DUWAMISH BASIN GROUNDWATER PATHWAYS

DEVELOPMENT OF A THREE-DIMENSIONAL, NUMERICAL GROUNDWATER FLOW MODEL FOR THE DUWAMISH RIVER BASIN

by

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Background

The Duwamish Basin Groundwater Pathways Study, jointly funded by the City of Seattle and King County, is a part of the "Duwamish Industrial Area Hydrogeologic Pathways Project," an area-wide effort to understand the groundwater flow pathways in the Duwamish Valley. The overall goal of the Duwamish Hydrogeologic Pathways Project is to facilitate the redevelopment of "brownfields" in the Duwamish Corridor by improving the quality and pace of cleanup-related decision-making in the area. Improved understanding of groundwater conditions within the Duwamish Valley should facilitate long-term water quality protection and brownfields redevelopment. The study area includes the Duwamish Valley, from the origin of the Duwamish River at the confluence of the Green and Black Rivers in Tukwila, to the river mouth at Elliott Bay.

This report summarizes the results of the numerical modeling for the Duwamish Valley. It follows directly from the *Conceptual Model Report* (Booth and Herman, 1998), published in April 1998. The *Conceptual Model Report* provided a detailed characterization of the geologic and hydrogeologic conditions, based on comprehensive data collection and analyses. This effort produced the most complete picture of groundwater pathways currently available for the Duwamish Valley. The work on numerical modeling reported here quantitatively explores those patterns and predictions of groundwater movement through the Duwamish Valley articulated in the *Conceptual Model Report*.

Computer Code Selection and Model Discretization

The computer program used for the Duwamish numerical model is MODFLOW. It is a publicly available groundwater flow simulation program developed by the U.S. Geological Survey (McDonald and Harbaugh, 1988). MODFLOW is a well-documented model used by consultants, government agencies, and researchers, and it is widely accepted in regulatory and legal proceedings.

The three-dimensional numerical model of the Duwamish basin covers approximately 60 square miles. The ***model domain*** in MODFLOW exceeds the ***study area*** defined in the *Conceptual Model Report*, so that boundary conditions can be more naturally defined. The boundaries of the numerical model coincide with natural hydrogeologic boundaries to minimize the influence of artificial model boundaries on simulation results.

The average flow conditions in the Duwamish basin were simulated by MODFLOW using the steady-state option. The model does not include temporal variations caused by tidal fluctuations or seasonal variability.

Hydrostratigraphy and Hydraulic Parameters

The hydrostratigraphy used in the Duwamish model is based on the boring log data and geologic cross sections of the *Conceptual Model Report.* The numerical model defined six stratigraphic units: 1) bedrock, 2) glacial silt, 3) older alluvium, 4) younger alluvium, 5) Vashon glacial deposits, and 6) coarse-grained deposits of the Highline aquifer. Interpolation between boring logs and cross sections included in the *Conceptual Model Report* estimated the spatial distribution of these six materials in three-dimensional space.

Additionally, the model requires two principal hydraulic parameters as input, the hydraulic conductivity of the various stratigraphic units and the infiltration rate at the ground surface. It assumes the application of a uniform infiltration rate of 10 inches per year, based on recent work by the U.S. Geological Survey (Woodward et al., 1995). Initial estimates for hydraulic conductivity values were developed using ranges reported in the literature for similar material (Freeze and Cherry, 1979) and from measured values included in the *Conceptual Model Report*.

Model Calibration

Model calibration involves adjusting model parameters to obtain a reasonable match between observed and simulated output variables. The calibration focused on adjustment to hydraulic conductivity values, based on the assumption that uncertainties in the infiltration rate were small relative to uncertainties in hydraulic conductivity.

The comparisons in this study include qualitative and quantitative measures between observed and predicted water levels. The qualitative measures include the anticipated water level contours and overall hydraulic gradients predicted by the *Conceptual Model Report*. Quantitative measures involve calculating differences in observed and predicted water levels at discrete points within the model domain, using water levels from approximately 140 wells, in Appendix B of the *Conceptual Model Report*.

Model Results

General Paths of Groundwater Movement

The pattern of water level contours and groundwater flow predicted by the model are qualitatively similar to the inferred water levels presented in the *Conceptual Model Report*. Water levels along the western slopes range between 230 to 330 feet, and the levels in the Central Valley are 10 to 20 feet above the river level. The horizontal head gradients in the Central Valley, which are in the range of 0.001 to 0.01, are also consistent with the head gradients described in the *Conceptual Model Report*.

Estimated Groundwater Budget

The calibrated model produced an estimated groundwater flow budget for the model domain. The flow budget describes how much water leaves the groundwater system through groundwater seeps and through direct discharge to surface water bodies.

Groundwater exits the modeled region in one of four ways. Approximately 11% of the groundwater discharges directly to Lake Washington. This groundwater, which enters the lake through offshore sediments on the lake bottom, originated as infiltration within the model domain but outside of the study area defined in the conceptual report. An additional 24% of the groundwater volume discharges to groundwater seeps that eventually reach Puget Sound, Elliott Bay, or Lake Washington as surface flow. This, too, originated as infiltration in areas outside the study area. The remaining 65% of the groundwater included in the model domain discharge reaches the Duwamish Waterway. The model calculates that about half of this fraction discharges directly from the groundwater system to the waterway. This water enters the waterway along the sides and bottom of the channel. The other half discharges to groundwater seeps that eventually drain into the waterway via surface, piped, or channeled flow.

Groundwater Flow Directions and Locations of Groundwater Seeps

The general flow of groundwater within the study area converges on the Duwamish Waterway, which in turn carries the water to Elliott Bay. Groundwater discharges at two main zones in the vicinity of the Duwamish Waterway: seeps at the base of the upland slopes, and along the waterway itself. The discharge areas at the waterway indicate locations where groundwater is anticipated to discharge directly into the channel.

Model results indicate that groundwater flow originating along the ridges of the uplands penetrates relatively deeply into the flow system. Some flow lines penetrate to elevation -150 feet (below sea level) before bending upward and ultimately discharging along the surficial contact between the uplands and the valley floor. Water infiltrated along the flanks of the uplands generally follows a much shallower pathway. It discharges both to seeps along the lower parts of the uplands and directly to the Duwamish Waterway.

Flow directions within the valley sediments are relatively complex, and are a function of location and depth. At specific locations, the flow may be downward at some depths and upward at other depths. The ultimate discharge location, however, is the Duwamish Waterway or seeps that eventually drain to the waterway.

The discharge rates for the groundwater seeps are highest along the western edge of the of the valley sediments in the central and southern parts of the flow fields. This is generally consistent with the potential upland discharge zones identified in the *Conceptual Model Report*. The total discharge to these seeps within the Duwamish drainage basin is approximately 10 cubic feet per second (cfs), or 30% of the infiltration applied to the model domain.

Uncertainty and Sensitivity Evaluations

There is considerable generalization involved in the model representation of the valley sediments. The modeled sediments belong to one of two broad categories: “younger alluvium” and “older alluvium.” The “younger alluvium” category includes young alluvium and fill materials, common in the upper 10 to 20 feet of the valley. The location of the contact between these two primary units significantly affects local flow directions. However, the location of this contact does not significantly affect the overall water budget in terms of the amount of water that reaches the waterway.

There is significant uncertainty associated with the hydraulic conductivity parameters, especially at the scale of individual cells. The values of these parameters at a point can likely differ by one to two orders of magnitude from values that would be measured in the field. The uncertainties associated with these local values for hydraulic conductivity cause uncertainties in the local flow directions and magnitudes. However, the hydraulic conductivity values on a larger scale will have much less uncertainty than the local values. It is relatively unlikely that the average hydraulic conductivity values belonging to specific stratigraphic units will differ by more than an order of magnitude from the actual field value.

The most important source of boundary condition uncertainty arises from treating the Duwamish Waterway as a constant head boundary. The proportion of groundwater that discharges directly to this boundary is dependent upon the assigned head value of the waterway and/or the hydraulic conductivity values for the sediments in the vicinity of the waterway. The effect of uncertainties is large relative to the uncertainties in water levels and hydraulic conductivity.

The model does not include tidal effects in the boundary conditions. Boundary condition water levels are relative to average or mean sea level conditions. Tidal fluctuations do propagate upstream through the waterway and can cause short-term groundwater flow reversals in the immediate vicinity, as discussed in the *Conceptual Model Report*. However, in terms of annual averages, data reviewed for the *Conceptual Model Report* demonstrate that these tidal effects should not be large.

Sensitivity studies indicate that the infiltration rate and the hydraulic conductivity of the glacial silt have the largest affect on the water budget. The infiltration rate governs the total volume of water that enters the flow field and the hydraulic conductivity of the glacial silt affects the locations of the groundwater divides. The model predicts that flow volumes to the Duwamish Waterway are roughly proportional to the assigned infiltration rate: a 30% increase in infiltration rate will cause nearly uniform 30% increases in the discharge values to groundwater seeps and the Duwamish Waterway.

With modification of parameter values and stratigraphic units over a range of likely values, the model still shows the same basic behavior. This includes the presence of groundwater divides along the upland ridges, downward gradients in the uplands, seeps along the valley edges, and predominately upward gradients in the vicinity of the Duwamish Waterway.

Decisions Using Comprehensive yet Imperfect Data

The output from the Duwamish model can be divided, in very broad terms, into two categories: output associated with point values and output associated with average values. Point values include water levels, hydraulic heads, and groundwater velocities at specific points in the flow field. Average values include the rate of groundwater discharge or recharge along reaches of the Duwamish Waterway or to groundwater seeps.

Because of the relatively large uncertainties associated the spatial distribution of hydraulic conductivity, there is considerable uncertainty in estimates of the magnitude and direction of groundwater flow at any specific location within the model domain. Locally, the magnitudes may easily be incorrect by a factor of ten or more and the flow directions easily be wrong by 90 degrees. However, for the average of these velocities over relatively large areas, such as along a segment of the river, the uncertainty in the average is much less than the uncertainty in the point values. The model proves more useful in helping with decisions related to these average values, because prediction at this scale is more robust, being determined by the regional stratigraphic relationships and topography of the Duwamish Valley and its surrounding uplands. As a result, model outputs are rather insensitive to the characterization of local conditions.

Average values from the model should be useful in characterizing and quantifying the ground water flow patterns of the *Conceptual Model* Report. It will also prove valuable for setting plausible boundary conditions for smaller-scale models that may be developed subsequently to investigate groundwater movement in more localized areas.

1. INTRODUCTION

The Duwamish Basin Groundwater Pathways Study is a part of the "Duwamish Industrial Area Hydrogeologic Pathways Project", an area-wide effort to understand the groundwater flow pathways in the Duwamish Valley. The study area falls within the jurisdictions of the City of Seattle, the City of Tukwila, and unincorporated King County. It includes the Duwamish Valley, from the origin of the Duwamish River at the confluence of the Green and Black rivers in Tukwila, to the river mouth at Elliott Bay. The dredged portion of the river, most of its lower half, in this area is called the Duwamish Waterway.

The Duwamish Valley is a heavily industrialized area south of downtown Seattle. It includes approximately 5,000 acres of land designated for industrial activity. The legacy of the area's long-term industrial activity includes soil, groundwater, surface water, and sediment contamination. Over the past several decades, concern over the contaminant impacts to the long-term health of the area in general, and impacts to the Duwamish River and Puget Sound in particular, have combined with regulatory actions to improve operations and encourage cleanup. Spurred by growth management mandates, current efforts now focus on promoting reuse and redevelopment of this area for industrial purposes, which also encourages cleanup and pollution prevention.

A consistent area-wide understanding of groundwater conditions contributes to long-term water quality protection and "brownfields" redevelopment. This project has focused on summarizing groundwater flow patterns in the Duwamish Valley, so that ultimately a better understanding of the contaminant risk to human health and the environment can be made. It is part of the "Duwamish Industrial Area Hydrogeologic Pathways Project," conceived by the Duwamish Coalition committee, Preserving and Reclaiming Industrial Lands. The City of Seattle and King County jointly funded this project. The City and County worked with the University of Washington's Center for Urban Water Resources Management and an environmental consulting team led by Floyd & Snider, Inc. Both the Washington State Department of Ecology and the USEPA Region 10 Brownfield Office have been active participants in the scoping and execution of the project. The overall goal of the Duwamish Hydrogeologic Pathways Project is to facilitate the redevelopment of brownfields in the

Duwamish Corridor by improving the quality and pace of cleanup-related decision-making in the area.

This report summarizes the results of numerical modeling for the Duwamish Valley. The numerical model follows directly from the *Conceptual Model Report* (Booth and Herman, 1998), published in April 1998. That study, in turn, follows from a preliminary groundwater conceptual model developed for the City of Seattle Office of Economic Development (Hart Crowser, 1997). That previous work focused on identifying the criteria necessary to establish that the "most beneficial use" of shallow groundwater in the Duwamish Corridor is as source water for the Duwamish Waterway. In order to secure this "surface-water" designation for the groundwater in the area, the hydrogeologic conditions that define the groundwater system must be understood. These conditions include:

- The geologic history and framework;
- Aquifer and aquitard occurrence;
- Recharge and discharge factors;
- Groundwater flow patterns; and
- Water quality.

The *Conceptual Model Report* provided a detailed characterization of the geologic and hydrogeologic conditions, based on comprehensive data collection and analyses. The scope of work for development of that study included:

- Compilation and review of data collected from Ecology, EPA, Metro, King County, USGS, and consultant team files, including assistance with development of the database and mapping displays;
- Selection of the well and boring data for inclusion in the database, and criteria for the GIS mapping coverage for area including topography, geology, groundwater elevations, and other supporting mapping for presentation of the conceptual model;
- Review and analysis of site investigation reports for data that enhance understanding of the stratigraphy and groundwater flow at individual sites;
- Development of hydrogeologic cross sections, groundwater elevation contour maps, and illustrative groundwater flow-related graphs and maps for construction of the conceptual model.

This effort produced the most complete picture of groundwater pathways currently available for the Duwamish Valley. The work on numerical modeling reported here explores those patterns and predictions of groundwater movement through the Duwamish Valley as articulated in the *Conceptual Model Report*. Numerical modeling offers the ability to quantify the flux of groundwater as it travels between its various source areas and ultimate points of discharge, and to potentially explore a variety of alternative scenarios for future remediation or land-use changes. The overall representation of this area in the numerical model derives directly from the geologic and hydrologic characterization presented in the *Conceptual Model Report*, and thus the numerical results will be reliable only to the same degree that the conceptual model is accurate.

