Pacific
Groundwater
Group

Port of Seattle
Sea-Tac Third Runway
Embankment Fill Modeling in Support of Low-Streamflow Analysis

November 27, 2001

Pacific Groundwater Group
Seattle, Washington

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This work was performed in part, and reviewed in whole, by the undersigned.

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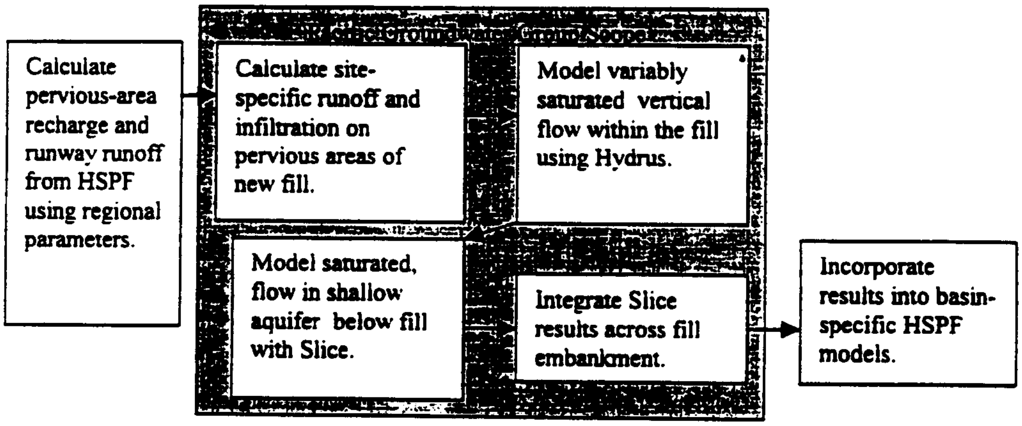
1. Introduction

The Port of Seattle ("the Port") proposes to place a fill embankment in an area west of the existing Sea-Tac Airport complex to build a third runway. Pacific Groundwater work analyzed selected hydrologic impacts for the Department of Ecology in 1999 (Pacific Groundwater Group, 1999). Hydrologic and hydrogeologic studies conducted by Earth Tech. Inc., Parametrix, Inc., Pacific Groundwater Group (PGG) and others then estimated groundwater and low-stream-flow impacts of the proposed fill embankment (Earth Tech, 2000; Pacific Groundwater Group, 2000; and Parametrix, 2001). As part of a more detailed study of low flow impacts to streams near the third runway, the Port contracted Parametrix, Earth Tech and PGG to reevaluate low-stream-flow impacts using a more detailed evaluation of hydrogeologic conditions and fill thickness in the embankment. PGG's role in the more detailed evaluation was to model recharge and redistribution of water within the fill embankment. This is the final report for PGG's portion of that project. The overall project study area includes the Miller Creek and Walker Creek basins, whereas PGG's evaluation was limited to a smaller portion of these basins that are proposed to be underlain by third-runway fill. PGG's evaluation was also limited to post-construction conditions, and did not attempt to simulate existing conditions or use existing conditions for calibration. PGG's study results were used by the HSPF modeling team to evaluate low-stream-flow impacts in the two basins.

1.1 Scope and Approach

PGG's scope of work was authorized by the Port on May 1, 2001. PGG's scope involved reapplication of previously-developed Hydrus and Slice models to post-construction conditions within the proposed embankment as follows:



Input to the modeling process consisted of the following two data sets provided to PGG by Aqua Terra Consultants:

1. direct infiltration from incident precipitation into pervious areas of new fill as calculated by HSPF (model parameter AGWI) for flat outwash

2. runoff from runways and taxiways as calculated by HSPF (model parameter SURO).

Output consisted of the timing and magnitude of runoff from the pervious area, water movement through the shallow aquifer above the till, and downward flow through the till. Output was provided to Aqua Terra and Parametrix Inc. as part of basin-wide simulation of post-construction conditions. The regional HSPF models were modified to allow replacement of regional-scale simulation with local-scale simulation (as described above) in the third runway vicinity. Specifically, Hydrus and Slice models ("Hydrus-Slice") were used instead of the regional HSPF model for the runway fill area, because HSPF was deemed incapable of simulating flow within the embankment. A simulation "test period", consisting of water years 1991 through 1994, was established for Hydrus-Slice modeling in discussions between the Port and the Department of Ecology ("Ecology").

The PGG scope consisted of the following tasks:

- Compile model input using existing information including
    - ➢ Fill thickness and extent
    - ➢ Hydrogeologic data for the fill area
    - ➢ Embankment geometries as represented by three (3) hydrogeologic cross sections
    - ➢ Hourly runoff and direct infiltration estimates provided by Aqua Terra Consultants
- Calculate fluxes into the fill based on hourly recharge and runoff estimates
- Calculate daily fluxes through the fill using Hydrus models
- Calculate daily flux through the shallow aquifer at the base of the embankment and the underlying till using Slice models as applied to each basin

Original modeling using the Hydrus-Slice approach was reported on August 8, 2001 (Pacific Groundwater Group, 2001). The modeling reported in this revised report was performed because the original modeling used HSPF parameter AGWO as input instead of the more appropriate parameter AGWI. In addition, the following improvements and changes were made to the revised groundwater modeling:

- PGG adopted the HSPF basin boundary to define the eastern extent of new fill instead of independently-derived boundaries. The independently-derived boundary used in original modeling was similar to the HSPF basin boundary, but not exactly the same. This is a small mathematical change, not a conceptual change.

- PGG included the 1998 fill as third runway fill. Original modeling excluded the 1998 fill because the air-photo-based elevation contours used to calculate fill thickness were flown after placement of the 1998 fill. This change results in a somewhat larger Miller Creek fill area than was originally modeled.

- PGG calculated runoff from pervious areas instead of assuming that all precipitation and runon becomes groundwater recharge. The use of hourly infiltration (AGWI) and runoff (SURO) data from HSPF results in prediction of runoff from filter strips (a portion of the pervious area next to the runways) that simultaneously receive precipitation and runway runoff. This is a more accurate accounting of water performed for the proposed third runway fill area.

- Hydrus 1-D was used to model variably-saturated flow in the fill instead of Hydrus 2-D that was originally used. Hydrus 1-D was required for the revised simulations because it remains stable under the wetter and more variable conditions predicted by the AGWI and SURO model input.

The work was performed, and this report prepared, in accordance with generally accepted hydrogeologic practices, used at this time and in this vicinity, for sole application to the simulation of low-flows under the built condition, and for the sole use of the Port of Seattle. This is in lieu of other warrantees, express or implied.

2. Extent of Fill Modeled by Hydrus-Slice

The modeled fill area (MFA) represents a portion of third runway fill, within the Walker and Miller creek groundwater basins, that would receive precipitation in a post-construction ("built") condition. This area was selected based on discussions with HSPF modelers at the onset of the project. The area was modeled by Hydrus-Slice rather than HSPF for the built condition.

2.1 Geographic Extent of Fill

PGG used existing GIS coverages of pre-fill topography, "built" topography, and third runway pavement distribution to calculate areas for Hydrus-Slice modeling. A graphical approximation of the areas modeled by Hydrus-Slice (and therefore removed from the HSPF model) is shown on **Figure 2-1**. The MFA includes proposed additional runway fill in the Miller and Walker Creek basins minus the steep perimeter slopes along the western and northern edges of the embankment. Steep perimeter slopes were not included in the Hydrus-Slice MFA because surface runoff is assumed to dominate flow in these areas and HSPF is better suited to model these hydrologic conditions. The eastern margin of the MFA is defined by the limit of proposed third runway fill as previously determined by HSPF modelers.

2.2 Thickness of Fill

Fill thickness was calculated by subtracting GIS coverages of pre-fill topography from the "built" topography. A fill thickness of up to 160 feet occurs behind the West Mechanically-Stabilized-Earth (MSE) wall with significantly less fill occurring over most of the third runway area (**Figure 2-1**). For the purpose of Hydrus modeling, fill thickness was descritized into representative values of 10, 20, 30, 50, 70, 90, 110, 130, and 150 feet. Fill thickness in the area of the 1998 fill was approximated and not directly calculated as the difference between two sets of elevations.

