discharges to Salmon Creek and the Black River.

The synoptic data set indicates that the horizontal hydraulic gradient within the central basin is very low (less than 0.001, or less than 4 feet of elevation change per mile).

Groundwater discharge from the ***Qvr*** aquifer occurs laterally to surface-water features, vertically downward through the ***Qvt*** aquitard to the ***Qva*** aquifer, and upward to plant roots. The relative magnitude of lateral and downward flow is affected by horizontal hydraulic conductivity, proximity to surface-water features, till hydraulic conductivity, and groundwater elevations in the ***Qvr*** and ***Qva*** aquifers. In general, downward flow increases with increasing distance from drainage features, increasing till conductivity, and increasing hydraulic gradient between the ***Qvr*** and ***Qva*** aquifers.

Drost and others (1999) estimated *hydraulic conductivity* in the ***Qvr*** using the results of short-term *specific capacity* tests conducted by drillers. The estimated values for horizontal hydraulic conductivity ranged from 14 to 2,100 ft/day, with a median value of 150 ft/day. They assumed that vertical hydraulic conductivity was 10 times less than horizontal hydraulic conductivity for aquifers. PGG measured local hydraulic conductivity by performing short pumping tests in the six new SCDP wells (**Appendix A**). Three of the wells yielded estimates of local *transmissivity* of 39, 95, and 180 ft^2/day. These transmissivity values indicate a lower hydraulic conductivity than reported by Drost. Drost's values are from domestic supply wells and are likely more representative of the lower, more gravelly portion of the unit where most horizontal flow occurs. Using Drost's median value of 150 ft/day for hydraulic conductivity, and the low gradient of the central basin, groundwater is estimated to flow horizontally less than 1 foot per day.

2.5.2 Vashon Till (*Qvt*)

Groundwater elevations in the ***Qvt*** are inferred to be similar to those of the ***Qvr*** and ***Qva*** aquifers although few measurements are available because wells are usually not screened within the till. The ***Qva*** is recharged by downward percolation through the ***Qvt***. Flow through the till is downward at most locations in the basin. The rate of flow depends on the hydraulic gradient between groundwater in the ***Qvr*** and the ***Qva*** aquifers as well as the hydraulic conductivity of the till. The till varies in hydraulic conductivity (based on texture) and thickness. It appears to be missing in places (**Figure 6**). Groundwater elevations in the ***Qvr*** and ***Qva*** are typically within a few feet of one-another. Near Pederson Place (Well MW-94-12), groundwater in the ***Qvr*** is usually about 2 feet greater than that in the ***Qva***. The vertical hydraulic gradient between a ***Qvr*** and ***Qva*** well pair at Pederson Place was about 0.02 when measured in 1995 (EES, 1997); however, if all the groundwater elevation difference indicated by those wells occurred across the till (5 feet thick), the gradient across the till would be on the order of 0.25.

New wells SCDP-MW2 and SCPD-MW1 are tandem wells in the ***Qvr*** and ***Qva*** aquifers, respectively. Simultaneous water level measurements collected by data loggers for this project indicate that the elevation of groundwater in the overlying ***Qvr*** aquifer remained 1.5 to 3.5 feet above the groundwater elevation in the underlying ***Qva*** aquifer (**Figure 8**). This difference and the ***Qvt*** thickness of 7 feet at that location suggests a downward hydraulic gradient of 0.2 to 0.5 across the till (1.5 to 3.5 feet of difference in groundwater elevation over 7 feet of vertical separation).

New well SCDP-MW5 is located near the deeper Elwanger residential well (identified as a ***Qvt*** well by Drost (1999)). Groundwater elevation in the lower well was higher than the shallower well during the synoptic measurement round, indicating upward flow of groundwater.

The hydraulic conductivity of the till has not been measured extensively. Drost and others (1999) assumed a <u>horizontal</u> hydraulic conductivity of 1 ft/day for the till and results of their model calibration resulted in a derived <u>vertical</u> hydraulic conductivity value of 0.002 ft/day (7x10-7 cm/sec). However, the basis of Drost and others' calibration is not clear and it apparently did not include groundwater elevations in the ***Qvr*** aquifer. The value of vertical hydraulic conductivity used by Drost and others appears unrealistically low in our opinion. Such a value appears contrary to the observed similarity in groundwater levels in the ***Qvr*** and ***Qva*** aquifers, the rapid response of ***Qva*** water levels to precipitation recharge, and would result in rates of flow through the till that are below all estimates of recharge through Puget Sound tills compiled by Booth, Massman, and Horner (1996) and Bauer and Mastin (1997).