2. REGIONAL FRAMEWORK

2.1 Geologic History of the Duwamish Area

The geology of the Duwamish Valley (Figure 1) reflects many of the processes that have shaped the Puget Lowland as a whole. The valley is a relic arm of Puget Sound, which was carved by the overriding ice sheet that last advanced into this area from British Columbia about 15,000 years ago. Through the scouring action of flowing ice and subglacial water, many hundreds of feet of sediment have been flushed out of what are now the multiple channels of the Sound, inundated with sea water once the ice retreated and global sea level rose to its present-day level.

At the time of ice retreat, the Duwamish arm of Puget Sound extended many miles farther south than it does today. Up until about 5700 years ago its shoreline reached to the city of Auburn, about 20 miles upstream of the present mouth of the waterway at Elliott Bay. At that time, a tremendous mudflow, the Osceola Mudflow, descended from the flanks of Mount Rainier along the valley of the White River, building a voluminous fan of sediment into the marine waters at Auburn and progressing downvalley as a submarine flow at least as far north as Kent (Dragovich and others, 1994). Over the subsequent centuries, the mudflow sediments were re-eroded from higher up the White River and re-deposited farther downstream. During this time flow from the White River apparently trended north, down the present Green River valley, and so this sediment rapidly advanced the shoreline up the Duwamish arm of Puget Sound, filling the bed upward with fine silt while the coarser sand and gravel advanced laterally at the water's edge. This sediment completely buried the pre-5700-year-old form of the valley. Only a few bedrock knobs, high enough for their tops to remain above the level of this infilling deposit, remain exposed at the modern ground surface.

After a long but indeterminate time of probably several thousand years, the advancing deposits of the ancestral White River reached Elliott Bay. Here, farther advance of the sediment wedge dramatically slowed because of the great depth of the bay. Upstream, the Duwamish arm was now land, probably completely filled by floodplain deposits as the combined flow of the White and Green rivers continued to transport sediment from Mount Rainier and the nearby Cascade Range down to Puget Sound. As the river episodically flooded and migrated back and forth across the floodplain, the local sediments already there were reworked by the river and augmented by additional riverine and floodplain deposits.

The most recent phase of the valley's geologic history includes the filling of tideflats and floodplains, and the subsequent dredging of a straightened channel of the meandering Duwamish River. Completed between 1913 and 1917 by the Duwamish Waterway District, the new channel was 4.5 miles in length from the East and West Waterways. As a result of the waterway development, 12.5 miles of old riverbed were abandoned. The excavated river material was used to fill these areas and the lowlands above flood levels. Subsequent filling for land development has resulted in a surficial layer of fill over most of the lower Duwamish Valley. The heterogeneous nature of fill materials can affect both infiltration characteristics and local groundwater flow where below the water table. Much of the thicker fills that occur below the water table were dredged from the Duwamish River, however, and so the silts and sands are difficult to distinguish from the native alluvium and have the same general hydrologic properties.

Deposits and landforms within the valley and adjacent uplands reflect each of these stages in the geologic history of the study area. In turn, these features influence the occurrence of groundwater and help explain the groundwater pathways. The regional stratigraphic units that make up the upland and valley deposits are described sequentially, from oldest to youngest, in the following section.

2.2 Regional Stratigraphic Units

Three principal geologic assemblages within the Duwamish Basin define the hydrogeologic system:

- Bedrock, which occurs as a basement material and bounds the area aquifers;
- A sequence of glacial and non-glacial sediments within the uplands which flank and define the valley, and establish groundwater flow boundaries to the valley aquifer system; and
- Valley alluvial deposits, which fill in the Duwamish trough and contain the aquifers and groundwater of most interest to this study.

2.2.1 Tertiary Bedrock

Bedrock is exposed in the eastern and southern parts of the study area, most extensively on the east side of the Duwamish River (Waldron and others, 1962; Waldron, 1962). North of these exposures, the bedrock surface descends from several hundred to over a thousand feet below the ground surface. Where exposed, bedrock consists of marine and continental sedimentary rocks and isolated igneous intrusions, all deposited during the Tertiary period (between about 40 and 10 million years in age in this area). More extensive exposures farther east suggest thicknesses in excess of 3,000 feet.

The Duwamish area bedrock is a part of part of a much larger, regional, bedrock rib which thrusts westward from the Cascade Range and extends, recognizably but somewhat discontinuously, across the entire Puget Lowland (Yount and Gower, 1991; Frizzell and others, 1984). To the east it is locally known as the Newcastle Hills, forming the high ridges of Cougar, Tiger, and Rattlesnake mountains. To the west it is less well exposed, but it does crop out on the south end of Bainbridge Island and again on Gold Mountain. To the south, the bedrock surface descends gradually as much as 2,000 feet below the surface. To the north, the bedrock descends down one of the steepest subsurface escarpments recognized in North America, attaining a depth of over 3,600 feet over a horizontal distance of only a mile or two. This escarpment marks the location of the "Seattle Fault" (Bucknam and others, 1992), the source of a major earthquake about 1,100 years ago that produced about 20 feet of vertical displacement on Bainbridge Island and which has likely been active for many hundreds of thousands of years. A southerly, presumably older and now inactive strand of this fault passes directly through the study area at about the latitude of Boeing Field. It separates younger rocks to the north from older rocks, now uplifted, to the south.

Groundwater flow in the bedrock is not expected to be significant relative to the glacial and alluvial sediments. This unit was assigned a low permeability in the numerical model in recognition of their generally poor water-bearing properties. For example, bedrock data collected during subsurface investigations along the Metro sewer line reported "impervious" and "relatively impervious" conditions within the bedrock encountered in the upper Duwamish basin.

2.2.2 Upland Glacial and Nonglacial Sediments

The topography of the Duwamish area is dominated by an extensive upland plain, mantled by a rolling surface of glacial till deposited during the last occupation of the Puget Lowland by the Vashon stade of the Fraser glaciation, (Armstrong and others, 1965) about 15,000 years ago. Beneath the Vashon deposits is a complex sequence of older unconsolidated sediments that extends far below sea level across most of the study area.

The older sediments are exposed at the modern ground surface where recent erosion has sliced through the glacial till—notably by the Duwamish River itself, and also by wave action along Puget Sound to the west. These older sediments are very compact, having been weighted down by one or more episodes of glaciation subsequent to their deposition. Many are also cemented by oxidation, a consequence of the many tens or hundreds of thousands of years of weathering that they have experienced. This older sequence of deposits is very complex and records the interfingering of two unrelated, but overlapping, geologic phenomena—glacial advances from British Columbia and volcanic eruptions from Mount Rainier—superimposed on the less dramatic, but ongoing, westward transport of sediment out of the Cascade Range by rivers.

The *Conceptual Model Report* compiled existing geologic data to describe the observed sequence of coarse and fine-grained materials overlying the bedrock. These layers were assigned correspondingly high or low permeabilities in the numerical model. One such deposit in particular, the "Highline aquifer" (unit Q(A)c in the *Conceptual Model Report*), is a particularly important regional aquifer for water supply and for the transmission of groundwater across the upland part of the study area.

However, the most extensive of these upland deposits are the youngest, deposited during the most recent regional glacial advance (the Vashon stade of the Fraser glaciation; Armstrong and others, 1965). During this time an ice sheet progressively advanced along the axis of the Lowland from the north (Clague, 1981), reaching its maximum extent about 15,000 yr B.P. and covering the Puget Lowland to a maximum depth of about 5,000 feet (Booth, 1987). Deposits of the Vashon stade have a variety of textural characteristics and topographic expression, owing to rapidly changing depositional environments caused by the advance and retreat of the ice sheet.

- **Glacial silt—**As the ice first advanced, it blocked northward lowland drainage out the Strait of Juan de Fuca, which now connects Puget Sound with the Pacific Ocean. In the impounded lakes that formed in the course of establishing southerly drainage out of the Puget Lowland, laminated silt and clay were deposited. This unit (Qtb on the geologic map) is a regionally significant aquitard, allowing very little movement of groundwater. It is typically found below about 200 feet elevation, in part forming the trough-like boundary for the younger Duwamish Valley sediments that are the focus of this study.
- **Advance outwash—**The initiation of the subsequent Vashon stade is marked by coarser outwash (unit Qva) deposited by streams derived from the advancing ice sheet. Coarse advance outwash at least a few tens of feet thick (and locally as much as 300 feet) underlies the broad uplands on both sides of the Duwamish Valley. Much of the total thickness of the bluffs along Puget Sound, from the city of Des Moines north to Duwamish Head, consists of advance outwash. This deposit is the primary shallow aquifer in the upland areas throughout the region.
- **Glacial till—**As ice covered the region, till (unit Qvt) was deposited by the melt-out of debris at the base of the glacier. This heterogeneous, compact sediment blankets the area to depths of several feet. Where present at the surface till provides a low-permeability cover to underlying aquifers, reducing recharge but also offering protection from surface contaminants. In a few areas it is overlain by younger and more permeable sediment, but the till is still commonly present at relatively shallow depth and so slows groundwater migration and recharge. The layer is nearly continuous across the tops of the upland plateaus of the region but has eroded away on their flanks. It is an important but imperfect barrier to groundwater infiltration into the underlying advance outwash, slowing the migration of any near-surface contaminants, but it is neither completely impervious nor everywhere present.
- **Recessional outwash—**Shortly after 15,000 years ago, the ice margin, which had advanced south of the city of Olympia, began to melt back. Recession of the ice sheet was accompanied by both outwash deposits and ice-dammed lakes, analogous to those formed during the ice advance. Streams draining from the ice sheet into that lake have left channels and more localized patches of gravel and sand (unit Qvr) that form unconfined, perched aquifers above the till.

2.2.3 The Duwamish Valley Alluvium

The near-surface sediments of the Duwamish Valley alluvium are set within the trough of the Duwamish estuary, carved by glacial ice and subsequently infilled by river sediment. The lower boundary of that trough is reached sporadically by deep borings, particularly in the south half of the study area. The pattern of those data indicate that the trough lies roughly two hundred feet below the modern ground surface along the axis of the valley, generally shallowing to the south and also towards the east and west valley walls. The boundary of these deposits is marked either by bedrock (where present to the south) or by the very dense upland glacial and nonglacial sediments that have been glacially overridden.

Above this boundary, the geologic history of the area suggests that a sequence of estuarine deposits, typically fine sands and silts with shells, should be found and should progress up into a more complexly interbedded river-dominated sequence of sand, silt, and gravel marking the advance of the sedimentary wedge fed by the Osceola Mudflow and later deposits. The mudflow itself would have been very thin and subaqueaous along the Duwamish Valley when first deposited, so the chances of intersecting (and recognizing) that layer by drill cores is probably low. The upper part of the river-deposited sediment shows the classic signs of continued slow overbank deposition by fine sand and silt, colonization by marshland plants, and occasional erosion and refilling by coarser sediment associated with the main channel of the migrating Duwamish River.

In the north part of the study area, the modern valley lies as much as a thousand feet or more above the floor of a bedrock trough, probably formed originally at least several million years ago. The trend of this bedrock trough is crudely northward and approximates the trend of the modern Duwamish Valley. Passing to the north, under and north of Harbor Island into Elliott Bay, the trough descends ever more abruptly out to the projected location of the Seattle Fault. Farther south, it continues to shallow until exposures of rock are seen sporadically at the modern ground surface near Boeing.

The post-glacial alluvium of the modern Duwamish River appears to fill an inset, glacial-age valley that is at least 170 feet deep in the center of the modern Duwamish Valley. The western part of that now-infilled glacial valley is walled and floored by silt and clay of the early Vashon “transitional beds” (Qtb), equivalent to the deposits commonly called “Lawton Clay” and recognized throughout the north Seattle area. There is no explicit data for the eastern part of the glacial valley, but near-sea-level exposures along the eastern wall of the Duwamish Valley suggest that the same silty deposits are present here as well.

The southern region is marked by a narrow infilled valley of sediments bounded on both sides by bedrock. The valley sediments range in thickness from a few tens of feet to about 200 feet. The common outcrops of bedrock in this area and the detailed investigations completed in the west upland and in the valley provide valuable data on the regional stratigraphy.

Within the valley alluvium, the following units were distinguished for purposes of numerical modeling:

- **Younger Alluvium—**The younger alluvium is identified by wood and organics in a silt and sand matrix. It is commonly identified as a clayey silt and organic silt, but it also includes sandy silts and silty sands with abundant organics. In the south, the younger alluvium typically occurs within the upper 15 to 20 feet of ground surface; in the north, however, the base of this unit deepens to perhaps elevation -100 feet, although the discrimination between "younger" and "older" alluvium becomes somewhat more arbitrary and less distinct in the tidally dominated, deltaic environment of the river's mouth. For modeling purposes this unit also includes variable thicknesses of overlying fill, which is likely to have similar (although locally quite variable) hydrologic properties.
- **Older Alluvium—**The younger alluvium grades downward into a coarser, predominately sandy alluvium, still containing silt but in smaller quantities. This deposit contains less organic material and is typically a fine to medium sand. In the south, the older alluvium is typically between 10 and 30 feet thick, occurring to an elevation of roughly -30 feet. In the center of the valley, it extends to depths of about 100 feet, becoming generally finer with increasing depth. Typically, the upper two-thirds are sand and silty sand; the lower third is more commonly described as sandy silt. In the north, however, the medium dense to dense sand of the older alluvium is significantly thinner and locally absent altogether, underlain by dense clay and silt. The northern area represents the farthest extent of the deltaic deposits into the marine environment and therefore has finest grained material of the alluvial sequence.

- **Glacially overridden sediments—**Glacially overridden deposits, particularly glacial silts, tend to form the north-descending base of the of alluvial sediments, lying only a few tens of feet below the surface in the south but as much as 200 feet deep in the north.

2.3 Regional Recharge and Discharge

Regional recharge and discharge relationships reflect the role of groundwater flow patterns within the hydrologic cycle. Recharge occurs where precipitation is able to infiltrate the ground surface and move downward to the water table. Once in the groundwater system the water moves from areas of higher groundwater elevation to areas of lower groundwater elevation through the more permeable materials, and ultimately discharges to surface water. In broad terms, water moves from areas of recharge to areas of discharge. Groundwater moves primarily through sands, gravels, and fractured bedrock. Very little groundwater moves through silts, clays, and unfractured bedrock.

The Duwamish Valley, by nature of its low elevation and surface water outlet, is a regional discharge area. The surrounding uplands, by virtue of their higher elevation, are recharge areas. A recharge area is indicated where there is a downward component to the groundwater flow, expressed by a downward vertical gradient in water levels in adjacent wells completed at different depths. Conversely, upward gradients are indicative of discharge areas.