2.3 Basin Boundaries and Area Calculations

Groundwater basin boundaries for Miller, Walker and Des Moines Creeks were located for purposes of allocating modeled groundwater flows in the MFA. The groundwater basin boundary of greatest significance in this study is the Miller-Walker divide because these are the receiving basins for groundwater discharge from the fill. A dashed line is drawn on **Figure 2-1** between the Miller and Walker Creek basins. The location of the line is co-incident with the surface water and groundwater basin boundaries used in the HSPF models of 1994 conditions (Parametrix, 2000, Figure B2-2 of Stormwater Management Plan). The Walker-Des Moines groundwater divide is south of the fill area, thus groundwater discharge from the fill will not flow to Des Moines Creek under the current or built condition. The fill areas presented in **Table 2-1** are derived from the basin boundary and model area perimeter shown on **Figure 2-1**. Areas are broken into impervious areas (IA), filter strips (FS), and other pervious areas (OPA). Impervious areas comprised 36 percent and 38 percent of the modeled fill areas in the Miller and Walker Creek basins, respectively.

IA in Walker Creek consists of only the western half of the third runway because runoff from the eastern half will drain to the east and will not flow onto new third runway fill. Runoff from the eastern half of the third runway in Walker Creek was modeled by HSPF.

3. Modeling of Infiltration with Runoff and Evapotranspiration

Precipitation on the MFA was used to calculate hourly runoff (SURO) from impervious surfaces (runway and taxiways) and hourly infiltration (AGWI) into pervious areas with a generic application of HSPF. Pervious areas were modeled as grass on flat outwash. This approach was selected, with agreement from Ecology and King County, to take advantage of HSPF's superior evapotranspiration (ET) and runoff-modeling capabilities. For pervious areas, the generic HSPF model yielded hourly volumes of water that infiltrate beyond the bottom of the root zone (AGWI) and therefore constitute groundwater recharge. That calculation was applied to filter strips and other pervious areas. A separate calculation then estimated the extent to which runoff from impervious surfaces would also infiltrate, or conversely, runoff, from filter strips. The total amount of infiltration into filter strips (a portion of AGWI and SURO) and other pervious areas (AGWI only) was then used as input to the Hydrus models. Calculated runoff was accounted-for but not used in groundwater modeling.

3.1 HSPF Input and Runoff Calculations

Aqua Terra accounted for precipitation, runoff, infiltration, and ET on an hourly basis between 1984 and 1994 using HSPF and regional parameters for grass on outwash soils with land slopes of less than five percent (Joe Brascher, personal communication, May 17, 2001). HSPF model output (AGWI) provided daily estimates of recharge below the root zone considering the effects of runoff and evapotranspiration.

HSPF also calculated hourly volumes of runoff (SURO) from a typical acre of impervious surface. Runoff from impervious surfaces will be routed into "filter strips" that treat the water prior to storage and discharge. The filter strips are part of the pervious surface of the new fill. Therefore, the SURO and AGWI water volumes were added together and compared to the infiltration capacity of the filter strips. Water in excess of the infiltration capacity of the filter strips was considered runoff, and remaining water was considered to infiltrate and become groundwater recharge. For these calculations, areas of impervious surface and filter strips were based on GIS analysis of design data. Flow was assumed uniform over the filter strip, and likely storage of water in surface irregularities was ignored. The infiltration capacity was calculated as the saturated hydraulic conductivity of the fill under a unit hydraulic gradient, over the area of the filter strip. The saturated hydraulic conductivity of the sandy fill matrix was assumed to be 1.35×10^{-4} cm/sec, and no flow was assumed to occur through the portion of the fill occupied by gravel particles, consistent with assumptions throughout PGG's involvement with this project. The total volume of runoff from the filter strips was 28 and 21 percent of the summed AGWI and SURO volumes for Miller and Walker Creek basins, respectively (water years 1991 through 1994 – Table 3-1).

A small amount of runoff was also calculated for "other pervious areas" (pervious areas that are not filter strips and therefore do not receive runoff) because AGWI exceeded the calculated infiltration capacity of other pervious area on occasions. This presumably occurred because of differences between HSPF predictions of runoff from flat outwash, and the runoff-evaluation method applied to the AGWI time series after receipt. The total volume of runoff from the other pervious areas was 6 percent of the AGWI volumes for both basins (water years 1991 through 1994 – Table 3-1).

The Port collected water stage measurements in a sedimentation pond that collected runoff from Phase I (1998) fill of the third runway fill embankment (Parametrix, 2000). The data were collected over about a one-month period in February 1999 and were later used by Parametrix to derive parameters for HSPF modeling of the fill. The interpretation implies a soil infiltration capacity (related to vertical hydraulic conductivity) that is lower than that of regional HSPF parameters for glacial till. The revised runoff calculations summarized above are in much better agreement with observed runoff volumes than the negligible runoff volumes assumed for original modeling reported on August 8, 2001. The observed and predicted runoff volumes are considered to be reasonably consistent although differences in the details may exist for a variety of reasons. As described in Section 4.3, the infiltration volume used in the current modeling could underestimate, and is not likely to over-estimate, actual infiltration. Modeled volumes of groundwater discharge from the fill may therefore be smaller, and are not likely to be larger, than actual discharge. For the purposes of low-flow streamflow assessment, this condition is considered conservative.

3.2 Effective Recharge

Effective recharge (ER) is the average downward groundwater flux over the entire pervious area, just below the root zone. It consists of those portions of AGWI and SURO that infiltrate. As discussed above, the filter strips and other pervious areas receive different amounts of water. In order simplify the analysis, the *average* effective recharge for the entire pervious area was calculated as the summed volume of water infiltrated in those two areas, divided by the total pervious area. Table 3-1 summarizes those water volumes.

4. Modeling of Vertical Flow Through Embankment Fill

Modeling of downward vertical flow through embankment fill describes water movement in the unsaturated or "vadose" zone between the land surface and the proposed drainage layer at the base of the fill. Downward unsaturated flow is the intermediate step between recharge at the land surface and saturated groundwater flow in the shallow aquifer (simulated by the Slice model). An overview of the unsaturated flow modeling completed for this study is presented in the following subsections.

4.1 Summary of Generic Hydrus Model

Vertical flow of effective recharge between the root zone and the water table within the embankment drainage layer was evaluated using the model Hydrus-1D, hereafter called "Hydrus" (Simunek and others, 1999). Hydrus simulates the vertical spreading of recharge fronts as they are predicted to move downward through the proposed embankment fill. Model results describe the lagging and dampening of the recharge pulse for different thicknesses of fill material. Hydrus output was used as recharge input to the Slice models (Section 5).

With the exception of using HSPF-derived recharge input values instead of values derived from average monthly rainfall, the modeling approach used in this study was conceptually identical to the Hydrus simulations completed for the Ecology study (see Appendix C of Pacific Groundwater Group, 2000). Soil characteristics were unchanged. Independent model runs were conducted for the Miller Creek basin using fill thicknesses of 150, 130, 110, 90, 70, 50, 30, and 10 feet. Model runs were conducted for the Walker Creek basin using fill thicknesses of 50, 30, 20, and 10 feet. Hydrus results indicate that substantial lagging and dampening (spreading) of seasonal recharge is likely within the fill, with the amount of lagging and dampening increasing with increased fill thickness. Discharge at the bottom of the fill is predicted to occur throughout the year.

4.2 Characterization of Fill as Soil

The texture of the modeled fill was calculated based on specifications for Phase 1 fill (installed in 1998 and 1999) and proposed embankment composition described by Hart

Crowser (1999). The calculations were also compared to the texture of Phase 1 fill based on soil samples collected by Terra Associates (1998). Details of the characterization of fill texture relative to Hydrus model input is presented in Appendix C of the Ecology study (Pacific Groundwater Group, 2000). Following are summaries of the two types of fill proposed for use in the embankment and designated in this study.