Downward flow through the till is probably highly variable in space and time. It varies in space because the till hydraulic conductivity and thickness vary in space. It varies in time as groundwater levels in the overlying and underlying aquifers change in response to recharge and drainage.

Flow through the till will likely require modeling to assess the efficacy of flood mitigation measures, particularly any involving groundwater pumping. A model will need to be developed to perform the calculations, and calibration of the model to observed water level responses in the ***Qvr*** and ***Qva*** is probably the best way to assess the regional ***Qvt*** hydraulic conductivity. In addition to the tandem well data at SCDP-MW1, water level data from wells located near Pederson Place, Bush Middle School, and Restover Truck Stop are applicable for this calibration purpose.

2.5.3 Vashon Advance Outwash (*Qva*)

Figure 10 shows contours of groundwater elevation for the ***Qva*** aquifer in March 1996**.** Although not current, the 1996 data are sufficient to indicate the perennial trend of groundwater flow directions. The elevations range from about 190 feet above NGVD29 in the south part of the project area to about 100 feet in the northeast part. Regionally, groundwater in this aquifer flows radially to the west, east, and north from the south part of the area. In the project area, flow is to the northeast in the northern half and radial in the southern half. Horizontal hydraulic gradients in this unit range from very low near near Bush Middle School (vicinity of Well MW-96-20) to as high as 0.02 near the Deschutes River bluff.

Interpreted flow lines converge near Trails End and Munn Lakes, indicating increased horizontal flow. This interpretation is strongly influenced by the assumption that the elevations of surface-water bodies (the lakes and the Deschutes River) closely reflect those of groundwater in the ***Qva***.

Comparison of groundwater flow directions in the ***Qvr*** (**Figure 9**) and ***Qva*** (**Figure 10**) aquifers suggests differences in the groundwater drainage patterns. The divide separating westward flowing groundwater from eastward flowing groundwater in the ***Qva*** aquifer is substantially west of the divide in the ***Qvr*** aquifer for March 2000. Whereas Salmon Creek itself and the Salmon Creek groundwater basin (as defined based on wet season ***Qvr*** groundwater flow) extend east to within a mile of the Deschutes River, the boundary in the ***Qva*** aquifer is about half-way between the Deschutes and Black Rivers. This suggests that the ***Qva*** is not influenced greatly by Salmon Creek but is instead controlled by the elevation of the Deschutes and Black Rivers. In the eastern portion of the basin it is therefore possible for groundwater moving horizontally in the ***Qvr*** aquifer to discharge to Salmon Creek, whereas nearby shallow groundwater that moves vertically down through the till to discharge to the Deschutes River.

Values of hydraulic conductivity in the ***Qva*** unit were estimated by Drost and others (1999a) using specific capacity tests by drillers. The hydraulic conductivity estimates ranged from 6.8 to 130,000 ft/day, with a median value of 180 ft/day; the median value is similar to that estimated for the ***Qvr***.

The results of two pumping test analyses indicate that the *transmissivity* of the ***Qva*** ranges from 1,600 ft^2/day (or 12,000 gpd/ft) at City of Tumwater's Well #11 to 21,000 ft^2/day (or 160,000 gpd/ft) near Tumwater MW-93-05 (PGG, 1993 and 1994). Aquifer tests indicate that the productive portion of the ***Qva*** is approximately 10 feet thick at Well #11; therefore, the hydraulic conductivity equals approximately 160 ft/day. During the test period, the unit behaved as a confined aquifer, with no apparent leakage from adjacent units. The response near MW-93-05, however, indicated leakage from adjacent units, most likely from the overlying ***Qvt*** aquitard. Since the ***Qva*** is approximately 65 feet thick at this point, the hydraulic conductivity is approximately 320 ft/day. Also, from the pumping test, the unit's *storativity* is estimated to be approximately 0.0002.

2.6 Surface Water

The principal surface-water drainages in the project area are shown on **Figure 1**. They include:

- Salmon Creek/Hopkins Ditch, in the central portion of the project area, which drains westward to the Black River.
- Blooms Ditch, along the southern boundary of the project area, which drains westward to the Black River.
- Black Lake, to the northwest, which drains mostly northward to Percival Creek.
- Black River, on the western boundary of the project area, which drains southward to the Chehalis River.
- Trosper Lake/Percival Creek, to the north side of the project area, which drains northward to Capitol Lake.
- Deschutes River, to the east, which also flows northward into Capital Lake.

2.6.1 Lakes

Several small glacial-kettle lakes with no surface drainage are present on the east side of the project area (Munn, Susan, Trails End, and Swamp Lakes) and on the north side of the project area (Barnes Lakes). The levels of these lakes are maintained by the inflow and outflow of groundwater. Barnes Lake's level also is controlled by an overflow pipe leading to Deschutes River. Stormwater runoff from the Olympia airport is directed into Swamp Lake.