2.3.1 Recharge Rates Estimates

Recharge rates will vary locally based on precipitation, geology and the characteristic surficial soils that develop, and the amount and density of land development. In areas where there is substantial till and silts, and where the land is highly paved, much of the precipitation is lost as runoff. In areas where the till has eroded away, and the more-permeable advance outwash occurs at the surface, greater infiltration is likely to occur.

The USGS estimated rates for the west upland area as part of a water-budget modeling analysis performed for the South King County Ground Water Management project (Woodward et al., 1995). Recharge rate estimates ranged from between 0 and 5 inches per year, in the heavily developed areas of the central west Seattle peninsula, to between 10 and 15 inches per year in the outer portions of the west upland area. In some areas where land development is sparse and glacial outwash lies at the ground surface, the report indicated annual recharge to be as much as 15 to 20 inches.

Recharge rates in the east upland are likely to be similar to the lower recharge rates (0 to 10 inches annually) estimated for the west upland area. The east upland is highly developed and has a substantial amount of bedrock and silt at ground surface. Likewise, recharge rates in the valley are also expected to be similar to the lower range estimated for the West Seattle upland area and the lower Green River valley. Large-scale industrial development is likely to limit recharge to rates less than 10 inches throughout most of the valley. To better estimate local recharge and runoff conditions more detailed land use and soils review could be performed in these areas, but any improvement in local characterization of this parameter will have minimal influence on overall groundwater flow patterns.

3. FLOW MODEL CONSTRUCTION

The primary tasks involved in developing the Duwamish groundwater flow model are 1) identifying a suitable computer code; 2) selecting the vertical and horizontal extent of the model domain; 3) constructing a finite difference grid for the model domain; 4) overlaying the hydrostratigraphy onto the finite difference grid; 5) assigning boundary conditions to simulate the Duwamish Waterway, Puget Sound, and Lake Washington; and 6) specifying hydraulic conductivity values for each stratigraphic unit or layer. The following sections describe each of these tasks in more detail below.

3.1 Code Selection and Description

The computer program selected for the Duwamish numerical model is MODFLOW. MODFLOW is a publicly available groundwater flow simulation program developed by the U.S. Geological Survey (McDonald and Harbaugh, 1988). It is well-documented and widely used by consultants, government agencies, and researchers and is consistently accepted in regulatory and legal proceedings. MODFLOW can simulate transient or steady-state saturated groundwater flow in three dimensions. It offers a variety of boundary conditions, including specified head, areal recharge, evapotranspiration, drains, rivers, and streams. Aquifers units may be confined or unconfined, or treated as convertible between confined and unconfined states. The three-dimensional capabilities and versatility in boundary conditions offered by MODFLOW are necessary to simulate groundwater flow in the Duwamish basin due to the relatively complex stratigraphy, topography, and boundary conditions of the model domain.

The average flow conditions in the Duwamish basin were simulated by MODFLOW using the steady-state option. The model does not include temporal variations caused by tidal fluctuations or seasonal variability. The limitations introduced by this steady-state assumption are discussed in the section on sensitivity and uncertainty assessment.

MODFLOW uses a numerical approximation technique known as the finite difference method. This method discretizes the flow field into a set of blocks or cells. It assumes that hydrogeologic properties within each block are homogeneous or uniform. The model output includes estimates of hydraulic head and groundwater velocity for each cell in the model. These values represent spatial average of the model results over the volume of the cell. The resolution and the degree of spatial heterogeneity included in the model depend upon the number of cells used to discretize the flow field.

The discretization process ultimately results in a system of simultaneous linear algebraic equations. MODFLOW includes several techniques for solving this set of algebraic equations. For this model, the strongly implicit procedure (SIP) was the most stable and accurate technique for solving the system of equations.

3.2 Model Discretization

The three-dimensional grid representing the Duwamish basin covers approximately 60 square miles. Figure 2 illustrates the model grid in plan view. Additionally it shows that the ***model domain*** in MODFLOW exceeds the ***study area*** defined in the *Conceptual Model Report*. This extension enables the more natural definition of boundary conditions. The design of the boundary conditions in the model domain attempts to coincide with natural hydrogeologic boundaries as much as possible in order to minimize the influence of model boundaries on simulation results.

The model domain spans approximately 9 miles in the north-south direction and 7 miles in the east-west direction. The finite difference grid consists of 78 columns, 94 rows, and 10 vertical layers for a total of 73,320 cells. Each cell has horizontal dimensions of 500 feet by 500 feet. Cells in the lower eight layers of the grid typically have a vertical thickness of 25 feet. These lower eight layers extend from elevation –200 feet to sea level (elevation 0). The cells in the top two layers, which extend from sea level to the ground surface, have variable thickness and incorporate subsurface and surface topography. King County Water and Land Resources Division provided the surface topography for the model domain shown in Figure 2.

3.3. Incorporating Hydrostratigraphy

The hydrostratigraphy used in the Duwamish model is based on the boring log data and geologic cross sections included in the *Conceptual Model Report* (Booth and Herman, 1998). The model defines six stratigraphic units for purposes of numerical modeling: 1) bedrock, 2) glacial silt, 3) older alluvium, 4) younger alluvium, 5) Vashon glacial deposits, and 6) coarse-grained deposits of the next-oldest unit, Q(A)c.

Interpolation between points with known and estimated stratigraphic information generated the estimated spatial distribution of the stratigraphic units. Sources for the locations of known points include bore logs (Appendix B of the *Conceptual Model Report)* and the analysis of surficial geology (Figure 1) combined with surface elevation information (Figure 2). The interpreted geologic cross-sections presented in the *Conceptual Model Report* allowed generation of additional estimated points by correlating known plan-view locations with the best estimate of the elevation of the stratigraphic units. Additionally, a regional study (Jones, 1996) provided additional points for bedrock stratigraphy where no other data were available. Approximately 75 bore logs, 40 estimated points, 40 regional estimated bedrock points, and over 500 surface elevation points contributed to the stratigraphic interpolation process.

Figure 3 shows the resulting generalized surface geology for the model, including the assumed projection of the (subsurface) Q(A)c aquifer. This aquifer resides in layer 3 of the model grid, occupying the elevation band –25 feet to sea level. Data describing the extent and distribution of the Q(A)c aquifer are particularly sparse beneath the west uplands in the central part of the model domain. There are no data that confirm the presence or absence of this deposit in the region between rows 57 and 24 (Figure 3). Because of potential concerns related to the impact of groundwater extraction in the Highline aquifer (the local name for this unit) on flows to or from the Duwamish Waterway, the model includes the Q(A)c deposits in this region as a conservative assumption. Section 5 explores sensitivity of model predictions to the assumed distribution of the Q(A)c aquifer.

Figure 4 shows a sample cross section. The cross sections are ideally discretized versions of the cross sections presented in the *Conceptual Model Report*. The cross section illustrated in Figure 4 corresponds to row 57 in the model grid, which is identified, on Figure 3. The right (or east) end of this section shows a relatively thick sequence of glacial sediments overlying bedrock. Sections north and south of this row, however, would display the bedrock that outcrops along the eastern upland in these areas.

3.4 Boundary Conditions

The model domain includes six major types of boundary conditions: 1) the Duwamish Waterway, 2) Elliott Bay, 3) Puget Sound, 4) Lake Washington, 5) no-flow boundaries representing topographic divides or flow lines, and 6) groundwater seeps (termed “drains” in MODFLOW). Figure 2 shows the locations of these boundaries.

The model treats the Duwamish Waterway as a constant head boundary. The water level in the river ranges from approximately 7 feet at the upstream edge of the model to sea level at Elliott Bay. These levels are based on data provided by King County Water and Land Resources Division.

Elliott Bay and Puget Sound exist as no-flow boundaries in order to simulate the effects of the interface between salt water and (less dense) fresh water. Groundwater discharges along these boundaries through seeps (described below) in the vicinity of the shorelines.

The model represents Lake Washington as a uniform, constant head boundary. It assumes a water head elevation equal to +10 feet based on data provided by King County Water and Land Resources Division. Additionally, the lake is assumed to be at least 200 feet deep with sides having a vertical to horizontal slope of at least 2:5, causing the lake to penetrate the full depth of the model grid across the width of a single, 500-foot wide cell.

The no-flow boundary along the southern edge of the model domain represents a groundwater divide. Groundwater in this area flows to the south and discharges at locations outside of the model domain. This boundary is in a location that will not significantly affect groundwater flow within the actual study area under natural flow conditions. The location of the groundwater divide, and therefore the no-flow boundary, might change if groundwater extraction wells are added in this area.

Groundwater seeps (called “drains” in MODFLOW) exist at locations were the water table has the potential to intersect the ground surface. For cells intercepted by the ground surface, the computer model calculates the water levels for each of the cells. If the water levels or hydraulic heads are greater than the elevation of the ground surface, it allows water to leave the cell at a rate that depends upon the hydraulic conductivity at that particular location. Although this approach increases the computational effort needed for developing a solution, it is a relatively common method for incorporating areas of groundwater discharge.

3.5 Hydraulic Parameters

The model requires two principal hydraulic parameters as input, the hydraulic conductivity of the various stratigraphic units and the infiltration rate. The infiltration rate is equal to precipitation minus surface runoff and evapotranspiration. Local infiltration rates depend upon topography, vegetation, and land use. Data describing spatial distributions of these variables were not readily available for the scale of the model grid. Impermeable surfaces, which reduce infiltration, would likely be more prevalent in the valley whereas steep slopes and vegetation, which also reduce infiltration, are more prevalent in the uplands. Uniform infiltration is a reasonable approximation given the spatial distribution of topography and land use. The limitations introduced by this assumption are discussed in the section on sensitivity and uncertainty assessment.

This model assumes the application of a uniform infiltration rate of 10 inches per year to each cell that is located at the ground surface, except for cells that represent bedrock outcrops. Bedrock has a very low hydraulic conductivity relative to the unconsolidated deposits, and so the model assumes no infiltration at all such cells.

General material types provided the basis for the estimates of hydraulic conductivity values. There were no data of sufficient quantity or quality to allow estimates based on interpolations from measured values. Literature for similar material types (e.g. Freeze and Cherry, 1979) provided order-of-magnitude estimates of the hydraulic conductivity. Table 1 summarizes the initial estimates for each of the 6 stratigraphic units described in Section 3.3, including the range of values typical for each geologic material type.

MODFLOW requires "drain conductance" values for each cell that represents a potential groundwater seep. These conductance values control the rate of seepage at locations where the groundwater table intersects the ground surface. This model calculated the drain conductance values at each individual cell by multiplying the hydraulic conductivity of the cell by the assumed length and width of the groundwater seep. Seeps were assumed to be 5 feet running the full length of the cell, which is 500 feet.

Table 1. Initial estimates and calibrated values for hydraulic conductivity.

	INITIAL RANGE	CALIBRATED VALUE
1) Bedrock	<1 x 10^{-7} cm/s	Impermeable
2) Glacial silt		
a. Western slope	10^{-4} to 10^{-3}	2 x 10^{-4} cm/s
b. Eastern slope	10^{-4} to 10^{-3}	7 x 10^{-4}
3) Older alluvium		
a. Upstream	10^{-3} to 10^{-2}	5 x 10^{-3}
b. Central	10^{-3} to 10^{-2}	1 x 10^{-2}
c. Downstream	10^{-3} to 10^{-2}	1 x 10^{-3}
4) Younger alluvium	10^{-3} to 10^{-2}	1 x 10^{-2}
5) Vashon deposits(Qva, Qvt)		
a. Western slope	10^{-3} to 10^{-2}	1 x 10^{-2}
b. Eastern slope	10^{-3} to 10^{-2}	1 x 10^{-2}
6) Highline aquifer (Q(A)c)	10^{-3} to 10^{-2}	1 x 10^{-3}

3.6 Model Calibration

Model calibration involves adjusting model parameters to obtain a reasonable match between observed and simulated output variables. The adjustable input variables are termed *calibration parameters* and the output variables that are compared to observed data are termed *calibration targets*. Water levels are the most typical calibration targets, although hydraulic head gradients, groundwater flow rates, or discharge volumes can also be useful. Potential calibration parameters for the Duwamish Waterway model are the infiltration rates and hydraulic conductivity values. The calibration focused on hydraulic conductivity values, based on the judgement that uncertainties in the infiltration rate were small relative to uncertainties in hydraulic conductivity.

The model calibration used an iterative process that begins with a relatively broad range of possible hydraulic conductivity values. This range, given in Table 1, is derived from a combination of qualitative information and limited field data. The method narrows the range of values by running the model, comparing predicted and observed water levels, and then adjusting the hydraulic conductivity based on this comparison.

The development of the calibrated parameters followed the principle of parameter parsimony. This principle, which means that the simplest model is preferred, is based on the goal of seeking an adequate calibration of a model with the fewest number of model parameters. Using large numbers of model parameters may allow a better "fit" between observed and calculated values, but it also often creates a non-unique situation where many combinations of parameter values produce equivalent calibration results. For the Duwamish Waterway model, parameter parsimony corresponds to using as few material types or hydraulic conductivity values as possible. This reduces the risk of non-uniqueness and results in a more reliable model.

The comparison between observed and predicted water levels can include quantitative or qualitative measures. Quantitative measures involve calculating differences in observed and predicted water levels at discrete points within the model domain. Observed water levels were available from approximately 140 wells (Booth and Herman, 1998, Appendix B).

The effects of tidal fluctuations, however, complicate the comparison of predicted and observed values in a quantitative way, especially in areas immediately adjacent to the Duwamish Waterway, Elliott Bay, and Puget Sound. The groundwater model calculates steady-state or average water levels while the field measurements represent "snap-shots" that give water levels at discrete points in time. For example, some of the water level data reported in the *Conceptual Model Report* indicated water levels below mean sea level. These data were apparently collected during low-tide periods. The model calculated all water levels to be not less than sea level because the lowest water-elevation boundary condition the model domain is mean sea level. This lowest elevation occurs where the Duwamish Waterway discharges to Elliott Bay.

The effects of spatial averaging are also important. The field measurements represent water levels averaged over the length and diameter of the monitoring well screen (typically 5 to 10 feet and 2 inches, respectively), while the model output represents water levels averaged over the volume of the cell (typically 500 feet by 500 feet by 25 feet).

Because of the issues associated with a relatively sparse data set and the effects of spatial and temporal averaging, the calibration process included qualitative information related to groundwater levels. This qualitative information includes the inferred water level contours and hydraulic gradients from the *Conceptual Model Report* (Booth and Herman, 1998), particularly illustrated in Plate 6 of that report.