4.2.1 General Fill

Except for Type 1 soils used as fill in limited areas near the MSE walls and runways, the embankment will be comprised of imported material termed "general fill." Average bulk texture for the general fill was estimated to be 55 percent gravel and 45 percent sand-plus-fines matrix. The sand-plus-fines matrix was further estimated to be comprised of an average of 63 percent sand and 37 percent silt; clay was assumed to be absent. Soil-moisture characteristic curves and hydraulic conductivity distributions were developed for the Hydrus runs using Hydrus' version of the U.S. Soil Salinity Laboratory's computer program "Rosetta" based on the grain-size distribution of the matrix.

4.2.2 Type 1 Fill

According to embankment designs presented by Hart Crowser (1999), Type 1 soils are comprised of sand and gravel; they contain virtually no fines. These materials will be used as backfill for the MSE walls and under runways where greater compaction and drainage properties are required. Type 1 soils were assumed to be infinitely permeable and therefore provide immediate delivery of recharge to the underlying drain layer in the Slice models. Type 1 soils were therefore not modeled explicitly using Hydrus although recharge to the drain layer was considered where Type 1 soils existed in modeled areas.

4.3 Representation of Fill in Hydrus

The sand-plus-silt matrix was modeled as an evenly-distributed 45 percent of the general fill and all water flow was assumed to occur within this active matrix. To maintain a water balance while modeling water flow only through the active matrix, effective recharge values were divided by 0.45 and used as the upper boundary condition flux in Hydrus. This matrix-scaled recharge rate used in Hydrus is called the "effective matrix recharge." Logic for using this rate can be understood by considering that any precipitation falling-on, or percolating-into, clusters of gravel particles is likely to be absorbed by the surrounding sand-plus-silt matrix somewhere within the embankment. The gravel fraction of the general fill is therefore treated as inactive. The output at the bottom of the Hydrus model was then multiplied by 0.45 to redistribute flux to the bulk fill body and maintain a long-term water flux equal to the effective recharge rate.

Modeled hydraulic properties for the active fill matrix were generated with Rosetta, based on the percentages of sand and silt summarized in Section 4.2. Rosetta provides estimates of five parameters used to generate the soil moisture characteristic curve; saturated water content, residual water content, "alpha", "N", and "M" (van Genuchten, 1980). Rosetta also provides an estimate of saturated hydraulic conductivity and a factor "L" used to relate the characteristic curve to the unsaturated hydraulic conductivity curve (Mualem, 1976). A default "L" value of 0.5 was assigned by Rosetta in Hydrus, and was used in this analysis. **Table 4-1** presents the hydraulic parameters generated by Rosetta for the general fill matrix. The saturated hydraulic conductivity calculated by Rosetta was 1.35×10^{-4} cm/sec. This value is near the middle of the range presented in Freeze and Cherry (1979) for silty sand. It is near the high end of the reported glacial till range and lower than the clean sand and gravel ranges reported by the same reference.

Although the actual value(s) of hydraulic conductivity are not known for the proposed future embankment, the value calculated by Rosetta is reasonable for the anticipated texture and density of the general fill *matrix*, and is consistent with the active/inactive matrix method of modeling unsaturated flow in the embankment. Experience with testing *saturated* hydraulic conductivity of soils similar in texture to the modeled fill suggests that the Rosetta-calculated value is too low for the bulk (matrix plus gravels) general embankment fill; however, the reason for this discrepancy is the presence of large pores associated with gravels. Large pores associated with gravel deposits dominate saturated flow but can be reasonably assumed inactive under most unsaturated flow conditions because:

- the fill should remain unsaturated except in extreme conditions, and therefore unsaturated flow should predominate,
- large diameter pores associated with gravels will be the first to desaturate as drying occurs,
- over the course of the flow path, water in saturated pores will be absorbed into the finer pores due to matric tension,
- percolation theory (Silliman and Wright, 1988) suggests that continuous paths of finer pores within the matrix will exist throughout the embankment at the modeled texture (it also predicts continuous coarse pore paths which would be predominant in saturated flow),
- it was not feasible for this project to characterize soil moisture retention characteristics of gravels

This representation should be accurate for classical unsaturated flow modeling used by Hydrus and for nearly all other unsaturated flow prediction methods. However, it does not account for the observation that "fingering" of flow can occur in coarse soils under very wet conditions. Fingering occurs when saturation builds-up at one location and then rapidly drains downward through large connected pores in a saturated finger. Such fingering flow will only occur during recharge events when the ground surface, or a subsurface soil zone, becomes saturated. If fingering flow occurs because of a saturated ground surface, this modeling approach will underestimate infiltration. The likelihood of underestimating infiltration has increased relative to the original modeling approach reported on August 8 2001 because of the more variable moisture conditions predicted using hourly precipitation data and the explicit calculation of volumes that will runoff. If fingering flow occurs for substantial distances within the body of the fill, the Hydrus model will overestimate groundwater travel times between ground surface and the water table. The likelihood of overestimating vertical groundwater travel times for the wettest conditions is also somewhat increased relative to the modeling reported on August 8 2001 because of the more variable moisture conditions used in the current assessment.

4.4 Spatial Discretization of Hydrus Models

As described in Section 4.1, Hydrus models were set up to simulate a total of twelve vertical profiles for the proposed fill. Eight different thickness simulations were run for Miller Creek fill and four different thickness simulations were run for Walker Creek fill. Model runs for a given basin differ in fill thickness only. Separate runs were required for the two basins because slightly different IA/PA ratios led to different effective recharge rates.

Nodes representing the land surface were specified flux boundaries. The bottom two nodes were assigned the "water table" boundary condition, which is a constant head boundary equal to elevation head, simulating saturated conditions beneath the embankment fill. Time-series data for flow rates (specific discharge) exiting the bottom of the model domain at the water table boundary nodes were extracted and used as input to the Slice models.

Discretization of the soil profile emphasized detail within the top and bottom six inches of the column to accommodate dramatic changes in recharge and flow. Finer detail within these portions of the soil column improves accuracy in variable flow and water balance calculations as well as improving numerical model performance. Cell size increased in from a minimum of 0.01 cm at the top of the soil profile to about 0.3 inch at a depth of 6 inches. At a depth of 6 inches cells were a constant 6 inches down to 6 inches above the water table, at which point the change in intervals reverted back to 5 percent differences.

4.5 Temporal Discretization

Daily stress periods were used, and daily effective matrix recharge estimates were applied to the top of each model. Model timesteps were automatically optimized by Hydrus, and were typically on the order of 0.10 days. The models were run for water years 1984 through 1994, with only the last four water years comprising the test period. Output from the initial six years was examined visually to assure that residual effects from the initial conditions (uniform moisture) were not present during the 1991-1994 test period.

4.6 Results

Figure 4-1 shows eight daily outflow graphs for the Miller Creek basin fill over the test period. The outflow graphs represent the daily average flow of water to the embankment drain layer (or the water table within the drain) for any one of eight modeled fill thickness intervals. **Figure 4-2** presents comparable results for the Walker Creek fill. Fill thickness intervals correspond with the range of fill geometries occurring in each basin as presented in **Figure 2-1.** Effective recharge into the fill (Hydrus model input) is not shown on these figures because the input is very "spikey" and the lines obscure the model results. Nonetheless, the character of the effective recharge input can be inferred from the 10-foot-thick-fill output, which is only slightly damped and delayed relative to the input.

Figures 4-1 and 4-2 show that the recharge below the root zone is predicted to be lagged and dampened as a function of the thickness of the fill. Lagging causes the arrival of the recharge pulse to be delayed from its introduction at the land surface to its arrival at the bottom of the fill. Dampening causes a reduction in the overall range of flux in the deeper fill. Lagging and dampening both increase with increasing fill thickness and decrease with increasing annual recharge. These effects on the timing of recharge affect the arrival of flow to the top of the slice model (i.e., to the water table in the embankment drainage layer), and ultimately the arrival of baseflow to streams bordering the study area.