Black Lake, in the northwest corner of the project area, is fed by several small streams and has two outlets. The natural channel at the south end has long been dammed by dozens of beaver dams and has silted in to the extent that little flow leaves the lake in that direction. To relieve flooding around the lake, the Black Lake ditch was excavated to drain water northward, where the ditch joins the west branch of Percival Creek. The elevation of Black Lake is about 130 feet NGVD29.

Trosper Lake has no inlet stream but flows out as Percival Creek. The elevation of Trosper Lake is between 155 and 160 feet NGVD29.

Springs occasionally issue from the base of the slopes along Deschutes River Valley, at elevations ranging from 100 feet on the north to 150 feet on the south.

2.6.2 Streamflow Measurements

The USGS has measured streamflow at various gaging stations in the project area along the Deschutes River, Black River, and Black Lake. Data collection continues at the E Street bridge in downtown Tumwater. The Black River was gaged at the 128th Street bridge in Littlerock for a short time by the USGS, Ecology, and Thurston County.

Prior to this project, flow in Salmon Creek and Blooms Ditch was measured only a few times at sporadic intervals. Small creeks discharging along the east shore of Black River and Black Lake apparently have never been measured. All gaging stations were inactive or abandoned as of the start of this study.

As part of this project, streamflow in the Salmon Creek, Blooms Ditch, and Fish Trap Creek watersheds was monitored between mid-November 1999 and November 30 2000. Two continuous recorders were located in the Salmon Creek drainage and one each in Blooms Ditch and Fish Trap Creek. In addition, water levels were recorded twice monthly at eight other locations, six within the Salmon Creek basin, and two in the adjoining Blooms Ditch watershed. Therefore, surface-water elevations were recorded at a total of 12 stations within the three watersheds**. Figure 1** shows the station locations, **Tables 2 and 3** describe stations, and **Appendix B** is the surface water monitoring report by Larson and Associates Inc.

In-stream discharge measurements were made at the four stations with continuous recorders and at four of the additional stations within the Salmon Creek basin. Hourly streamflow records were derived from the discharge measurements and the continuous record of water level. The records at the non-continuous stations were *regressed* against the nearest continuous recorder to generate an hourly record at these sites as well. However, since they are based on a regression, the similarity in "shape" between hydrographs at the non-continuous and continuous stations may be an artifact of the calculation method. Unique responses of stations without continuous recorders may be missed by this approach. Judgement should be exercised in using the hydrographs generated based on regression analysis.

A staff gage was installed at each of the four stations with continuous recorders (SC-01, SC-02, SC-08, and SC-14). At stations without staff gages, a measuring point (mp) was marked and a steel tape used to measure from the mark down to the water level. All staff gage 0.00 marks and other measuring points were referenced to NGVD29 elevations based on surveyed benchmarks. Using these references, water levels were converted to water-surface elevations in feet.

The four continuous water level stations were equipped with a Geokon brand data logger and matching pressure transducer. Data loggers were set to record at 15-minute intervals. Records were then averaged to produce hourly and mean daily values. Output from the transducers was field calibrated to stage in feet via correlation with recorded staff gage readings.

Stream discharge was measured up to five times at each of the eight discharge stations (SC-01, SC-02, SC-05, SC-06, SC-07, SC-08, SC-10, and SC-14). *Rating equations*, to convert water-surface elevation to discharge, were calculated by regressing discharge against respective elevation. Application of the rating equations to respective hourly water levels resulted in an hourly and mean daily record of stream discharge in cubic feet per second (cfs).

Individual stream discharge measurements followed the U.S. Geological Survey's mid-section method. Depth and velocity were measured with a top-setting wading rod and a Swoffer brand velocity meter. Field measurements and the results of the mid-section method calculations are included in **Appendix B**.

2.6.3 Streamflow Data Interpretation

Both Salmon Creek and Blooms Ditch are relatively flat, low-gradient watersheds. Excluding the east and west extremities of the Salmon Creek basin, over 21,000 ft. (about 4 miles) of channel have an elevation drop of only about 30 ft. Most of this drop occurs in the first one and one-half miles above SC-01 (**Appendix B).**

The maximum water-surface elevation recorded at SC-01 near the mouth of Salmon Creek was 157.96 ft occurring on December 15, 1999. The associated discharge was approximately 204 cfs. This discharge exceeds the reasonable range of the rating equation and is an estimate. The minimum flow at that location occurred over several days near the end of August 2000. The minimum elevation was 155.11 ft. with a discharge of about 0.5 cfs. The maximum water-surface elevation and discharge at SC-02 on Blooms Ditch occurred at the same time as on Salmon Creek. The elevation was 166.12 ft. and the estimated discharge exceeded 200 cfs. Minimum elevations (161.59 ft.) and flows (0.1 cfs) occurred in late August, 2000.