Figure 5 shows the water levels and groundwater flow directions that result from the final, calibrated set of conductivity values. The water level contours represent the head value in the highest active layer for each column of cells in the model; the flow directions are displayed for layer number 3. The lower face of this layer corresponds to elevation –25 feet, and the top face resides at sea level in the west hillside and 5 feet above bedrock in the east valley slopes. Although the actual flow directions may be different for other layers in the model, the general pattern shown in Figure 5 is consistent with the water-level patterns and flow directions throughout the model domain.

Additionally, Figure 5 includes observed water levels from the *Conceptual Model Report* (Booth and Herman, 1998). It should be noted these observed levels were measured in wells completed at a variety of depths, depending upon the location of the well screen.

The pattern of model predicted water level contours shown in Figure 5 is qualitatively similar to the inferred water levels in the *Conceptual Model Report* (Booth and Herman, 1998). The water levels along the western slopes are in the general range of 230 to 330 feet and the levels in the Central Valley are 10 to 20 feet above the river level. The horizontal head gradients in the Central Valley, which are in the range of 0.001 to 0.01, are also consistent with the head gradients described in the *Conceptual Model Report*. There is an area with relatively flat gradients and low groundwater flow between the waterway and the bedrock outcrop in the central valley. This correlates reasonably well with the high-salinity area identified on Figure 6 in the *Conceptual Model Report*. Low rates of groundwater flow in this area may explain the observed brackish water quality.

4. MODEL ANALYSIS

The three-dimensional model described in Section 3 can be used to evaluate the groundwater flow budget for the model domain and the directions and rates of groundwater flow in the vicinity of the Duwamish Waterway. The flow budget describes how much water leaves the groundwater system through groundwater seeps and through direct discharge to surface water bodies. Groundwater pathlines show how groundwater moves from the uplands to the valley, eventually discharging at groundwater seeps or in the Duwamish Waterway.

4.1 Water Budgets

Annual precipitation in the Duwamish Basin is approximately 40 inches per year. Surface runoff and evapotranspiration account for approximately 10 and 20 inches per year, respectively (Woodward et al., 1995). This leaves approximately 10 inches per year for groundwater infiltration. Essentially all groundwater in the Duwamish Waterway model results from this infiltration.

Groundwater exits the modeled region in one of four ways, as summarized in Figure 6. Approximately 11% of the groundwater discharges directly to Lake Washington. This groundwater, which enters the lake through off-shore sediments on the lake bottom, originated as infiltration within the model domain but outside of the study area defined in the *Conceptual Model Report*. An additional 24% of the groundwater volume discharges to groundwater seeps that eventually drain into Puget Sound, Elliott Bay, or Lake Washington. This, too, originated as infiltration in areas outside the study area. The remaining 65% of the groundwater included in the model domain discharge reaches the Duwamish Waterway. The model calculates that about half of this fraction discharges directly from the groundwater system to the Waterway. This water enters the Waterway along the sides and bottom of the channel. The other half discharges to groundwater seeps that eventually drain into the Waterway via surface, piped or channeled flow.

Table 2 lists the total volumes of groundwater discharge. As indicated in this table, the total groundwater outflow equals the total infiltration. The mass balance error (the degree to which the sum of inputs do *not* equal the sum of outputs, useful as one measure of model validation) is less than 1% for the Duwamish Waterway model with the calibrated model parameters. The model predicts that the groundwater within the model domain contributes approximately 20 cubic feet per second (cfs) to flow in the Duwamish Waterway. Approximately one-half of this amount (10 cfs) is due to direct groundwater discharge to the Duwamish Waterway. The remaining one-half (10 cfs) derives from groundwater that first discharges to seeps and then reaches the Duwamish Waterway via surface, piped or channeled flow. The total groundwater discharge to the Waterway within the study area represents no more than 10 percent (based on annual average values), and more likely about 5 percent, of the minimum summertime flow in the Duwamish Waterway (USGS Water-Data Reports WA-92-1 through WA-96-1, 1992-1996).

4.2 Groundwater Flow Directions

The groundwater velocity vectors shown in Figure 5 give the general flow directions in plan view. Locations where the flow arrows diverge represent groundwater divides. These divides appear in the south-eastern, north-central, and south-western parts of the model domain. These groundwater divides essentially lie along the edges of the study area defined in the *Conceptual Model Report*. The divide along the southeastern part of the study area separates areas that contribute groundwater to Puget Sound from areas that contribute groundwater to the Duwamish Waterway. The north-central and southwestern divides separate areas that contribute groundwater to Lake Washington from areas that contribute to the Duwamish Waterway.

Although there are localized areas in which flow is diverted around bedrock outcrops, the general flow direction within the study area is toward the Duwamish Waterway. The flow arrows converge on the waterway, which then transmits the flow to Elliott Bay. Other combinations of hydraulic conductivity values explored during model calibration and preliminary sensitivity analysis result in similar flow directions. For example, lower conductivity values result in higher water levels and higher head gradients, but the flow directions remain fairly consistent.

The flow vectors shown in Figure 5 also distinguish groundwater discharge areas from groundwater recharge areas. The red arrows indicate downward flow directions, which correspond to groundwater recharge areas. These occur primarily in the uplands. The blue arrows show upward groundwater flow and identify groundwater discharge areas. There are two main discharge areas in the vicinity of the Duwamish Waterway: along seeps at the base of the uplands and at the waterway itself. The discharge areas where the valley meets the uplands represent groundwater seeps. The discharge areas at the waterway generally represent locations were groundwater discharges directly into the channel.

It should be noted that the flow vectors in Figure 5 describe flow in layer 3, which corresponds to elevation –25 feet to sea level or 5 feet above bedrock, whichever is higher. The vertical cross sections shown in Figures 7 through 9 identify groundwater flow direction in all layers for three east-west sections, located on Figure 3. These cross sections illustrate typical flow directions in the northern, central, and southern portions of the model domain. The cross section in Figure 7 shows flow directions along row 24 in the northern quarter of the flow field, where row 1 corresponds to the northern edge of the model domain and row 92 corresponds to the southern edge of the area. The cross section in Figure 8 corresponds to row 57 in the model grid, which is located in the middle part of the flow field and the section in Figure 9 corresponds to row 72 in the southern part of the flow field. The flow lines shown in Figures 7 through 9 describe the pathways followed by groundwater that originate in the top layer of the model. These figures also show flow lines in plan-view in the vicinity of the cross sections. Inclusion of these plan views emphasizes that the flow paths are three-dimensional and that the cross sections represent two-dimensional "slices" that do not show all horizontal components of flow.

The flow patterns for the cross section in Figure 7 show relatively complex pathways for flow lines that originate along the western uplands. This complexity is primarily due to topography. The flow lines are relatively shallow along the western edge of the uplands and then drop beneath the ridge east of Longfellow Creek before discharging to seeps or the waterway. The flow lines along the eastern part of the valley are shallow and also discharge to the waterway.

The cross section along row 57 (Figure 8) shows the groundwater divides along the western and eastern sides of the model domain. The flow lines on the western side terminate in Puget Sound and flow lines on the eastern side end in Lake Washington. The flow lines that originate along the top of the western uplands penetrate relatively deeply into the flow system. The deepest flow line shown on this section drops to elevation –150 before it bends upward and ultimately discharges along the contact between the uplands and the valley sediments. Infiltration along the flanks of the western uplands follows a much shallower pathway. It also discharges to seeps along the lower parts of the uplands. Infiltration along the western part of the valley floor stays relatively shallow and discharges directly to the Duwamish Waterway.

Flow lines that originate along the eastern uplands along row 57 also penetrate relatively deeply into the flow system before reaching the bedrock contact. Most of these flow lines discharge directly to the waterway. Flow lines that originate along the eastern part of the valley floor also flow downward before eventually discharging to the waterway. It should be noted that flow directions within the valley are relatively complex, and depend upon location and depth. At specific locations, the flow may be downward at some depths and upward at other depths. The ultimate discharge location, however, is the Duwamish waterway or seeps that eventually drain to the waterway.

Figure 9 shows flow lines along a cross section in the southern part of the flow field. The flow pattern along this section is similar the patterns shown in Figure 8 in that there are groundwater divides on each uplands and in that the flow lines beginning in the central part of the western uplands penetrate relatively deeply before discharging into the Waterway. One difference, however, is that groundwater discharge from the eastern uplands is low because of the bedrock outcrops.

Figure 10 shows the location and magnitude of groundwater seeps. Within the model domain, these seeps occur along Longfellow Creek (under the northwest corner of the map, trending north-south) and along the contact between the uplands and the valley sediments. The discharge rates for these seeps are highest along the western edge of the of the valley sediments in the central and southern parts of the flow field. This is generally consistent with the potential upland discharge zones identified in the Conceptual Model Report. The total discharge to these seeps within the Duwamish drainage basin is approximately 10 cfs, or 30% of the infiltration to the basin (Table 2 and Figure 6).

Table 2. Groundwater discharge estimated with the calibrated model
(all values are cubic feet per second. Percentages are given as a fraction of the total infiltration.)

TOTAL INFILTRATION:	**30 cfs**
Direct groundwater discharge to Lake Washington	3.2 (11%)
Groundwater discharge to seeps that eventually reach Puget Sound, Elliot Bay or Lake Washington	7.2 (24%)
Direct groundwater discharge to the Duwamish Waterway	9.4 (32%)
Groundwater discharge to seeps that eventually reach the Duwamish Waterway	10.1 (33%)
Total groundwater discharge	**30.0 (100%)**

Figure 11 shows the cumulative groundwater discharge to the Duwamish Waterway. The lower curve in this figure represents direct discharge from groundwater to the Waterway while the upper curve represents direct discharge plus discharge from drains. These curves show relatively low discharge between river miles 8 and 12. The steep portions of the upper curve represent areas with high rates of discharge to seeps. This occurs most prominently between miles 1 and 2 and miles 4 and 5. Finally, Figure 12 identifies the groundwater and surface water tributary areas within the model domain. The surface water tributary area represents the areas that contribute surface water to the Duwamish Waterway based on surface topology. Precipitation that falls within the surface water tributary area generates surface runoff that eventually reaches the waterway. The groundwater tributary is predicted by the model itself. Infiltration that occurs within the groundwater tributary area eventually reaches the waterway through groundwater discharge to seeps or directly to the channel of the waterway.

These tributary areas constitute approximately 50% of the model domain. Surface water and groundwater that originate from precipitation falling outside these areas eventually discharge to Puget Sound, Elliott Bay, or Lake Washington.

5. UNCERTAINTY AND SENSITIVITY ASSESSMENT

5.1. Types of Uncertainty in the Duwamish Model.

The sources of uncertainty in the Duwamish model originate from four general sources, as summarized below.

5.1.1 Process Uncertainty

Process uncertainty relates to the correctness of the mathematical expressions used by the model to represent the physical processes that occur in the field. The Duwamish model describes groundwater flow, not solute or contaminant transport. The physical processes governing groundwater flow are well-understood and reliable mathematical expressions have been developed to describe these processes. In relative terms, process uncertainty is not significant for the Duwamish groundwater model.

5.1.2 Geological Uncertainty

Geological uncertainty relates to the degree to which the stratigraphy assumed in the model adequately represents the geology in the Duwamish basin. This type of uncertainty is largely geometric. The development of the model assumes a finite number of geologic layers with known thickness and extent. In practice, the number, thickness, and extent of the layers are generally uncertain. Although there are selected regions within the Duwamish model that contain relatively high densities of boreholes, other regions have relatively few boreholes and therefore have significant geological uncertainty.

There is considerable uncertainty regarding the stratigraphy within the valley sediments. The model divides these sediments into two broad categories: older alluvium and younger alluvium (including fill materials). Furthermore, the model divides the older alluvium into three subsections corresponding to upstream, central, and downstream areas. In the downstream part of the valley the older alluvium is assumed to be about an order of magnitude less permeable than the younger alluvium. The location of the contact between these two units, which is generally unknown, will significantly affect local flow directions. The overall water budget in terms of the amount of water that reaches the waterway, however, will not be significantly affected by the location of this contact.

5.1.3 Parameter Uncertainty

Parameter uncertainty describes the certainty of the known range of values for the geologic parameters used in the model. The parameters in this steady-state model are hydraulic conductivity and recharge rates. There is generally considerable uncertainty associated with the hydraulic conductivity parameters, especially for individual cells. The values assigned to a specific cell could very likely differ by one to two orders-of-magnitude from values that would be measured in the field. The uncertainties associated with these local values for hydraulic conductivity cause uncertainties in the local flow directions and magnitudes.

The assigned hydraulic conductivity values on a larger scale will have much less uncertainty than the local values. For example, the "average" hydraulic conductivity assigned to the glacial silt in the western part of the flow field was 2×10^{-4} cm/s, as shown in Table 1. It is relatively unlikely that the actual average value in the field differs by more than an order of magnitude from this estimate. For example, calibration results show that for a value of 2×10^{-5} cm/s, the calculated water levels are much higher than observed water levels. Similarly, for a value of 2×10^{-3} cm/s, results in water levels in the uplands that are much lower than observed values.

This assertion, that regional averages are relatively certain, would be in error if the infiltration estimate of 10 inches per year is itself in error. If infiltration is reduced by an order of magnitude (to one inch per year) then hydraulic conductivity values would also need to be reduced by a similar magnitude to maintain predicted water levels similar to observed values. It is doubtful that errors in recharge would be of this magnitude, however, at least at a basin-wide level.

5.1.4 Boundary Condition Uncertainty.

Boundary condition uncertainty describes uncertainties in the imposed characterization hydrogeologic conditions along the boundary of the model. A conscientious effort was made in developing the Duwamish model to avoid imposing boundary conditions unless these conditions were relatively certain based on topographic, geologic, or hydrologic information. This is reason that the model domain is nearly twice as large as the study area defined in the *Conceptual Model Report*. The groundwater divides in the southwestern, north-central, and southeastern parts of the study area were not imposed on the model but instead were calculated based on estimated recharge rates and hydraulic conductivity values.

The most important source of boundary condition uncertainty arises from treating the Duwamish Waterway as a constant head boundary. The proportion of groundwater that discharges directly to this boundary is dependent upon the head value assigned to the waterway and/or the hydraulic conductivity values for the sediments in the vicinity of the waterway. The effect of uncertainties is large relative to the uncertainties in water levels and hydraulic conductivity.