The Hydrus models were marginally stable during times of maximum wetness. During some model time steps, saturation was indicated at land surface as would be predicted by the runoff analysis. Hydrus was setup to permanently exclude water that would not enter the land surface at each time step. Water thus excluded was removed from the model and accounted for as a small additional component of runoff (RO3 on Table 3-1). Also, to increase model stability, recharge during one event was artificially lowered, with the removed water accounted as a fourth runoff component (RO4 on Table 3-1). RO3 and RO4 sum to less than 0.3 percent of total water and are insignificant. The runoff time series provided HSPF modelers as a product of this work included all runoff components.

Quality assurance review included comparison of total outflow between runs, and comparison of total inflow to the average total outflow. All model runs had the same total outflow to within 3 percent and 1.6 percent, respectively, for Miller and Walker Creek Hydrus models. For the Miller Creek models, total effective recharge was about 1.4 percent less than the average total outflow, likely as a result of lower storage at the end of the simulation than at the beginning. For the Walker Creek Hydrus models, total effective recharge was about 0.1 percent less than the average total outflow (for the same reason).

Hydrus erroneously predicted zero flux at the bottom boundary in a handfull of time steps. These time steps are apparent on **Figures 4-1 and 4-2.** Review of the time series output and the good mass balance indicates that errors introduced are spurious and not significant.

5. Modeling Saturated Flow Beneath the Embankment Fill

Three simple finite difference slice models were developed to simulate lateral and vertical groundwater flow within the drain layer and existing soils below the embankment. Slice configurations were based on subsurface data described in available geotechnical and hydrogeologic reports and from the pre-fill and "built" topography of the third runway area as supplied by Parametrix and the Port. Slice alignments were located based on the availability of subsurface data and are considered to describe the range of hydrogeologic and fill conditions that exist in the embankment area.

The slice models were used to accumulate recharge in the shallow water table aquifer and move it downgradient to the Miller Creek or Walker Creek wetlands under "built" conditions. Slice 1 was originally developed for the Ecology study (Pacific Groundwater Group. 2000). It was re-applied for this low-flow analysis using daily recharge data for 1984 through 1994 and a more representative runway configuration, but otherwise remained unchanged. Slices 2 and 3 were developed for the low flow analysis using new interpretations of existing hydrogeologic and fill data. The three different versions of the model were constructed to represent a range of conditions that exist within the fill embankment. The slice models are a simplification of subsurface conditions within each hydrogeologic cross section. **Figures 5-1 through 5-3** present simplified cross sections of the slice models used in this study. Slice locations are shown on **Figure 2-1**. Slice 2 was modified slightly from the version reported on August 8 2001 to include the 1998 (Phase 1) fill.

The slice models are based on a quasi-two-dimensional finite-difference formulation of the partial differential equation describing transient groundwater flow through a saturated medium. Model cells were only connected to laterally adjacent neighbors as opposed to overlying or underlying cells – thus the quasi-two-dimensional nature of the model. Each model cell can contain up to three different "soil layers", differing in thickness and hydraulic conductivity. The bottom elevation of each cell is defined by the top of the till layer. and downward flow through the till was simulated. For each cell, the model also specified a uniform specific yield of 30 percent. Recharge for each stress period (day) was derived for each cell from Hydrus output for the appropriate overlying fill thickness. The model assumes unconfined flow (variable transmissivity) under horizontal gradients defined by head differences between adjacent cells. The model was implemented in a Microsoft Excel spreadsheet, using direct (explicit) methods to solve the finite-difference equation. Details of the slice model input and functions are described further in Appendix E of the Ecology study report (Pacific Groundwater Group, 2000).

Downward flow through till was calculated using Darcy's equation, a uniform hydraulic conductivity of $4\text{x}10^{-3}$ ft/day ($1.4\text{x}10^{-6}$ cm/sec), a uniform thickness of 10 feet, and a model-calculated gradient. To calculate the gradient, the head of groundwater above the till was calculated by the model. and head at the bottom of the till was considered to be one of three values. Groundwater head at the bottom of the till was assumed equal to the elevation of that contact where groundwater in the underlying Qva aquifer was expected to be unconfined (see **Figures 5-1 through 5-3**). This condition prevailed in the eastern portions of Slices 1 and 2, and throughout Slice 3. Groundwater head below the till was considered to be equal to groundwater head above the till where the conceptual model predicted highly confined conditions. This "no vertical flow" condition was actually implemented in the model by assigning a zero hydraulic conductivity to the till where highly confined conditions were expected. That condition prevailed in the western lowland portions of Slices 1 and 2. Groundwater head at the bottom of the till, in locations of intermediate confinement of Qva groundwater, was assigned a value equal to the elevation of the mid-point of the till.

5.1 Cross Section 1 and Slice 1

This cross section is located through the thickest portion of the fill embankment with a fill thickness of up to 160 feet (**Figure 2-1**). A simplified cross section showing Slice 1 is presented in **Figure 5-1**. Slice 1 is located at the same location as the original slice model developed by PGG in the Ecology study. Hydrogeologic conditions were defined by eight subsurface explorations located along the 1,320-foot slice alignment. Fill located behind the West MSE wall was modeled using Slice 1.

The geometry and material types represented in the cross section of **Figure 5-1** were used to construct the Slice 1 model. **Tables 5-1 and 5-2** present Slice 1 model cell parameters. Because the removed portion of the HSPF model does not include the steep slopes of the embankment fill, results from Slice 1 were extracted from the portion east of cell 43 ("active model cells").

5.2 Cross Section 2 and Slice 2

Slice 2 is located through the northern portion of the fill embankment near the northern end of the third runway (**Figure 2-1**). A simplified cross section showing Slice 2 is presented in **Figure 5-2**. The slice is located to represent an intermediate fill thickness of up to 100 feet thick and crosses one taxiway in addition to the third runway. Slice 2 was developed from a generalized hydrogeologic cross section originally created by Hart Crowser through the northern toe of the fill embankment (see Section A-A' of Hart Crowser, 1999a) with supplemental information from more recent borings and shallow test pits (Hart Crowser, 2000a). The slice location is based on availability of suitable subsurface data with seven explorations located near the 1,420-foot slice alignment. Slice 2 represents subsurface conditions for the bulk of Miller Creek embankment fill.

The geometry and material types represented in the cross section of **Figure 5-2** were used to construct the Slice 2 model. **Tables 5-3 and 5-4** present Slice 2 model cell parameters. Because the removed portion of the HSPF model does not include the steep slopes of the embankment fill, results from Slice 2 were extracted from the portion east of cell 38 ("active model cells").

5.3 Cross Section 3 and Slice 3

Slice 3 is located immediately north of the South MSE wall (**Figure 2-1**). A simplified cross section showing Slice 3 is presented in **Figure 5-3**. A fill thickness of up to 40 feet occurs in the western end of this slice. The slice location was chosen through fill of intermediate thickness for the Walker Creek fill and minimal thickness for the Miller

Creek fill. Although this slice does not completely describe the variety of fill thicknesses in Walker Creek basin, the thicker portion of the fill is of small areal extent and does not justify an additional slice model. Slice 3 is partially based on a generalized hydrogeologic cross section originally created by Hart Crowser through the northern end of the South MSE wall study area (see Section E-E' of Hart Crowser, 2000b). The hydrogeologic interpretation for this slice has been modified using geotechnical data (Hart Crowser. 2000a), existing and "built" topography, and available till mapping data (AESI. 1999). Eight subsurface explorations occur along the 625-foot slice alignment.

The geometry and material types represented in the cross section of **Figure 5-3** were used to construct the Slice 3 model. **Tables 5-5 and 5-6** present Slice 3 model cell parameters. Because the removed portion of the HSPF model does not include the steep slopes of the embankment fill, results from Slice 3 were extracted from the portion east of cell 25 ("active model cells").