Salmon Creek's average discharge during the 13 month study period was 18.2 cfs at SC-01, 13.4 cfs at SC-05, 13.0 cfs at SC-06, 7.2 cfs at SC-08, and 2.1 cfs at SC-10. The southern tributary (SC-07) contributed only a negligible 0.3 cfs. The average discharge of Blooms Ditch was only slightly less at 16.9 cfs. The average discharge of the much smaller Fish Trap Creek was 3.6 cfs.

The flow of Salmon Creek throughout the monitoring period is shown in **Figure 11**. This figure portrays the differences in streamflow as one moves from the upper (SC-10) to the lower station (SC-01) and from the wet winter season to the dry summer. The station locations are shown on **Figures 1 and 9**.The low gradient of the upper watershed (between SC-06 and SC-10), combined with extensive wetlands and open pasture, results in an efficient storage of water. In relation to the lower watershed (between SC-01 and SC-06), the upper watershed is slower to respond to rainfall, retains captured water longer, and maintains a relatively greater baseflow in proportion to watershed area. The upper watershed also produces the most water per mile of main channel. Over the study period, the watershed area between SC-06 and SC-10 produced about 5.3 cfs/channel mile, while the lower basin, between SC-01 and SC-06, produced about 2.8 cfs/channel mile. The greatest increase in streamflow (5.9 cfs/channel mile) occurred between SC-06 and SC-08, a portion of the watershed that includes the crossing of the I-5 corridor.

A similar relationship was found during the peak flow season, November through March, when the watershed above SC-06 produced about 15.5 cfs/channel mile while the lower basin produced 6.9 cfs/channel mile. This is not unusual, since most watersheds are pear-shaped with the majority of contributing area in the upper basin. This result was even more pronounced during baseflow (August through September) when the watershed above SC-06 continued to produce about 0.15 cfs/channel mile while production from the lower basin was reduced to 0.05 cfs/channel mile. The accentuated differential in water production during the baseflow period is consistent with the observation that the area contributing groundwater flow to the creek during baseflow is limited largely to the southeastern hills and area near SCDP-MW-4.

While these numbers emphasize the importance of the upper basin in streamflow production, this importance is as much the result of the greater size of the upper basin as compared to the lower, as it is to any other factor. Nevertheless, because of this greater area and total water production, activities that impact runoff in the upper basin will have significant effects on streamflow at SC-01.

Flow in Salmon Creek and Blooms Ditch are similar. The Salmon Creek basin, however, appears slightly better than the Blooms Ditch watershed at storing water. Although high flows are similar, Salmon Creek maintains a greater low flow for a longer period than does Blooms Ditch. Fish Trap Creek, although a smaller drainage, is the most efficient at water storage. Although the peak flow of Fish Trap Creek was only slightly greater than 20 cfs, the lowest flow never dropped below one cfs. Fish Trap Creek is gauged at the outflow of a series of large and small wetlands. Those wetlands receive groundwater from the large groundwater basin immediately north of the Salmon Creek groundwater basin (**Figure 9**).

3. Quantitative Description of Groundwater Flooding

Two methods were used to provide quantitative descriptions of the groundwater flooding problem. The frequency and severity of historical flooding over the past 50 years was evaluated using an *antecedent precipitation index for head* (APIH). Based on that analysis, the maximum historical groundwater flooding event probably occurred in the late winter of 1999. Field data from that period of 1999 were assembled, contoured, and used to estimate depth-to-water for the entire basin during that worst-case event. The following two subsections present these analyses.

3.1 Antecedent Precipitation Index for Head (APIH)

This section describes an analysis performed to evaluate the frequency of groundwater flooding. It uses a correlation between the long precipitation record and shorter groundwater elevation (*head*) records to simulate historical and possible future flooding.

The APIH is a mathematical predictor of groundwater elevations based on historical (antecedent) precipitation (Swope, 1990). The influence of precipitation decreases with its age; therefore, precipitation that is more recent is given greater weight by use of a decay coefficient. APIH is applicable to regions where groundwater elevations are dominated by the effects of direct precipitation rather than by surface-water or tidal interactions or by infiltration of snow melt.

Generally, precipitation measurements have a longer period of record and are more frequent than measurements of head. Therefore, where an index based on precipitation correlates reasonably well with nearby heads, it can be used to simulate historical heads, the frequency of groundwater flooding, and future heads if future precipitation is assumed. (A reasonably good correlation will have a correlation coefficient, r, of 0.85 or greater, although no objective standard can be defined).