Also, the model does not include tidal effects in the boundary conditions. Water levels are based on average or mean sea level conditions. Tidal fluctuations will propagate upstream in the waterway and will cause short-term flow reversals in the immediate vicinity of the waterway, as discussed in the *Conceptual Model Report*. In terms of annual averages, however, data reviewed for the *Conceptual Model Report* demonstrate that these tidal affects will not be large.

An additional source of boundary condition uncertainty in the Duwamish model is due to uncertainties in the location and the effects of the saltwater wedges in the vicinity of Puget Sound and Elliot Bay. The model treats the saltwater-freshwater interfaces as no-flow boundaries and assumes that groundwater discharges to Puget Sound and Elliot Bay occur at seeps near the shoreline. Changing the location of these interfaces may cause some changes in the locations of the groundwater divide in the southeastern part of the flow field. It is doubtful that these changes would significantly affect the overall water budget, however, in terms of the 30 cfs that the model predicts for discharge to the waterway.

5.2 Quantifying the Effects of Uncertainty in the Duwamish Model

The three principal sources of uncertainty in the Duwamish model are geological uncertainty, parameter uncertainty, and boundary condition uncertainty. Two steps are required to quantify how these uncertainties in model input translate into uncertainties in model output. The first step involves quantifying the magnitude of uncertainty in the input variables. For the parameter uncertainty, this involves estimating the likely range of hydraulic conductivity values for the various geologic strata and estimating the range of recharge or infiltration rates. For geological uncertainty, this includes varying the thickness and lateral extent of the individual layers used to describe stratigraphy. Quantifying input uncertainty can be done on a purely statistical basis if sufficient data are available or it can be based, somewhat subjectively, on a combination of professional judgement and statistical data. The relative sparseness of data regarding the

Duwamish basin, especially related to hydrogeologic parameters, will make the professional judgement approach more feasible than the purely statistical approach.

The second step in quantifying the effects of uncertainty involves evaluating the degree to which the model output will change for a given change in model input. Model output includes water levels in the various layers used to describe the stratigraphy, groundwater velocities within these various layers, and groundwater discharge to the Duwamish River. Methods that have been used to estimate these sensitivities include perturbation methods and Monte Carlo methods. The model itself can also be used to estimate the sensitivity coefficients by simply changing the input variables by a fixed amount and observing the magnitude of the change in the output variables. This approach proves most appropriate for the Duwamish model.

Table 3 summarizes the results of the sensitivity studies. The sensitivities are compared based upon the flow budget. These budgets integrate the flows throughout the model domain and describe in a general but concise way the distribution of flows to the Waterway, seeps, Lake Washington, and Puget Sound.

The sensitivity studies indicate that most important input parameters affecting the water budget are the infiltration rate and the hydraulic conductivity of the seeps. The infiltration rate governs the total volume of water that enters the flow field and the distribution of this volume. For example, a 30% reduction in the infiltration rate causes the percentage of discharge to the Waterway to increase from 32% to 36% while the percentage of discharge that reaches the Waterway through seeps decreases from 34% to 30%.

The conductivity of the drains control the amount of water that leaves the site through seeps versus direct discharge to the Waterway. Doubling the drain conductivity has relatively little effect on the total discharge to the Waterway (19 cfs versus 19.5 cfs in the base case), but it does change the amount of direct discharge from groundwater to the Waterway. In the base case, 32% of the model discharge is directly to the Duwamish Waterway. Doubling the drain conductivity causes this to decrease to 27%. In a similar manner, reducing the drain conductivity by a factor of 2 causes the direct discharge to increase to 36%. Changing the drain conductivity also changes the distribution of hydraulic heads within the flow domain. The predicted water levels for simulations with larger and smaller drain conductivity do not match the observed water levels as well as the base-case simulation.

The distribution and hydraulic conductivity of the glacial silt affect the location of the groundwater divides shown in Figures 5 and 7. The location of these divides in turn controls the size and shape of the groundwater tributary areas shown in Figure 9. Increasing the conductivity for the glacial silt in the western uplands tends to shift the groundwater divide farther to the east, causing a larger proportion of the groundwater in model domain to flow towards Puget Sound. Increasing hydraulic conductivity by a factor of 2 result in shifts on the order of several cells. These changes are considered relatively small in terms of their effect on the overall water budget.

The effect of the Q(a)c deposit is also shown in Table 3. Decreasing the Q(a)c conductivity to $2x10^{-4}$ cm/s is equivalent to removing this deposit from the model (the conductivity of the glacial silt is also equal to $2x10^{-4}$ cm/s). This change has essentially no effect on the predicted discharges to the Waterway.

It should be noted that the changes described in the previous paragraphs are, in many ways, of second-order importance compared to the overall flow system predicted by the model. Parameter values and stratigraphic units can be modified over a wide range of likely values and the model still shows the same basic behavior of the calibrated model. This basic behavior includes groundwater divides along the upland ridges, downward gradients in the uplands, seeps along the valley edges, and predominately upward gradients in the vicinity of the Duwamish Waterway.

Table 3. Results of sensitivity analysis

	Total Model Discharge		**Percent of Total Model Discharge**			
	Flow to Waterway (cfs)	Flow *not* to Waterway (cfs)	Flow to Waterway		Flow *not* to Waterway	
Simulation			% GW	% Seeps	% GW to LW	% Seep
Base Case	**19.5**	**10.4**	**32%**	**34%**	**11%**	**24%**
Decrease Recharge to 7 in/yr	13.8	7.2	36%	30%	12%	22%
Double Drain Conductivity	19.0	10.9	27%	37%	10%	27%
Half Drain Conductivity	19.8	10.1	36%	31%	12%	22%
Decrease Qva/Qvt to 5×10^{-3} cm/s	19.6	10.3	32%	34%	11%	24%
Increase Glacial Silt by Factor of 2	19.6	10.3	34%	31%	11%	23%
Young Alluvium 5×10^{-3} cm/s	19.4	10.5	31%	34%	11%	24%
Decrease Q(a)c to 2×10^{-4} cm/s	19.4	10.5	31%	33%	11%	24%
Increase Q(a)c to 5×10^{-3} cm/s	20.1	9.8	32%	35%	11%	22%

5.3 Range and Types of Decisions Using Comprehensive yet Imperfect Data

The output from the Duwamish model can be divided, in very broad terms, into two categories: output associated with point values and output associated with average values. Point values include water levels, hydraulic heads, and groundwater velocities at specific points in the flow field. Average values include the rate of groundwater discharge or recharge along reaches of the Duwamish Waterway or to groundwater seeps.

Because of the relatively large uncertainties associated the spatial distribution of hydraulic conductivity, there are large uncertainties in the output associated with individual point values. For example, there is considerable uncertainty associated with estimates of the magnitude and direction of groundwater flow at a specific location within the model domain. Locally, the magnitudes may easily be incorrect by a factor of ten or more and the flow directions easily be wrong by 90 degrees. However, for the average of these velocities over relatively large areas, such as along a segment of the river, the uncertainty in the averages is much less than the uncertainty in the point values. The model, of course, will be more useful in helping with decisions related to these average values, because prediction at this scale is much more robust, being determined by the regional stratigraphic relationships and topography of the Duwamish Valley and its surrounding uplands. As a result, model outputs are rather insensitive to the characterization of local conditions.

Average values from the model should be useful in characterizing, and quantifying the ground water flow patterns of the *Conceptual Model Report;* they will also prove valuable for setting plausible boundary conditions for smaller-scale models that may be developed subsequently to investigate groundwater movement in more localized areas.

6.0 RECOMMENDATIONS

The groundwater model described in this report provides considerable insight in terms of water budgets and groundwater flow directions. However, it should be viewed as a resource that will be improved as additional data and information are collected about the study area. The model can also be used to further identify and prioritize data gaps. Specific topics or areas in which improvements or applications might be particularly important and valuable are summarized below.

1. Additional sensitivity studies

The model could be used to prioritize data collection activities in the Duwamish Basin. Additional sensitivity studies could identify areas that are most critical in terms defining stratigraphy and hydrogeologic parameters. The model could also identify areas in which water level measurements would be most valuable in terms of constraining the stratigraphy and input parameters.

2. Transient modeling to evaluate effects of tidal fluctuations

The existing model is a steady-state model that estimates flow rates under average or mean tidal conditions. It could also be run in a transient mode to consider the extent of tidal fluctuations in the waterway and in Elliott Bay. This would involve specifying storage coefficients for the various stratigraphic units. The results might be useful to evaluate the effects of tidal fluctuations on data collection activities in the vicinity of the waterway.

3. Refining recharge rates based on information regarding land use, vegetation, and topography

The model assumes a uniform infiltration rate of 10 inches per year. Additional data from GIS databases describing land use, vegetation, and topography could be used to estimate spatial distributions for recharge rates. While this will not likely affect the average water budget, it may affect local flow directions and flow rates.

4. Developing local-scale models in sensitive or high-interest areas

The model described in this report can be used to define boundary conditions for smaller scale models that could provide more detailed pictures of local flow systems. These smaller-scale models might be used in conjunction with contaminant transport models to evaluate presumptive remedies for site remediation activities or to better define the effects of tidal fluctuations on subsurface concentrations.