5.4 Individual Slice Model Results

Figures 5-4 through 5-6 present individual Slice model results for Slices 1 through 3 for water years 1991 through 1994. Results are presented as daily time series plots for three Slice model terms: Qvr/drain outflow flow downward through till. and recharge to the drain layer from the fill. The Qvr/drain outflow term is lateral groundwater flow at the western edge of the fill embankment discharging through the shallow (Qvr) aquifer and the constructed drain layer. The Qvr/drain outflow term is extracted from the western-most "active" cell in the slice, and represents subsurface flow towards downgradient receiving waters. Downward flow through till and recharge to the drain layer from the fill are summed for all active cells in the slice. Downward flow through the till represents vertical drainage to the deeper (Qva) aquifer below the till. Recharge to the drain from the fill is obtained by summing Hydrus output as it varies along the slice due to the varying thickness of overlying fill. Model results represent flow for a one-foot-wide slice of the embankment with units reported in cubic feet per day, per foot of width (ft^2/d or ft^3/d-ft).

Results vary substantially between the slices and indicate that a complex set of factors control the relationship between input (recharge to the drain) and output (Qvr/drain outflow and downward flow through till):

- The timing of recharge to the drain layer is controlled by the type and thickness of fill in the slice. More uniform fill thickness in Slice 3 results in more seasonal variability of recharge to the drain layer compared to Slices 1 and 2.
- Differences in the variability of Qvr/drain outflow shows that the presence of Type 1 fill causes output to be nearly as variable as input on Slice 1 where Type 1 fill exists, and to be rather smooth for the other slices where Type 1 fill is assumed to not exist. Transition of flow from wholly within the moderately-transmissive Qvr during dry and moderate periods, to a combination of the Qvr and the highly-transmissive drain layer during wet periods, may also contribute to this effect at Slice 1. The spikiness of modeled Slice 1 Qvr/drain outflow is likely greater than would actually occur.

- Longer flow-length paths and lower gradients within the Qvr and drain layer should contribute to longer horizontal travel time delays. However, longer flow lengths and steeper gradients in Slices 1 and 2 compare to shorter lengths and gentler gradients in Slice 3. This combination of gradient and flow paths for the two sets of slices causes horizontal travel time delays are more similar between the slices than might otherwise occur.
- Downward flow through the till is seasonal due to changes in aquifer saturation. Downward flow through till is also greater on average than Qvr/drain outflow, and is sensitive to till permeability. Qvr/drain outflow exceed downward flow through till during intense recharge events at Slice 1 (through Type 1 fill), and during some seasonal maxima at Slices 1 and 3.
- Seasonal maxima in Qvr/drain outflow are lagged more in dry years than in wet years (this be more a result of vertical flow delays than lateral flow delays).

Quality assurance review of Slice model results included comparison of total inflow, outflow and change in storage between runs. In all cases, the mass balance error in this comparison was less than one percent.

5.5 Method for Integrating Slice Results Over Entire Fill Areas

Groundwater discharge quantities for Miller and Walker Creeks were calculated by multiplying unit-width flow quantities from representative Slice model output by an effective basin width (EBW). This process integrates the slice model results over the entire basin. The EBW represents an idealized length over which groundwater within the embankment will discharge to the respective downgradient receiving waters. EBWs were measured (or calculated) parallel to the long axis of embankment fill, an orientation perpendicular to the slice models and expected groundwater flow lines. EBWs are associated with each Slice model and depend on the width of the basin with characteristics similar to the slice (i.e., thickness and lateral extent). For instance, the entire Walker Creek basin is best represented only by Slice 3 because the embankment fill in this basin is relatively narrow and has limited thickness variation (typically less than 40 feet thick). Walker Creek is therefore modeled by Slice 3 only and the results are integrated over the basin using a single EBW. In contrast, Miller Creek is represented by a combination of Slices 1, 2. and 3 because of variable fill geometries that occur in this basin (fill thickness ranging up to 160 feet over a variety of fill lengths). **Figure 2-1** presents the approximate segments of the Miller and Walker Creek basins that are represented by each of the Slice models. A summary of effective basin widths is presented in **Table 5-7**.

The derivation of EBWs is discussed in the following sections followed by a summary of the integrated flow results for each basin.

5.6 Effective Basin Width for Walker Creek

The EBW for Walker Creek basin was calculated to maintain a water balance for the modeled fill area (MFA) measured for the basin, where MFA=IA+FS+OPA as defined in Section 2.3. To maintain a water balance, the integrated area of the slice models must equal the MFA of the basin. When this condition is met, effective recharge for the basin should equal the effective recharge of the integrated slice model results. In the Walker Creek Basin, an EBW of 2,084 feet was calculated based on a Slice 3 length of 350 feet and an MFA of 729,547 square feet.

5.7 Effective Basin Width for Miller Creek

The total EBW for Miller Creek basin is comprised of four segments that are represented by Slices 1, 2 and 3 (**Figure 2-1**). Multiple slices were used to describe groundwater flow to Miller Creek because of the variable fill width and fill thickness in this basin. Similar to Walker Creek, the EBW for Miller Creek was adjusted to maintain a water balance for the MFA measured previously for the basin. That is, the Miller Creek basin fill area (and therefore basin recharge area) defined by the calculated total EBW was the same as the MFA used for Hydrus and Slice modeling. Because the average fill length (east-west) is considerably less than the Slice 2 modeled fill length (east-west) used to represent the north and south ends of the basin, the Slice 2 EBW was reduced to achieve the desired MFA.

The EBW for the segment represented by Slice 1 adjacent to the West MSE wall was assigned a value of 1,600 feet based on map measurements (**Figure 2-1**). The fill length over this reach is relatively uniform at approximately 1,000 feet and is close to the 1,050-foot Slice 1 model length. The map-measured length was therefore considered representative for this reach of the basin and the map length was adopted as the EBW.

The Miller Creek basin reach located north of the West MSE wall is represented by Slice 2. The northeastern corner of the runway fill has an irregular shape where the actual fill length (east-west) is less than the Slice 2 model length. The basin reach immediately south of the West MSE wall is also represented by Slice 2. The combined map width of the two Miller Creek reaches represented by Slice 2 is approximately 3,700 feet. However, to maintain a water balance for the basin, the combined EBW for Slice 2 segments was reduced relative to map widths shown on **Figure 2-1**. The combined EBW for Slice 2 segments was adjusted to 2,699 feet to maintain the water balance. By adjusting the Slice 2 EBW in this manner, an MFA of 5,001,390 square feet was calculated which is approximately equal to the GIS-measured MFA of 5,001,205 square feet.

The southern reach of the Miller Creek basin is represented by Slice 3 where the fill is relatively thin and narrow (east-west). The EBW for this reach of Miller Creek was assigned as the map-estimated length 930 feet. The actual fill length (east-west) of 340 feet is closely approximated by the modeled slice width of 350 feet. The map-measured EBW is therefore considered representative for this reach of the basin as mass balance is maintained.

5.8 Integrated Flow Estimates for Walker Creek Fill

Integrated estimates of Qvr/drain outflow and downward flow through till for the Walker Creek fill area for water years 1991 through 1994 are presented in **Figure 5-7**. Also shown is the effective recharge input to the Hydrus model. Thus, Figure 5-7 indicates changes in timing of flows resulting from both vertical and lateral groundwater travel. Integrated flows for Walker Creek are the product of the 2,084-ft EBW discussed in Section 5.6 and the model results for Slice 3 discussed in Section 5.4. **Figure 5-7** shows that the timing and magnitude of Qvr/drain outflow varies seasonally, with maximum flows predicted during spring or early summer and minimum flows predicted during winter. Estimated annual maximum Qvr/drain outflows through the fill range between about 3,500 cubic feet per day (cfd) in water year 1991 with a peak flow predicted in late March, and about 1500 cfd in 1994 with a peak flow predicted in late April. Estimated annual minimum Qvr/drain outflows are predicted to occur between October and December, with some years experiencing a period of no flow from the Qvr/drain. High flows lag behind the onset of recharge season because time is required for unsaturated flow to transport recharge through the embankment fill and because time is required for lateral flow from areas of recharge to the downgradient end of the model.