An APIH was developed using heads from four wells completed in the ***Qvr*** and daily precipitation at the Olympia airport:

- The City of Tumwater's Monitoring Well MW-94-12 at Pederson Place
- Texaco Well No. 1 at the Texaco Bulk Plant
- Ecology's Well AAB707, just south of Salmon Creek basin
- Well MW-20A at Restover Truck Stop on 93rd Street at I-5

These wells have relatively long periods of record for heads in the project area. Their locations are shown on **Figure 1** (except well AAB707). Results of the APIH calculations and correlations are shown on **Figures 12, 13, 14, and 15**.

3.1.1 APIH and Correlation Equations

The following equations are used to calculate daily APIHs:

$$APIH_d = (APIH_{d-1}\ C)+P_d \qquad \text{Equation 1}$$

and

$$Head_d = A\ (APIH_{d-1}) + B \qquad \text{Equation 2}$$

Or, by combining Equations 1 and 2:

$$Head_d = A\ ((APIH_d - P_d)/C) + B \qquad \text{Equation 3}$$

Where:

$APIH_d$ = antecedent precipitation index for day d

$APIH_{d-1}$ = antecedent precipitation index for day d-1

C = decay coefficient

P_d = precipitation for day d

A = slope, and

B = intercept

To calculate APIH, the decay coefficient, C, was derived by trial and error. The C in Equation 3 that resulted in the best linear correlation or "match" between $APIH_d$ and $Head_d$ in Equation 3 was chosen to represent that well/weather-station pair. The best match between $APIH_d$ and $Head_d$ was identified when the linear correlation coefficient (r) between $APIH_d$ and $Head_d$ was maximum. As part of that iterative, trial and error process, A and B of Equations 2 and 3 were therefore also determined.

Each well/weather-station combination may have a unique C. For the Salmon Creek examples, the Cs are similar, ranging from 0.9945 to 0.9975. These high values (close to 1.0) reflect the fact that groundwater drainage is slow and that infiltrating precipitation accumulates over a long period.

Second, Equation 2 was used to simulate heads for times when head data were not available. By assuming future daily precipitation, future APIH and heads were also estimated (Pacific Groundwater Group, 2000).

Because of its cumulative aspect, approximately the first year of the APIH should not be correlated with heads to derive C, the decay coefficient. In this case, no arbitrary initial value of APIH was used; rather, the early values of APIH were low and inaccurate because of APIH's cumulative nature, and were therefore not used to establish correlations and C values.

3.1.2 Simulating Groundwater Flooding

Groundwater flooding was assumed to occur when the simulated head was at least as high as the lowest land-surface elevation in the vicinity of the well. Then, from the simulated heads, statistics for the frequency of groundwater flooding were computed. The local land surface elevations are shown on **Figures 12, 13, 14, and 15**.

3.1.3 APIH Findings

Figures 12 through 15 present the APIHs, measured heads, correlation equations, and estimated elevations of groundwater flooding for the four wells. Each figure contains three graphs.

- Graph **a** ("Historic Record") presents the calculated APIH and simulated head for the period of record, indicating the head at which flooding may occur. The APIH and correlation equations are also shown inset to Graph **a**.
- Graph **b** ("Correlations") presents observed head and APIH (these data are the basis for selection of C values and correlations).
- Graph **c** ("Statistics") presents the statistical distribution of all the APIH values in Graph **a**.

Table 5 summarizes the APIH calculation results from these figures, including the correlation coefficients and the inferred frequency of flooding. Note that since Well AAB707 lies outside the basin, no evaluation of flooding was performed for the well.

In the following discussion of results, **Figure 12** is used as an example; other figures can be used in the same way.

The APIH for Pederson Place Well MW9412 correlates to measured head with a correlation coefficient of over 0.95. The APIHs for early 1999 (the 99th percentile year) were the largest in the 50-year precipitation record **(Figure 12a)**.

The recurrence of flooding is indicated by the frequency of APIH values above the "onset of flooding" line on **Figure 12a**. Based on the index, flooding probably occurred, to some extent, during Water Years 1951, 1956, 1961, 1972, 1974, 1997, 1998, and 1999. **Figures 12a and 12c** suggest that flooding in the vicinity may have occurred on about 2 percent of the days during the period of record and on a least 1 day during 16 percent of the years of record.

The match between measured head and APIH deteriorates at high values for the wells at Pederson Place and Texaco, as observed for Water Year 1998, possibly because of the extensive flooding in the area **(Figures 12b and 13b)**. After groundwater reaches land surface, the increase in head per inch of precipitation slows and alters the correlation.