FIGURES

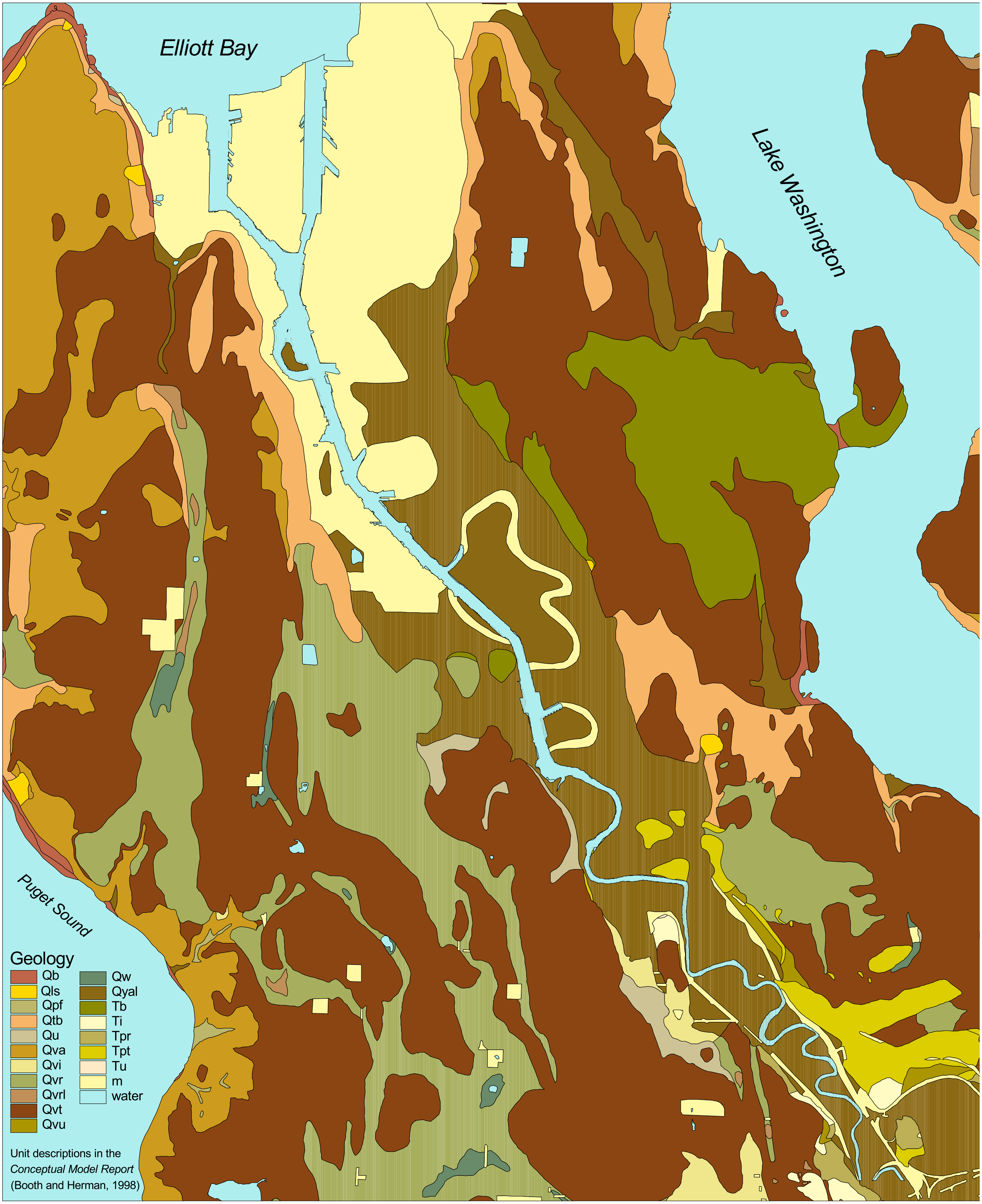


Figure 1 - Surficial Geology

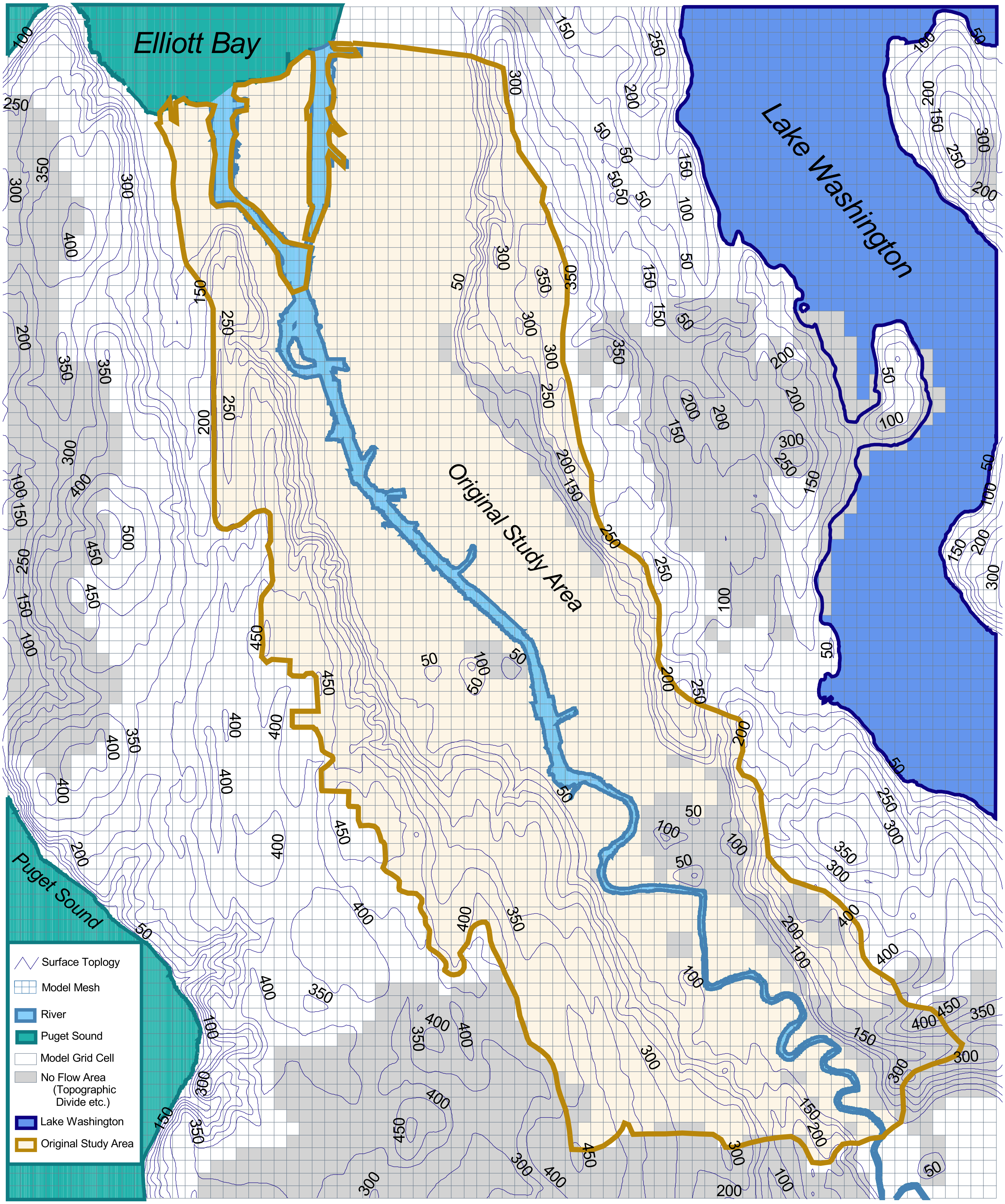


Figure 2 - Plan View of Model Domain

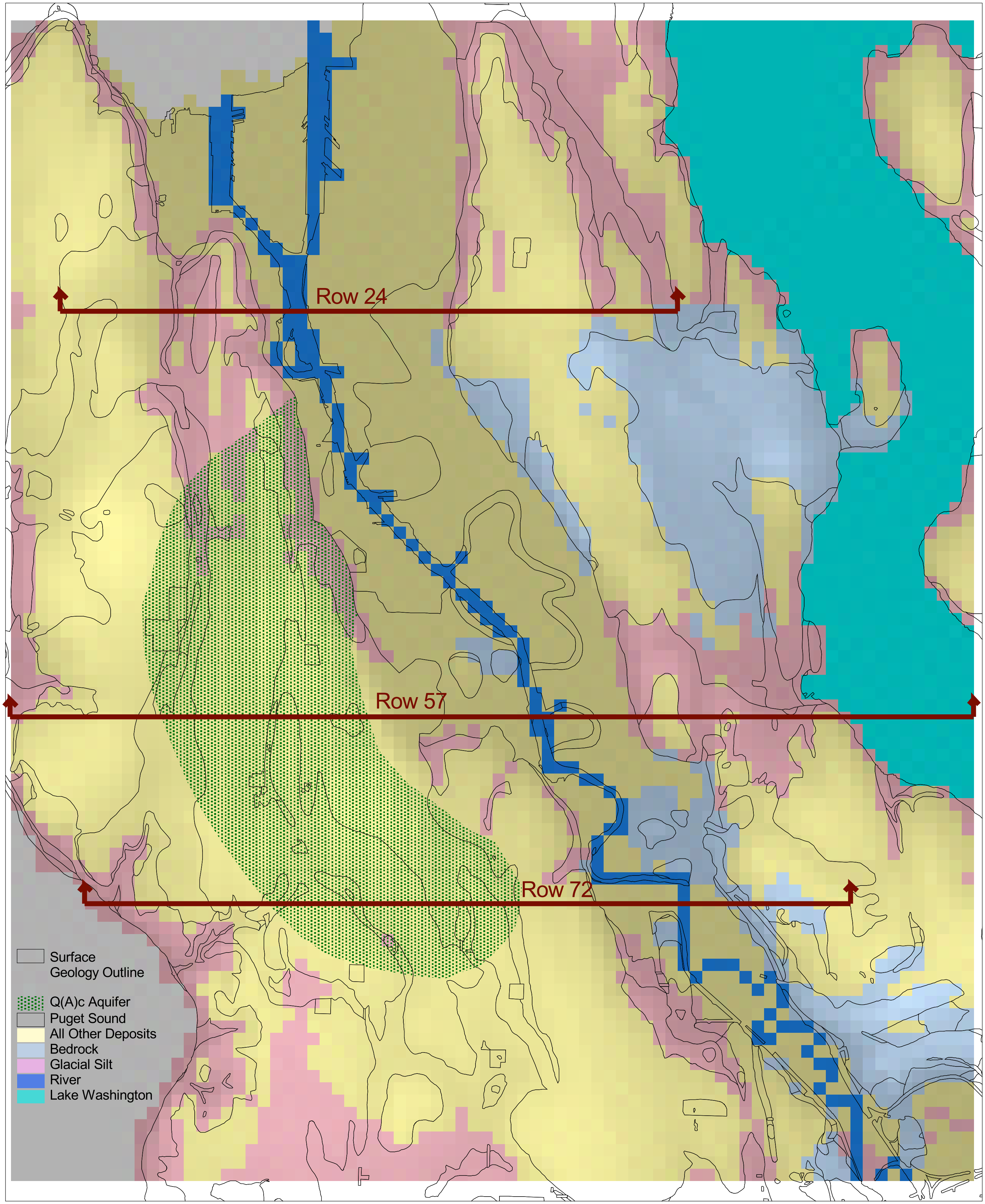


Figure 3 - Generalized Outcrop Map

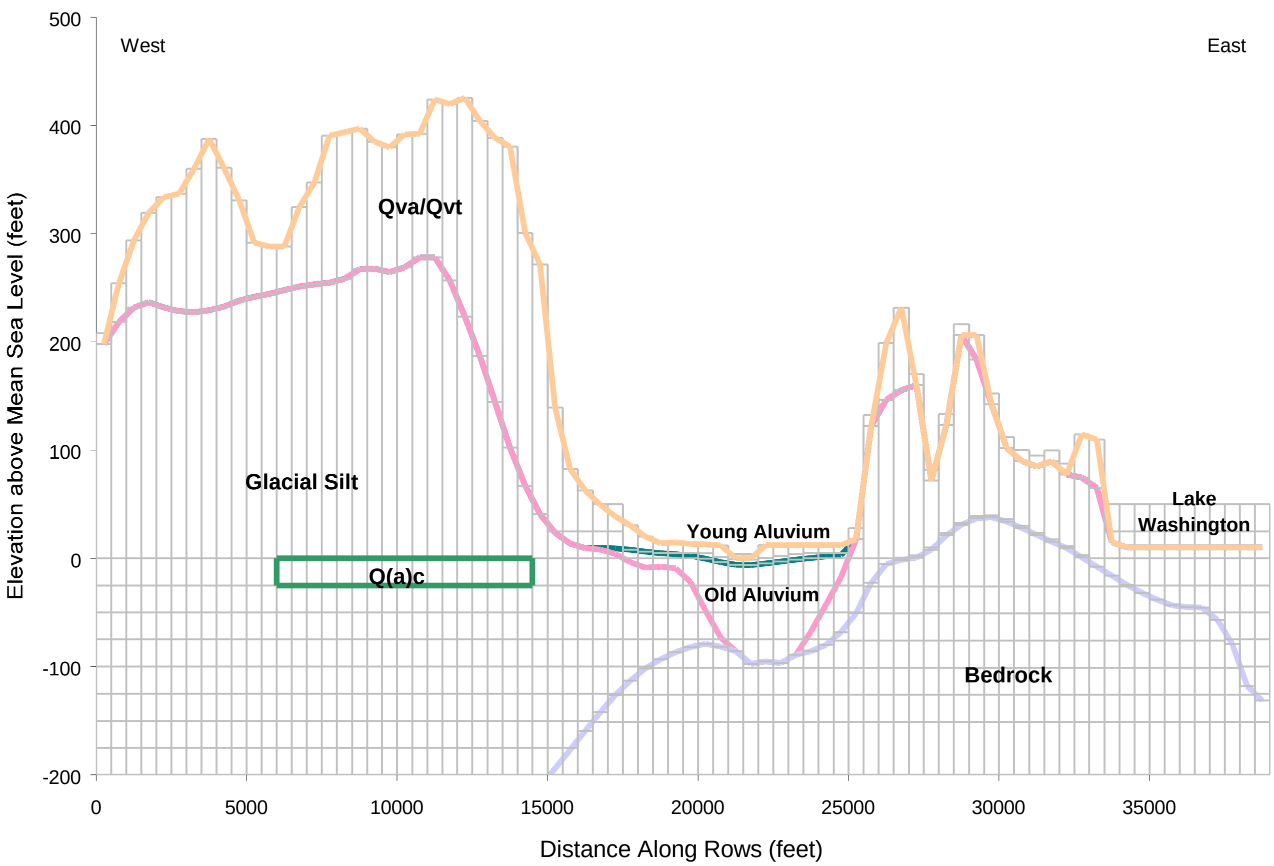


Figure 4 – Example Cross-Section

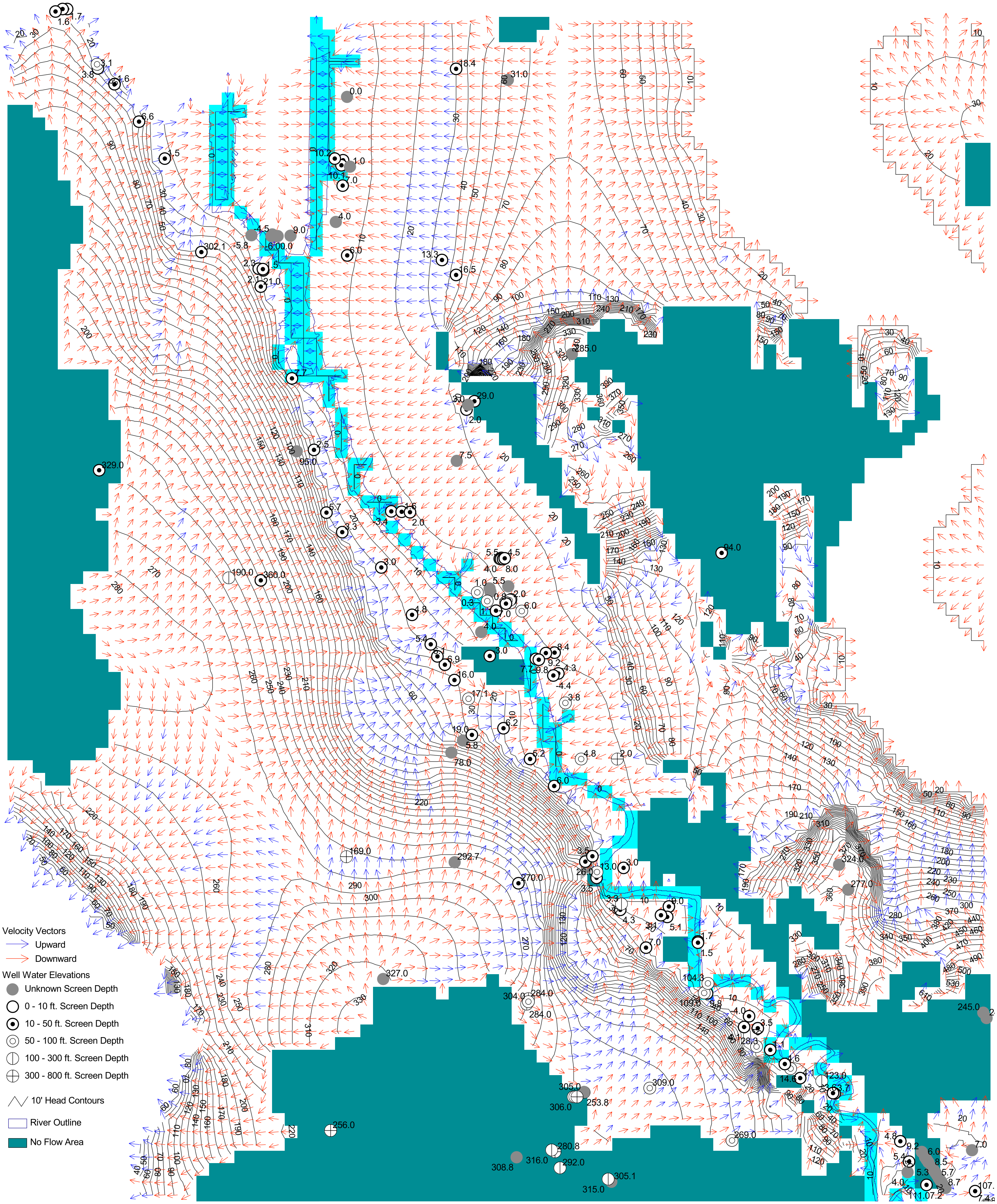


Figure 5 - Base Case Heads with Flow Arrows

Calibrated, No Pumping. Flow Arrows shown at mean sea level or 5' above bedrock, which ever is higher.