Integrated till seepage rates for the Walker Creek basin fill increase rapidly in November or December when the downward moving recharge within the embankment reaches the water table. This effect is accentuated in the Walker Creek case because of the narrow range of fill thicknesses. After a long period of nearly constant discharge following the sudden rise, a gradual decline occurs in late summer. Seepage through the till is estimated to occur at maximum annual rates of 2200 to 2400 cfd for the four year period shown in **Figure 5-7**. Downward flow through the till is predicted to occur at some rate over the entire year.

Quality assurance review included comparison of total inflow to total outflow. For Walker Creek, integrated outflow was about 4 percent greater than total effective recharge for the 11-year test period, likely as a result of lower groundwater storage at the end of the simulation than at the beginning, and/or the coarseness of slice model cell resolution which prevented exact replication of the GIS-measured IA and PA.

5.9 Integrated Flow Estimates for Miller Creek Fill

Integrated estimates of Qvr/drain outflow and downward flow through till for the Miller Creek Fill area for water years 1991 through 1994 are presented in **Figure 5-8**. Integrated flows are the sum of the products of the effective basin widths discussed in Section 5.7 and the model results for Slices 1, 2, and 3 presented in Section 5.4. **Figure 5-8** shows relatively constant Qvr/drain outflow rates from the Miller Creek fill embankment, punctuated by spikes during rainstorms, and a seasonal maximum in June and July of the relatively wet year of 1991. The spikiness is to some extent a modeling artifact of the infinite permeability assumed for Type 1 fill. Actual flow rates would likely be steadier. Estimated annual maximum Qvr/drain outflows range from about 18,000 cfd in April of 1991 to about 8,000 cfd in late-July of 1994 following a year of low recharge.

Integrated downward flow through the till for the Miller Creek basin fill is relatively constant, but with a smooth seasonal pattern. Model estimates of flow range from about 16,000 to 7,000 cfd. Maxima are in April to June. Minima are in October and November.

Quality assurance review included comparison of total inflow to total outflow. For Miller Creek, integrated outflow was 3 percent greater than total effective recharge for the 11-year test period, likely as a result of lower groundwater storage at the end of the simulation than at the beginning, and/or coarseness of cell size resolution in the slices which prevented exact replication of the GIS-measured IA and PA.

5.10 Use of Integrated Flow Estimates

Integrated flow estimates for Miller and Walker Creek basins were transmitted to Parametrix and Aqua Terra for use in HSPF models of Miller and Walker Creeks. Time series of total daily discharge (volume per day) from above the till (Qvr/drain outflow), and total daily discharge through the till (downward flow through the till) were provided. In addition, total runoff as an hourly time series was provided. All volumes were for the MFAs within the Miller Creek and Walker Creek basins. Parametrix and Aqua Terra used the flow estimates developed in this modeling study as part of a low-stream-flow impact evaluation.

6. References

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TABLES

Table 2-1
Summary of Areas Modeled by Hydrus-Slice

	Miller Creek Basin		Walker Creek Basin	
	square feet	acres	square feet	acres
Filter Strip Area (FS)	1,456,854	33.44	353,133	8.11
Other Pervious Fill Area (OPA)	1,746,649	40.10	99,342	2.28
Runway and Taxiway Impervious Area (IA)	1,797,702	41.27	277,072	6.36
Total Modeled Fill Area (MFA) in Basin	5,001,205	114.81	729,547	16.75
IA/total pervious area	0.56		0.61	
FS/PA	0.45		0.78	
IA/total Area	0.36		0.38	

Table 3-1
Summary of Water Volumes

	Water Available to Filer Strip	Water Available to OPA	Runoff from Filter Strip (RO1)	Runoff from Other Pervious Area (RO2)	Water excluded by Hydrus (RO3)	Water artificially removed from Hydrus to promote stability (RO4)	Total Runoff	Total Infiltration
Miller Creek Modeled Fill Area (ft3)	69,006,366	29,689,341	19,625,881	1,652,948	220,585	0	21,499,415	77,196,293
Miller Creek Modeled Fill Area (percent of total water)	70%	30%	20%	2%	0%	0%	22%	78%
Walker Creek Modeled Fill Area (ft3)	12,821,485	1,688,604	2,650,317	94,013	40,091	8,686	2,793,108	11,716,981
Walker Creek Modeled Fill Area (percent of total water)	88%	12%	18%	1%	0%	0%	19%	81%

Table 4-1

Summary of Hydraulic Parameters Used for Fill Matrix in the Hydrus-2D Model

Sand Fraction of matrix	63%
Silt Fraction of matrix	37%
Clay Fraction of matrix	0
Saturated Volumetric Water Content of matrix	0.25
Residual Volumetric Water Content of matrix	0.02
"alpha" (1/cm)	0.088
"N"	1.35
Saturated Hydraulic Conductivity (cm/sec) of matrix	1.35×10^{-4}

Table 5-1
Slice 1 Model Parameters for Different Cell Types

Model Parameters for Cells Types

	Cell Type 1	Cell Type 2	Cell Type 3
Surficial Soil	removed	removed	removed
Aquifer Materials	fill	outwash stringers	peat & outwash
Land Cover	embankment	embankment	embankment
Wetland/Upland	upland	upland	wetland
Bottom Layer Hydraulic Conductivity (ft/d)	300	6	2.65
Top of Bottom Layer (ft above till)	4	7.5	7.5
Middle Layer Hydraulic Conductivity (ft/d)		300	300
Top of Middle Layer (ft above till)		11.5	11.5
Upper Layer Hydraulic Conductivity (ft/d)			
Top of Upper Layer (ft above till)			
Maximum Saturated Thickness (ft)	4	11.5	11.5
Gradient of Top of Till (ft/ft)	18.75%	18.75%	3.60%
Full Thickness Hydraulic Conductivity (ft/d)	300	108.2608696	106.076087
Maximum Subsurface Flow (cfd)	225	233.4375	43.9155
Maximum Downgradient Flow (cfd)	233.4375	43.9155	124.2
Cell Length (ft)	25	25	25
Specific Yield	0.3	0.3	0.3
Maximum Storage (cubic ft)	30	86.25	86.25
Bottom Layer Storage (cubic ft)	30	56.25	56.25

Model Constants

Till Thickness (ft)	10
Till Permeability Beneath Uplands (ft/d)	0.004
Till Permeability Beneath Wetlands (ft/d)	0
Outwash Permeability (ft/d)	6
Peat Permeability (ft/d)	1
Percent Outwash in Peaty Aquifer	0.33
Peaty Aquifer Permeability (ft/d)	2.65
Drain Material Permeability (ft/d)	300
Till Derived Soil Permeability (ft/d)	4
Outwash Derived Soil Permeability (ft/d)	4
Wetland Surficial Soil Permeability (ft/d)	1
Minimum Saturation Considered for h and T (ft)	0.0001

NOTE: All values are for a vertical slice of 1-foot width.