3.2 Depth-to-Water

Pacific Groundwater Group prepared the depth-to-water-table (DTW) map shown on **Figure 16** to accompany the interim-development guidelines for the Salmon Creek Drainage Basin, Thurston County (URS, 2000). The map indicates the approximate position of the water table below ground surface, on a 100-foot grid spacing, for the flooding episode of winter 1999, the period of maximum groundwater flooding in recent years. The color-coding on the grid map indicates four categories of depth-to-water-table: greater than twelve feet below land surface, six-to-twelve feet below ground surface, zero-to-six feet below land surface, and at or above land surface. Interpretations indicate that 23 percent of the basin had water levels at or above ground surface, and that groundwater was within 6 feet of ground surface over 68 percent of the basin at that time.

The three types of data used to construct the DTW map are (1) elevations at the boundaries of flooded areas identified by Thurston County Geodata Center (shown in red on **Figure 1**), (2) elevation of the water table measured in wells, and (3) land-surface elevation at streams and wetlands.

The flood data provided by Thurston County GeoData Center was prepared based on a mixture of field observations and interpretation of color-infrared photos taken during the flooding. Several factors influence the accuracy of the boundaries of the flooding as mapped by Thurston County. The exact boundaries of the flooding could not always be seen in the photos, because of tree canopies. In most cases, the boundaries were adjusted to correspond with particular land-surface-elevation contours that are at two-foot intervals. The County mapping and observations were conducted over much of the Salmon Creek Basin; however, mapping and observations were not made along much of Hopkin’s Ditch and Blooms Ditch in the southern part of the basin.

The sources for the water-table elevations were the various government agencies and consultants that routinely monitor groundwater in the basin. Few of the wells were measured on a daily basis. Some were measured less than once per month and probably did not record the maximum water-table elevation during the flooding. However, most values are thought to be within three feet of the true maximum. This is commensurate with the accuracy of the flood elevations and is the best available information. The maximum measured value for January, February or March 1999 was used for the DTW map. Therefore, the map may indicate less than the maximum value for many cells of the grid.

The flood mapping and well data were not sufficient to define groundwater heads along creeks and wetlands in the south and west portions of the basin. Therefore groundwater elevations were assigned based on land surface elevations at streams and wetlands. **Appendix C** presents a detailed description of the map generation process.

The depth-to-water map was reviewed with respect to the conceptual model of groundwater occurrence and agreement with the observed flood areas. Flood observations were not made in extensive areas in the southern part of the basin and therefore confirmation of the predicted flooding in those areas is not possible. Agreement between the predicted flood areas and the conceptual model and observations was generally good with the following exceptions:

- Near 93rd and Littlerock Road where flooding was mapped by Thurston County but groundwater levels were below ground surface at monitoring well LRS-007.
- Along 93rd Avenue east of Tilley Road where groundwater gradients and land surface relief are high. The gridded groundwater gradient is probably not as steep as actually occurs in this area, and thus extensive flooded areas are predicted at the base of hills.

To complete the map and take maximum advantage of the County flood mapping work, the mapped flood areas were added to the map. This was done by coloring the observed flood areas the same as the predicted flood areas. The underlying grid values within the flood areas were not forced to agree with the County flood map.

4. Definitions, Acronyms, and Abbreviations

The following is a glossary of technical terms, acronyms, and abbreviations used in this report. The purpose of this glossary is to provide a reference for readers who are less familiar with terms often used in technical discussions about hydrogeologic concepts. This compilation includes a list of abbreviations and acronyms used throughout this report. Terms in italics within a definition also are defined in this glossary.

aquifer: A *hydrostratigraphic* unit that yields significant (economically feasible) amounts of water to wells.

aquitard: A *hydrostratigraphic* unit that does not yield significant amounts of water to wells. Aquitards can store large quantities of water but do not readily transmit water.

base flow: The component of streamflow caused by *groundwater* discharging to a river or stream.

confined aquifer: An *aquifer* that is overlain by an *aquitard* and contains *groundwater* under sufficient pressure to rise above the top of the aquifer. In some cases, groundwater levels may be above land surface and wells completed in a confined aquifer may flow.

evapotranspiration: The portion of precipitation returned to the atmosphere by direct evaporation of water and by plant transpiration, both of which are greatest during the warmer months.

facies: A lateral subdivision of a stratigraphic unit based on comparative characteristics, particularly texture.

ft/day: feet per day, a unit of measurement used to describe aquifer *hydraulic conductivity*. It is a simplification of ft^3 (volume of water) per ft^2 (area through which water flows) per day.

gpm: gallons per minute; a unit of measurement used to describe "instantaneous" pumping rate.

gpd/ft: gallons per day per foot; a unit of measurement used to describe aquifer *transmissivity*.

groundwater: Water that is stored under the earth's surface in interconnected pores of materials that lie below the water table.

head: Numerically equal to the elevation of the upper *groundwater* level in a well. Where no well exists, its value is the sum of the water pressure and the elevation above a measuring point.