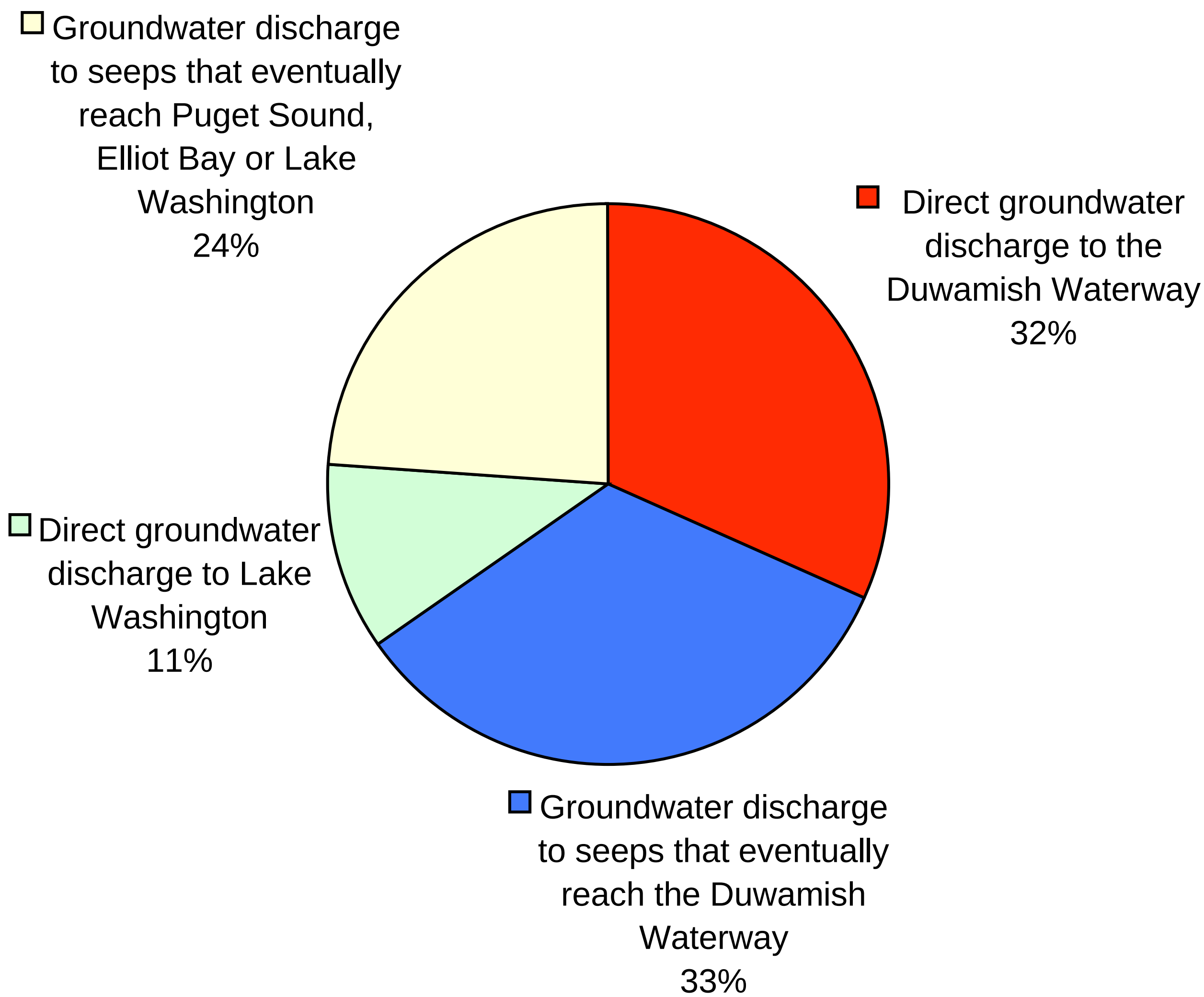
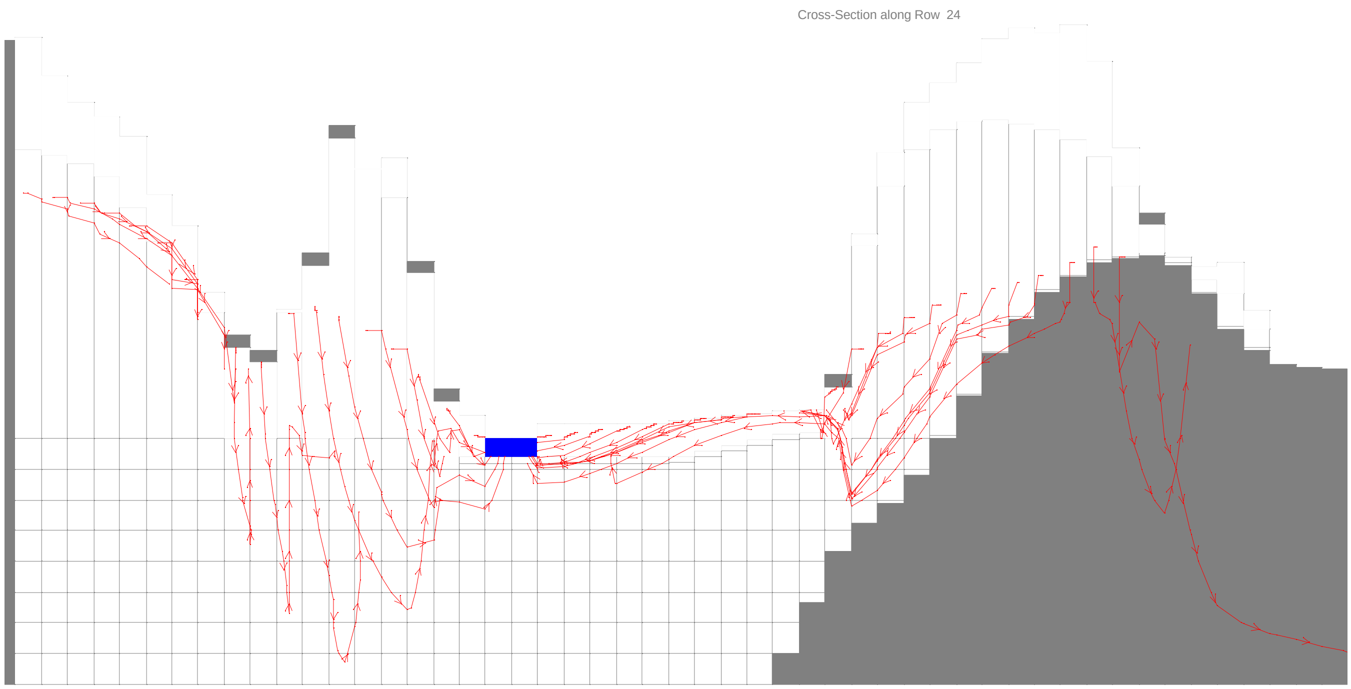


Figure 6 – Flow Budget in the Model Domain



Cross-Section View – Row 24

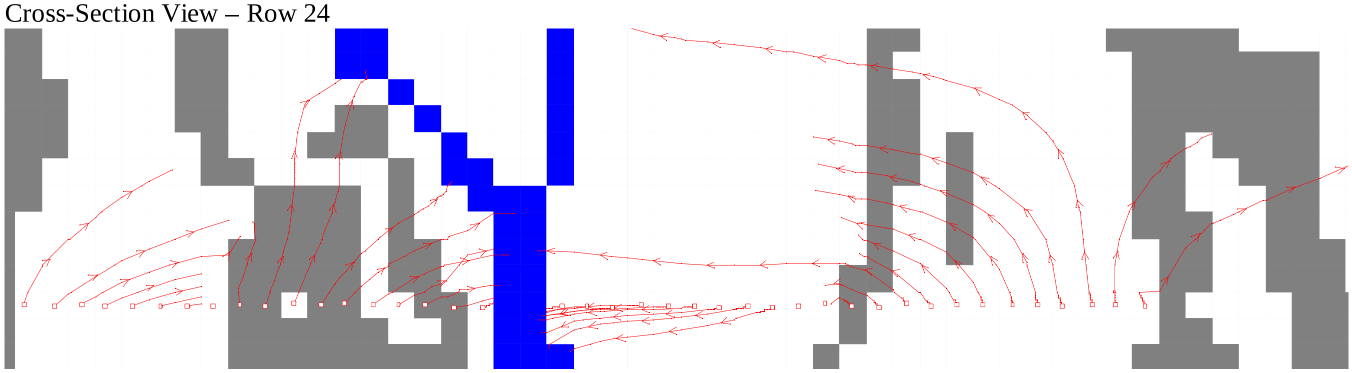
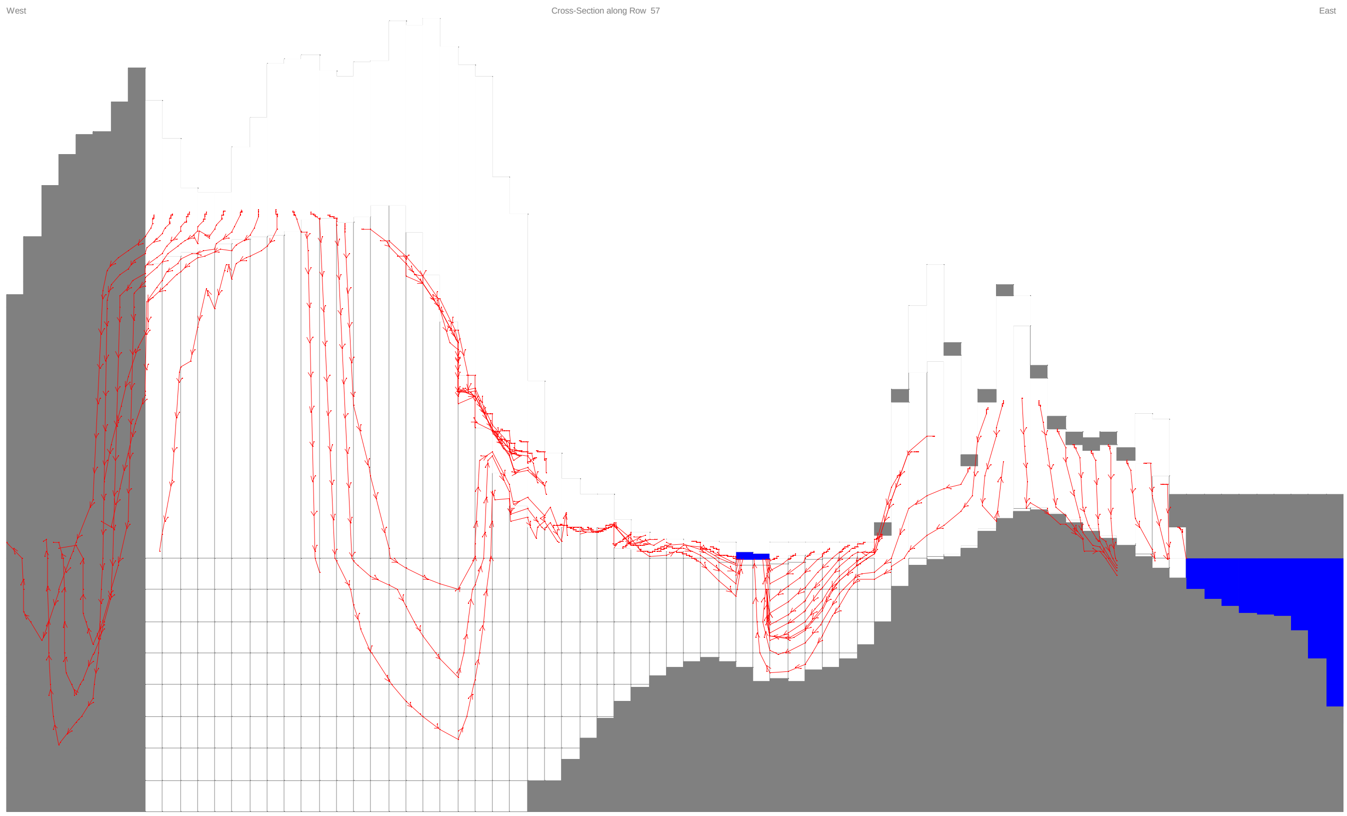

Plan View – Layer 1

Figure 7 – Row 24 Cross-Section with Groundwater Flow Paths

Blue Cells contain a river (constant head) boundary condition while gray cells correspond to an inactive cell (bedrock for example).



Cross-Section View – Row 57

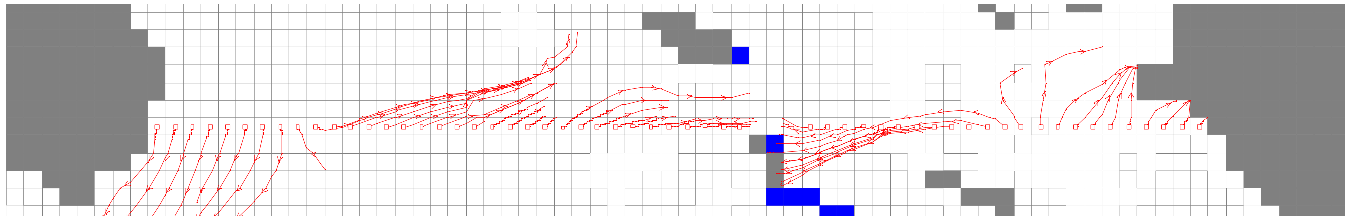
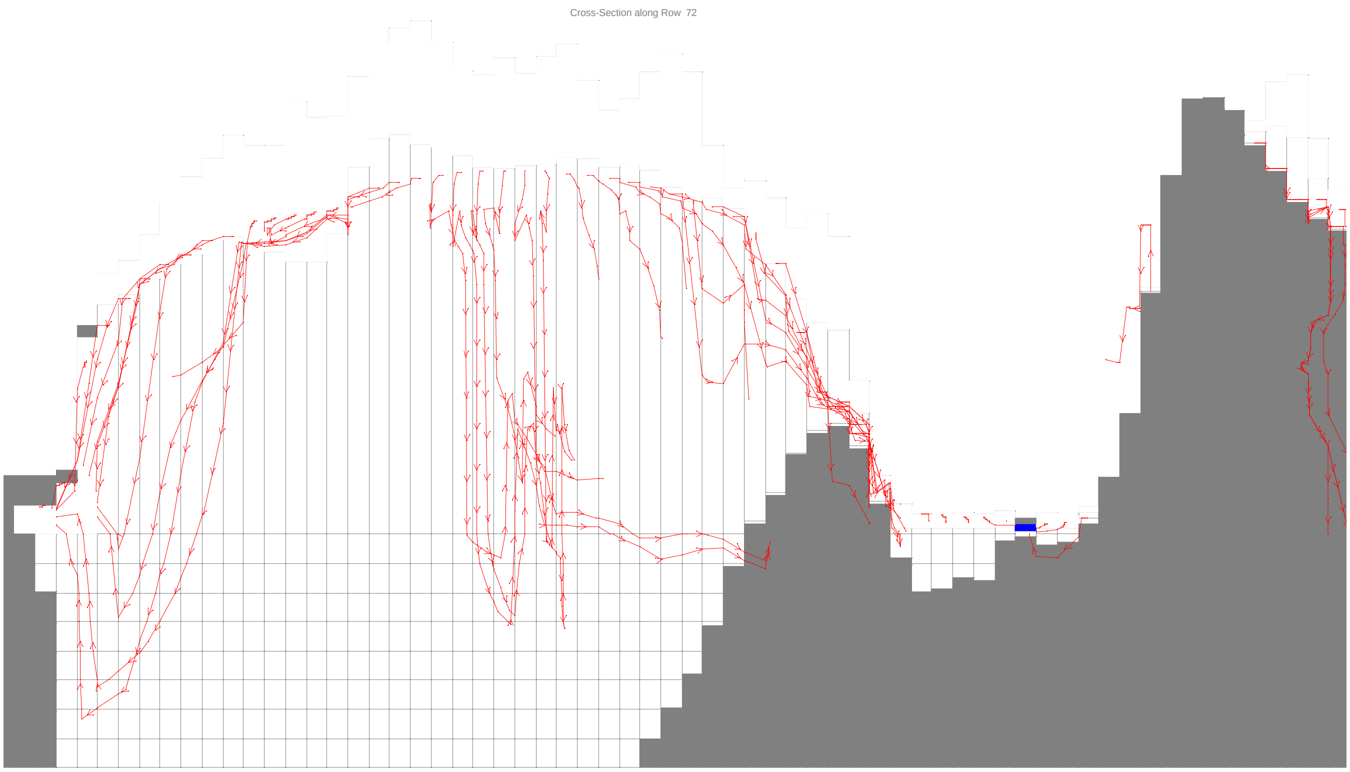
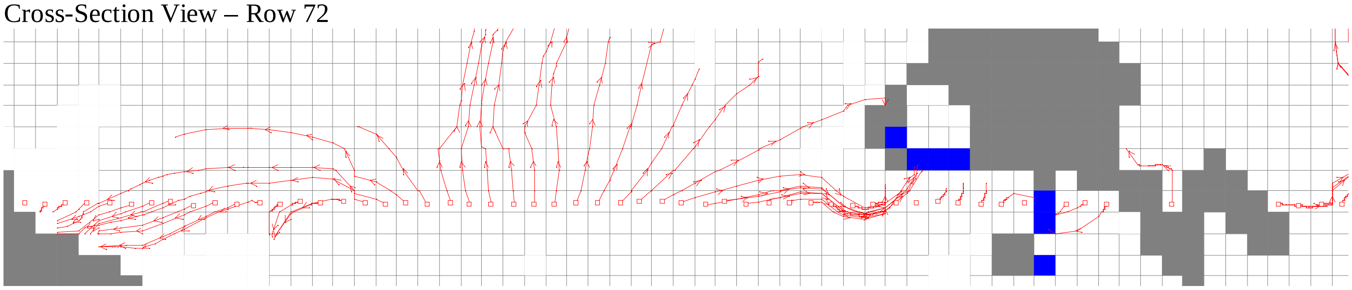