Time Stepping

user defined model timestep (d)	0.1

Table 5-2
Slice 1 Model Cell Parameters

Cell ID	Distance from Outlet	Top of Till Elevation	Cell Length (ft)	Cell Type	Till Perme-ability (ft/d)	Head at Bottom of Till	Maximum Subsurface Outflow (cf/d)	Specific Yield	Maximum Storage (cf)	Fill Material	Embankment Thickness (ft)	Modeled "Effective" Embankment Thickness (ft)	
1	1137.5	385.0438	25	1	0.004	375.0438	225	0.3	30	Type 2	3	0	
2	1112.5	380.3563	25	1	0.004	370.3563	225	0.3	30	Type 2	7	10	
3	1087.5	375.6688	25	1	0.004	365.6688	225	0.3	30	Type 2	11	10	
4	1062.5	370.9813	25	1	0.004	360.9813	225	0.3	30	Type 2	14	10	
5	1037.5	366.2938	25	1	0.004	356.2938	225	0.3	30	Type 2	19	10	
6	1012.5	361.6063	25	1	0.004	351.6063	225	0.3	30	Type 2	24	-99	taxiway, no recharge
7	987.5	356.9188	25	1	0.004	346.9188	225	0.3	30	Type 2	27	30	
8	962.5	352.2313	25	1	0.004	342.2313	225	0.3	30	Type 2	32	-99	taxiway, no recharge
9	937.5	347.5438	25	1	0.004	337.5438	225	0.3	30	Type 2	35	30	
10	912.5	342.8563	25	1	0.004	332.8563	225	0.3	30	Type 2	40	-99	taxiway, no recharge
11	887.5	338.1688	25	1	0.004	328.1688	225	0.3	30	Type 2	44	50	
12	862.5	333.4813	25	1	0.004	323.4813	225	0.3	30	Type 2	49	-99	taxiway, no recharge
13	837.5	328.7938	25	1	0.004	318.7938	225	0.3	30	Type 2	54	50	
14	812.5	324.1063	25	1	0.004	314.1063	225	0.3	30	Type 2	57	-99	taxiway, no recharge
15	787.5	319.4188	25	1	0.004	309.4188	225	0.3	30	Type 2	60	50	
16	762.5	314.7313	25	2	0.004	304.7313	233.4375	0.3	86.25	Type 2	64	-99	taxiway, no recharge
17	737.5	310.0438	25	2	0.004	300.0438	233.4375	0.3	86.25	Type 2	69	70	
18	712.5	305.3563	25	2	0.004	295.3563	233.4375	0.3	86.25	Type 2	74	70	
19	687.5	300.6688	25	2	0.004	290.6688	233.4375	0.3	86.25	Type 2	78	70	
20	662.5	295.9813	25	2	0.004	285.9813	233.4375	0.3	86.25	Type 2	84	90	
21	637.5	291.2938	25	2	0.004	281.2938	233.4375	0.3	86.25	Type 2	90	90	
22	612.5	286.6063	25	2	0.004	276.6063	233.4375	0.3	86.25	Type 2	96	90	
23	587.5	281.9188	25	2	0.004	271.9188	233.4375	0.3	86.25	Type 2	101	110	
24	562.5	277.2313	25	2	0.004	267.2313	233.4375	0.3	86.25	Type 2	105	110	
25	537.5	272.5438	25	2	0.004	267.5438	233.4375	0.3	86.25	Type 2	111	110	
26	512.5	267.8563	25	2	0.004	262.8563	233.4375	0.3	86.25	Type 2	116	-99	runway, no recharge
27	487.5	263.1688	25	2	0.004	258.1688	233.4375	0.3	86.25	Type 2	120	-99	runway, no recharge
28	462.5	258.4813	25	2	0.004	253.4813	233.4375	0.3	86.25	Type 2	125	-99	runway, no recharge
29	437.5	253.7938	25	2	0.004	248.7938	233.4375	0.3	86.25	Type 2	128	-99	runway, no recharge
30	412.5	249.1063	25	2	0.004	244.1063	233.4375	0.3	86.25	Type 2	132	-99	runway, no recharge
31	387.5	244.4188	25	2	0.004	239.4188	233.4375	0.3	86.25	Type 2	138	-99	runway, no recharge
32	362.5	239.7313	25	2	0.004	234.7313	233.4375	0.3	86.25	Type 2	142	-99	runway, no recharge
33	337.5	235.0438	25	2	0.004	230.0438	43.9155	0.3	86.25	Type 2	147	-99	runway, no recharge
34	312.5	232.25	25	5	0	222.25	43.9155	0.3	86.25	Type 2	148	-99	runway, no recharge
35	287.5	231.35	25	5	0	221.35	43.9155	0.3	86.25	Type 2	148	150	
36	262.5	230.45	25	5	0	220.45	43.9155	0.3	86.25	Type 2	148	150	
37	237.5	229.55	25	5	0	219.55	43.9155	0.3	86.25	Type 2	148	150	
38	212.5	228.65	25	5	0	218.65	43.9155	0.3	86.25	Type 2	148	150	
39	187.5	227.75	25	5	0	217.75	43.9155	0.3	86.25	Type 2	148	150	
40	162.5	226.85	25	5	0	216.85	43.9155	0.3	86.25	Type 1	148	0	
41	137.5	225.95	25	5	0	215.95	43.9155	0.3	86.25	Type 1	146	0	
42	112.5	225.05	25	5	0	215.05	43.9155	0.3	86.25	Type 1	145	0	
43	87.5	224.15	25	5	0	214.15	43.9155	0.3	86.25	Type 1	115	0	not included in mass balance
44	62.5	223.25	25	5	0	213.25	43.9155	0.3	86.25	Type 1	35	0	not included in mass balance
45	37.5	222.35	25	5	0	212.35	43.9155	0.3	86.25	Type 1	7	0	not included in mass balance
46	12.5	221.45	25	5	0	211.45	9999	0.3	86.25	Type 1	0	0	not included in mass balance

Table 5-3
Slice 2 Model Parameters for Different Cell Types

Model Parameters for Cells Types	cells 1-3, 8-9 **Cell Type 1**	cells 4-7 **Cell Type 2**	cells 10-13 **Cell Type 3**	cells 14-28 **Cell Type 4**	cells 29-43 **Cell Type 5**	cells 44-46 **Cell Type 6**
Surficial Soil	removed	removed	removed	removed	removed	removed
Aquifer Materials	outwash stringers	outwash stringers	outwash stringers	outwash stringers	outwash stringers	outwash stringers
Land Cover	embankment	embankment	embankment	embankment	embankment	embankment
Wetland/Upland	upland	upland	upland	upland	upland	upland
Bottom Layer Hydraulic Conductivity (ft/d)	6	6	6	6	6	6
Top of Bottom Layer (ft above till)	39.5	45	28.25	15	15	15
Middle Layer Hydraulic Conductivity (ft/d)	300	300	300	300	300	300
Top of Middle Layer (ft above till)	43.5	49	32.25	19	19	19
Upper Layer Hydraulic Conductivity (ft/d)						
Top of Upper Layer (ft above till)						
Maximum Saturated Thickness (ft)	43.5	49	32.25	19	19	19
Gradient of Top of Till (ft/ft)	0.0908	0.0908	0.0908	0.0908	0.0507	0.0165
Full Thickness Hydraulic Conductivity (ft/d)	33.03448276	30	42.46511628	67.89473684	67.89473684	67.8947368
Maximum Subsurface Flow (cfd)	130.4796	133.476	124.3506	117.132	65.403	21.285
Maximum Downgradient Flow (cfd)	133.476	65.403	21.285	117.132	65.403	21.285
Cell Length (ft)	30	30	30	30	30	30
Specific Yield	0.3	0.3	0.3	0.3	0.3	0.3
Maximum Storage (cubic ft)	391.5	441	290.25	171	171	171
Bottom Layer Storage (cubic ft)	355.5	405	254.25	135	135	135

Model Constants	
Till Thickness (ft)	10
Till Permeability Beneath Uplands (ft/d)	0.004
Till Permeability Beneath Wetlands (ft/d)	0
Outwash Permeability (ft/d)	6
Peat Permeability (ft/d)	1
Percent Outwash in Peaty Aquifer	33%
Peaty Aquifer Permeability (ft/d)	2.65
Drain Material Permeability (ft/d)	300
Till Derived Soil Permeability (ft/d)	4
Outwash Derived Soil Permeability (ft/d)	4
Wetland Surficial Soil Permeability (ft/d)	1
Minimum Saturation Considered for h and T (ft)	0.0001
user defined model timestep (d)	0.1

NOTE: All values are for a vertical slice of 1-foot width.