Holocene (or Recent) Epoch: The span of geologic history from about 10,000 years ago, after the last glaciers receded, to present time.

***hydraulic conductivity*:** In this report also called *permeability*. A coefficient of proportionality describing the rate at which water moves though a porous medium under a certain hydraulic gradient, that is, the volume of water moving through a unit area during a unit time period. Commonly, it is expressed in units of feet per day (ft/day) or centimeters per second (cm/sec) or gallons per day per foot squared (gpd/ft^2). It is equal to the *transmissivity* of an aquifer divided by its saturated thickness.

hydraulic gradient: The change in *groundwater* elevation over a distance in a given direction. Expressed as a unitless number representing ft (head change)/ft (distance), it is the driving force for groundwater flow.

hydrostratigraphy: The stratigraphy of hydrogeologic units. Stratigraphy is a branch of geology involving study of the formation, composition, sequence, and correlation of rock strata.

Hydrograph: A chart of water elevation over time.

msl: mean sea level. Elevation relative to 0 feet for mean sea level in accordance with the National Geodetic Vertical Datum (NGVD) of 1929.

outwash: Sand and gravel deposited by melt water streams from a glacier.

permeability: see hydraulic conductivity

Qal: modern alluvium deposits

Qva: Vashon advance outwash deposits

Qvr: Vashon recessional outwash deposits

Qvt: Vashon till

Rating Curve: A chart and equation that defines the relationship between stream water elevation and stream flow quantity.

Regressed: The process of generating an equation that most-closely predicts one number, if another number is known.

specific capacity: A measure of how much water a well can produce; specifically, the rate of discharge from a well per foot of drawdown, expressed in gpm/ft. Specific capacity usually decreases with continued pumping over time, even though the pumping rate remains unchanged.

stage: The level or elevation of a river or other *surface-water* body.

storativity: Also referred to as “storage coefficient,” the volume of water an aquifer releases, or absorbs, per unit surface area of an aquifer per unit change in head.

surface water: Bodies of water on the earth’s surface, such as rivers, streams, creeks, lakes, and ponds.

Synoptic: Involving data from a wide area at one point in time.

till: Unstratified, poorly sorted sediments deposited along the bottom of a glacier; as such, they are typically very dense, compact, and consolidated. Till often looks like concrete and commonly is called "hardpan" by well drillers. The texture often ranges from clay to gravel.

transmissivity: A measure of an *aquifer's* ability to transmit water; the rate at which water is transmitted through 1 foot of aquifer width under a hydraulic gradient of 1. Transmissivity equals the hydraulic conductivity of an aquifer times its saturated thickness. It is commonly expressed in gpd/ft, ft^2/day, or m^2/day.

unconfined aquifer: An *aquifer* that is not overlain by a confining unit and in which pore water pressure at the upper groundwater surface is atmospheric; heads in such an *aquifer* lie below the top of the aquifer.

USGS: United Stated Geological Survey, Department of the Interior.

watershed: The land area potentially contributing water via runoff to a certain location.

water table: the top surface of a body of *unconfined groundwater* at which the pore pressure equals that of the atmosphere.

5. References

Applied Hydrogeologic Research. 1999. *Shallow Groundwater Monitoring Network Final Report*. Report to the Thurston County Department of Water and Waste Management, dated January 15.

Associated Earth Sciences, Inc. 1997. *City of Tumwater Groundwater Resource Investigation*.

Bauer and Mastin 1997. Recharge from Precipitation in Three small Glacial-Till –Mantled Catchments in the Puget Sound Lowland, Washington, U.S. Geological Survey Water Resources Investigation Report 96-4219

Berris, S.N. 1995. *Conceptualization and Simulation of Runoff Generation from Rainfall for Three Basins in Thurston County, Washington.* U.S. Geological Survey, Water-Resources Investigations Report 94-4038.

Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Donigian, A.S., and Johanson, R.C. 1997. *Hydrological Simulation Program Fortran, User's manual for version 11*. Athens, Georgia: U.S. Environmental Protection Agency, National Exposure Research Laboratory, EPA/600/R-97/080.

Booth, Massman, and Horner 1996. Groundwater-Related Issues, Northridge Development (Written Testimony at Northridge Development Land Use Hearing, May 14, 1996).

Christensen, K.N. 1995. *Black Lake Watershed, HSPF Calibration Report II*. Report to the Thurston County Department of Water and Waste Management, Storm and Surface Water Division, Grant No. 99299219, dated July.