Plan View – Layer 2

Figure 8 – Row 57 Cross-Section with Groundwater Flow Paths

Blue Cells contain a river (constant head) boundary condition or Lake Washington (constant head) boundary condition while gray cells correspond to an inactive cell (bedrock for example).



Cross-Section View – Row 72



Plan View – Layer 2

Figure 9 – Row 72 Cross-Section with Groundwater Flow Paths

Blue Cells contain a river (constant head) boundary while gray cells correspond to an inactive cell (bedrock for example).

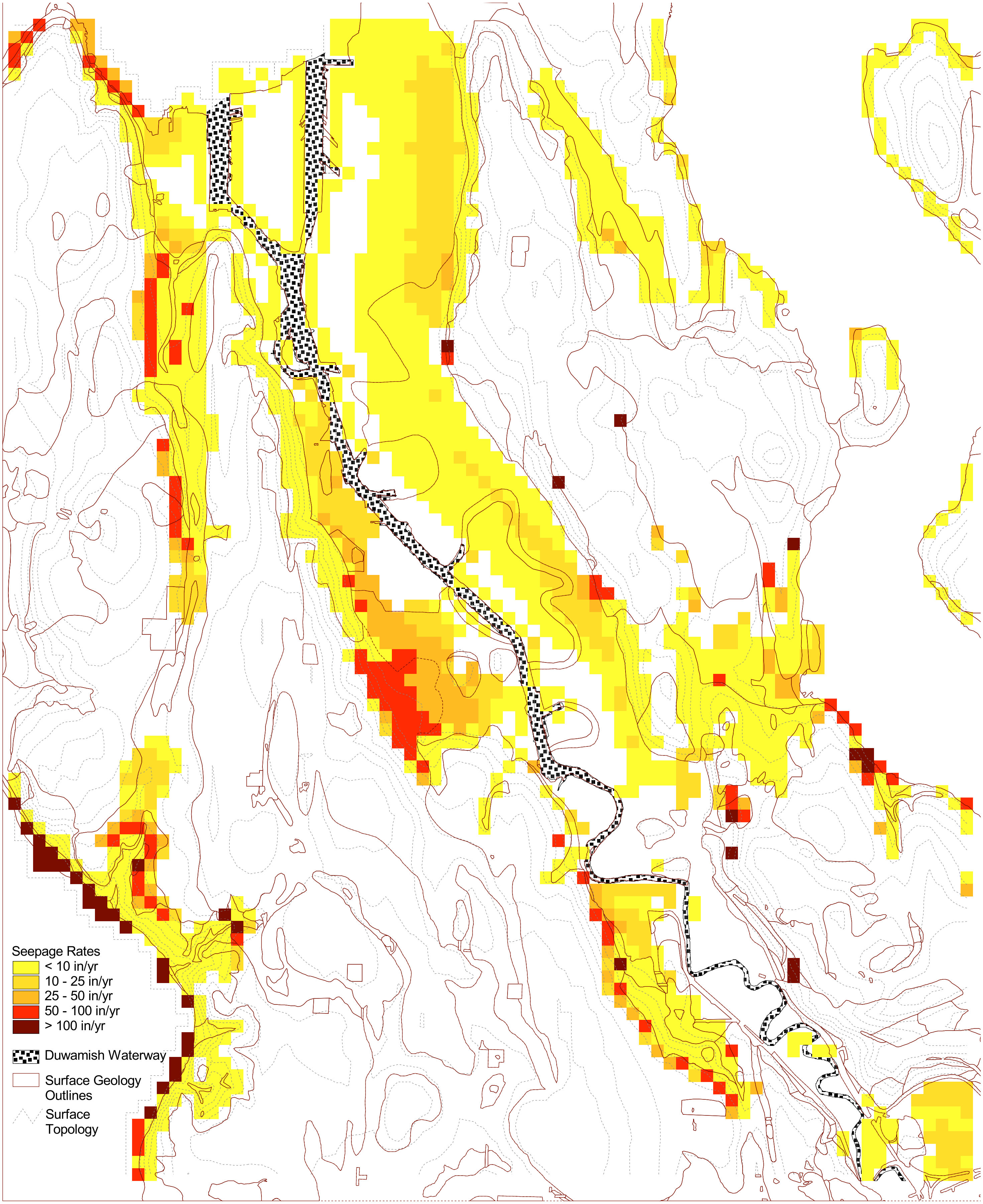


Figure 10 - Location and Magnitude of Groundwater Seepage

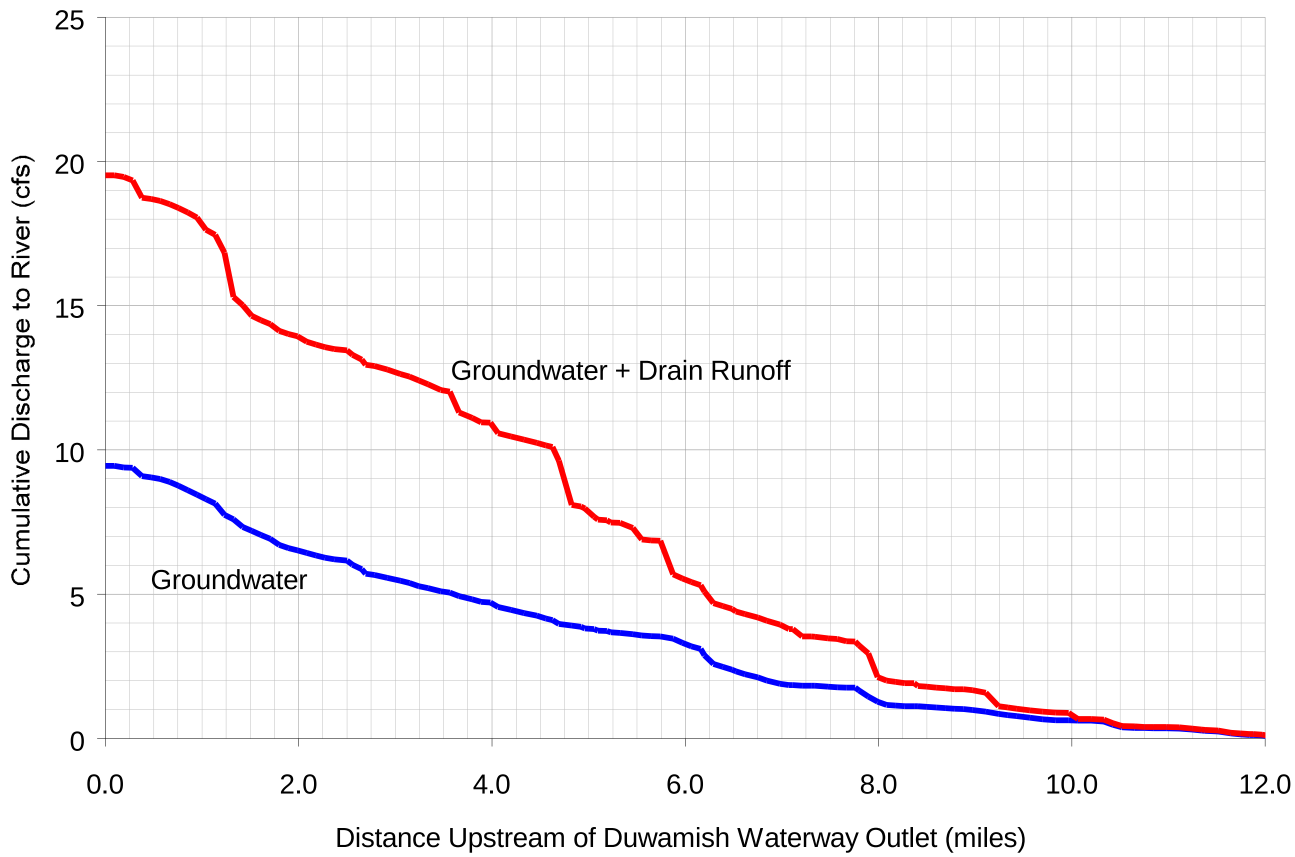


Figure 11 – Cumulative Discharge to Duwamish Waterway from Model Domain

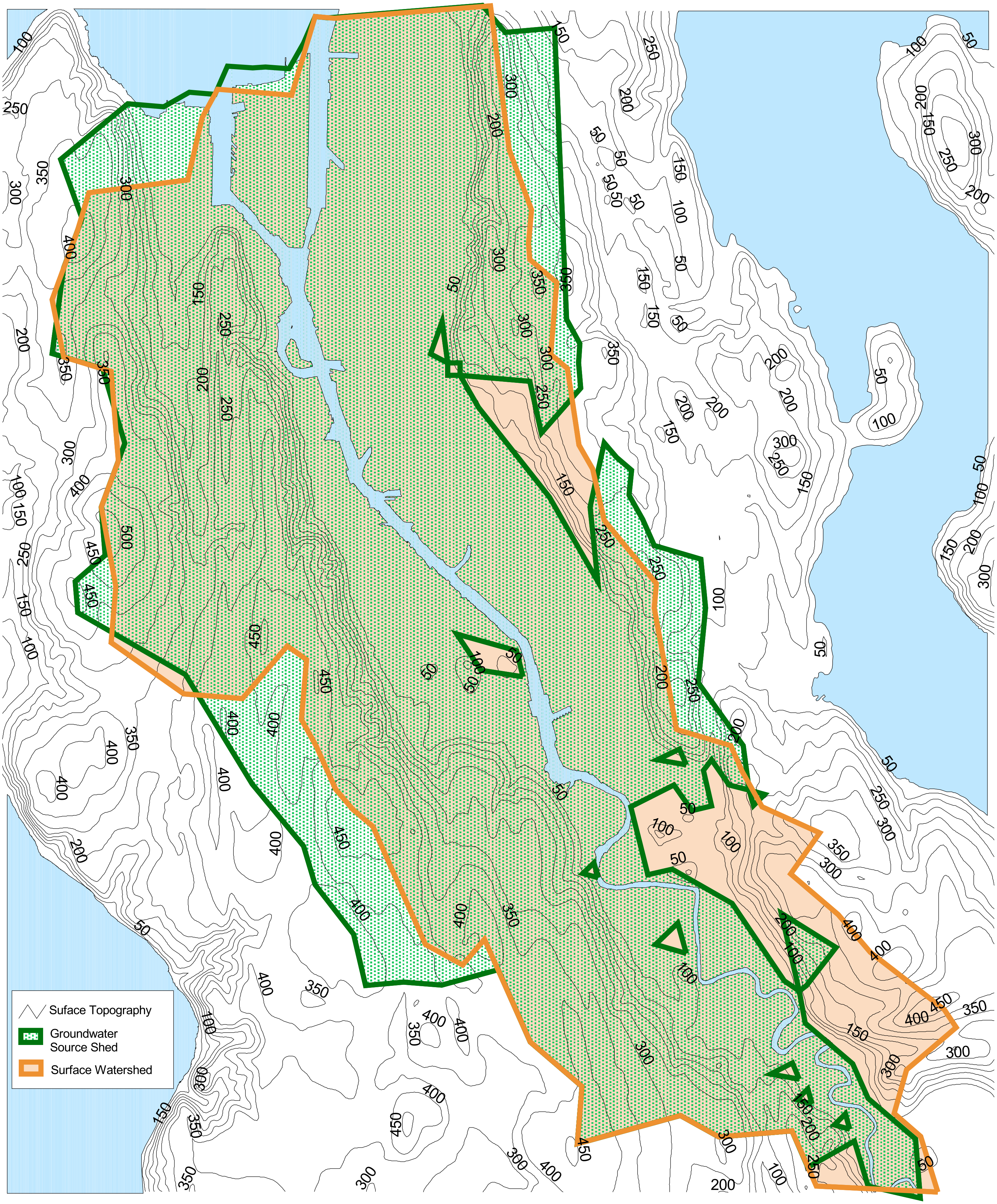


Figure 12 - Tributary Areas to the Duwamish Waterway within the Model Domain

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