Drost, B.W., Turney, G.L., Dion, N.P., and Jones, M.A. 1998. *Hydrology and Quality of Groundwater in Northern Thurston County, Washington*, Tacoma, Washington: U.S. Geological Survey, Water-Resources Investigations Report 92-4109 (Revised).

Drost, B.W., Ely, D.M., and Lum, W.E. 1999. *Conceptual Model and Numerical Simulation of the Ground-Water-Flow System in the Unconsolidated Sediments of Thurston County, Washington.* Tacoma, Washington: U.S. Geological Survey, Water-Resources Investigations Report 99-4165.

Economic and Engineering Services, Pacific Groundwater Group, and Daily Environmental. 1997. *City of Tumwater Wellhead Protection Plan*.

Franz, D.D., and Melching, C.S. 1997. *Full Equations (FEQ) Model for the Solution of the Full, Dynamic Equations of Motion for One-Dimensional Unsteady Flow in Open Channels and Through Control Structures*. U.S. Geological Survey Water-Resources Investigations Report 96-4240.

Groundwater Science Services. 1999a. *Groundwater Elevations for Littlerock Sub-Basin, October 1, 1998 through September 5, 1999.* Report to the Thurston County Department of Water and Waste Management, dated September 20.

______________________________. 1999b. *Precipitation for Littlerock Sub-Basin, October 1, 1998, through September 5, 1999.* Report to the Thurston County Department of Water and Waste Management, dated October 8.

Morrissette, Jerome W. & Associates. 1999. *Port of Olympia, New Market Industrial Campus Stormwater Master Plan*. Report to the City of Tumwater, Public Works Department, dated May 3.

Noble, J. and E. Wallace. 1966. *Geology and Groundwater Resources of Thurston County, Washington, Vol. 2*. Olympia, Washington: Department of Conservation.

Pacific Groundwater Group. 1994. Well completion report, Bush Middle School Production Well #14-94, City of Tumwater, Washington. Project JE91 05.04, December.

Pacific Groundwater Group. 1994. Well completion report, Well No. 12-94,City of Tumwater, Washington.

Pacific Groundwater Group. 1995. Initial Watershed Assessment Water Resources Inventory Area 13 Deschutes River Watershed. Open-File Technical Report 95-10. Prepared for Washington State Department of Ecology Water Resources Program.

Pacific Groundwater Group. 1997. *Littlerock Road Subarea Shallow Groundwater Assessment*. Report to the City of Tumwater.

Pacific Groundwater Group. 2000. Salmon Creek Drainage Basin Preliminary Conceptual Hydrologic Model and Data Collection Plan. Report to prime contractor URS Corp. and Thurston County.

Pacific Groundwater Group. 2000b. Groundwater Basin Boundary and Synoptic Water-Level Survey for Salmon Creek Area. Revised Technical Memorandum submitted to URS Corp. and Thurston County, August 17, 2000.

Swope, Stephen P. 1990. *Analysis of Water Level and Water Quality Data From Smelterville Flats, Kellog Idaho*. University of Idaho, Department of Hydrology, School of Mines Master's Thesis.

Tetra Tech, Inc. 1999. *Summary of February 1999 Groundwater Sampling Results, Webster Nursery, Olympia, Washington*. Memo report to John Felder, Washington Department of Natural Resources, April.

Toth, J. (1970) "A Conceptual Model of the Groundwater Regime and the Hydrogeologic Environment." *Journal of Hydrology*. 10:164-176.

U.S. Department of Agriculture, Soil Conservation Service. 1990. *Soil Survey of Thurston County, Washington*.

URS Corp. 2000. Interim Site Development Standards for New Development in Salmon Credk Basin. Prepared for Thurston County Department of Water and Waste Management, Storm and Surface Water Program

Wallace, E. and D. Molenaar. 1961. *Geology and Groundwater Resources of Thurston County, Washington, Vol. 1*. Olympia, Washington: Department of Conservation Water-Supply Bulletin 10.

Wildrick, L. 1995. *Initial Watershed Assessment, Water Resource Inventory Area 23, Upper Chehalis River*. Olympia, Washington: Open-File Technical Report 94-09.

Woodward-Clyde. 1997a. *Hopkins Ditch Feasibility Study*. Report to the Thurston County Department of Water and Waste Management, dated April 28.

______________. 1997b. *Technical Memorandum for South and West Hickman Ditch Designs*. Report to the Thurston County Department of Water and Waste Management, dated April 28.

Woodward, D.G., Packard, F.A., Dion, N.P., and Sumioka, S.S. 1995. *Occurrence and Quality of Groundwater in Southwestern King County, Washington*. Tacoma, Washington: U.S. Geological Survey Water-Resources Investigations Report 92-4098.