Table 5-4
Slice 2 Model Cell Parameters

Cell ID	Distance from Outlet	Top of Till Elevation	Cell Length (ft)	Cell Type	Till Perme-ability (ft/d)	Head at Bottom of Till	Maximum Subsurface Outflow (cfd)	Specific Yield	Maximum Storage (cf)	Fill Material	Embankment Thickness (ft)	Modeled "Effective" Embankment Thickness (ft)	
1	1365	371.9939	30	1	0.004	361.9939	130.4796	0.3	391.5	Type1	0	0	drain only, no overlying fill
2	1335	369.0941	30	1	0.004	359.0941	130.4796	0.3	391.5	Type1	0	0	drain only, no overlying fill
3	1305	366.1944	30	1	0.004	356.1944	130.4796	0.3	391.5	Type 2	0.5432	0	
4	1275	363.2946	30	2	0.004	353.2946	133.476	0.3	441	Type 2	1.3605	0	
5	1245	360.3949	30	2	0.004	350.3949	133.476	0.3	441	Type 2	2.1778	0	
6	1215	357.4951	30	2	0.004	347.4951	133.476	0.3	441	Type 2	9	10	
7	1185	354.5954	30	2	0.004	344.5954	133.476	0.3	441	Type 2	25	-99	taxiway/unspec., no recharge
8	1155	351.6956	30	1	0.004	341.6956	130.4796	0.3	391.5	Type 2	32	30	
9	1125	348.7959	30	1	0.004	338.7959	130.4796	0.3	391.5	Type 2	39	-99	taxiway/unspec., no recharge
10	1095	345.8961	30	3	0.004	335.8961	124.3506	0.3	290.25	Type 2	44	50	
11	1065	342.9964	30	3	0.004	332.9964	124.3506	0.3	290.25	Type 2	49	-99	taxiway/unspec., no recharge
12	1035	340.0966	30	3	0.004	330.0966	124.3506	0.3	290.25	Type 2	51	50	
13	1005	337.1735	30	3	0.004	327.1735	124.3506	0.3	290.25	Type 2	53	-99	taxiway/unspec., no recharge
14	975	334.2466	30	4	0.004	324.2466	117.132	0.3	171	Type 2	54	50	
15	945	331.3197	30	4	0.004	321.3197	117.132	0.3	171	Type 2	55	-99	taxiway/unspec., no recharge
16	915	328.3928	30	4	0.004	318.3928	117.132	0.3	171	Type 2	58	50	
17	885	325.4658	30	4	0.004	315.4658	117.132	0.3	171	Type 2	59	50	
18	855	322.5389	30	4	0.004	312.5389	117.132	0.3	171	Type 2	62.6913	70	
19	825	320.0984	30	4	0.004	310.0984	117.132	0.3	171	Type 2	66.5809	70	
20	795	317.669	30	4	0.004	307.669	117.132	0.3	171	Type 2	70.4705	70	
21	765	315.2396	30	4	0.004	305.2396	117.132	0.3	171	Type 2	74.3601	70	
22	735	312.8102	30	4	0.004	307.8102	117.132	0.3	171	Type 2	77.8707	-99	runway, no recharge
23	705	310.3808	30	4	0.004	305.3808	117.132	0.3	171	Type 2	81.0024	-99	runway, no recharge
24	675	307.9514	30	4	0.004	302.9514	117.132	0.3	171	Type 2	84.1341	-99	runway, no recharge
25	645	305.5219	30	4	0.004	300.5219	117.132	0.3	171	Type 2	86.9	-99	runway, no recharge
26	615	303.0925	30	4	0.004	298.0925	117.132	0.3	171	Type 2	89.3	-99	runway, no recharge
27	585	300.6631	30	4	0.004	295.6631	117.132	0.3	171	Type 2	91.1685	-99	runway, no recharge
28	555	298.4282	30	4	0.004	293.4282	117.132	0.3	171	Type 2	92.2579	-99	runway, no recharge
29	525	296.9078	30	5	0	286.9078	65.403	0.3	171	Type 2	92.7119	-99	runway, no recharge
30	495	295.3875	30	5	0	285.3875	65.403	0.3	171	Type 2	93.1633	90	
31	465	293.8671	30	5	0	283.8671	65.403	0.3	171	Type 2	93.7422	90	
32	435	292.3468	30	5	0	282.3468	65.403	0.3	171	Type 2	94.301	90	
33	405	290.8264	30	5	0	280.8264	65.403	0.3	171	Type 2	94.8599	90	
34	375	289.3061	30	5	0	279.3061	65.403	0.3	171	Type 2	95.1136	90	
35	345	287.7858	30	5	0	277.7858	65.403	0.3	171	Type 2	95.0621	90	
36	315	286.2654	30	5	0	276.2654	65.403	0.3	171	Type 2	95.0105	90	
37	285	284.7451	30	5	0	274.7451	65.403	0.3	171	Type 2	94.9444	90	top of embankment and western edge of area receiving recharge
38	255	283.2247	30	5	0	273.2247	65.403	0.3	171	Type 2	83.3366	-99	no recharge
39	225	281.7044	30	5	0	271.7044	65.403	0.3	171	Type 2	71.7288	-99	no recharge
40	195	280.184	30	5	0	270.184	65.403	0.3	171	Type 2	60.1209	-99	no recharge
41	165	278.6637	30	5	0	268.6637	65.403	0.3	171	Type 2	48.5131	-99	no recharge
42	135	277.1433	30	5	0	267.1433	65.403	0.3	171	Type 2	37.6989	-99	no recharge
43	105	275.623	30	5	0	265.623	65.403	0.3	171	Type 2	27.0434	-99	no recharge
44	75	274.7676	30	6	0	264.7676	21.285	0.3	171	Type 2	16.388	-99	no recharge
45	45	274.2734	30	6	0	264.2734	21.285	0.3	171	Type 2	5.5944	-99	no recharge
46	15	273.7791	30	6	0	263.7791	21.285	0.3	171	Type 2	0	-99	no recharge

Table 5-5
Slice 3 Model Parameters for Different Cell Types

	Cell Type 1	Cell Type 2	Cell Type 3
Surficial Soil	removed	removed	removed
Aquifer Materials	outwash stringers	outwash stringers	outwash stringers
Land Cover	embankment	embankment	embankment
Wetland/Upland	upland	upland	upland
Bottom Layer Hydraulic Conductivity (ft/d)	6	6	6
Top of Bottom Layer (ft above till)	2.5	2.5	4.75
Middle Layer Hydraulic Conductivity (ft/d)	300	300	300
Top of Middle Layer (ft above till)	3	6.5	8.75
Upper Layer Hydraulic Conductivity (ft/d)			
Top of Upper Layer (ft above till)			
Maximum Saturated Thickness (ft)	3	6.5	8.75
Gradient of Top of Till (ft/ft)	0.1711	0.0518	0.0518
Full Thickness Hydraulic Conductivity (ft/d)	55	186.9230769	140.4
Maximum Subsurface Flow (cfd)	28.2315	62.937	63.6363
Maximum Downgradient Flow (cfd)	28.2315	62.937	63.6363
Cell Length (ft)	25	25	25
Specific Yield	0.3	0.3	0.3
Maximum Storage (cubic ft)	22.5	48.75	65.625
Bottom Layer Storage (cubic ft)	18.75	18.75	35.625

Model Constants	
Till Thickness (ft)	10
Till Permeability Beneath Uplands (ft/d)	0.004
Till Permeability Beneath Wetlands (ft/d)	0
Outwash Permeability (ft/d)	6
Peat Permeability (ft/d)	1
Percent Outwash in Peaty Aquifer	0.33
Peaty Aquifer Permeability (ft/d)	2.65
Drain Material Permeability (ft/d)	300
Till Derived Soil Permeability (ft/d)	4
Outwash Derived Soil Permeability (ft/d)	4
Wetland Surficial Soil Permeability (ft/d)	1
Minimum Saturation Considered for h and T (ft)	0.0001
Time Stepping	
user defined model timestep (d)	0.1

NOTE: All values are for a vertical slice of 1-foot width.

Table 5-6
Slice 3 Model Cell Parameters

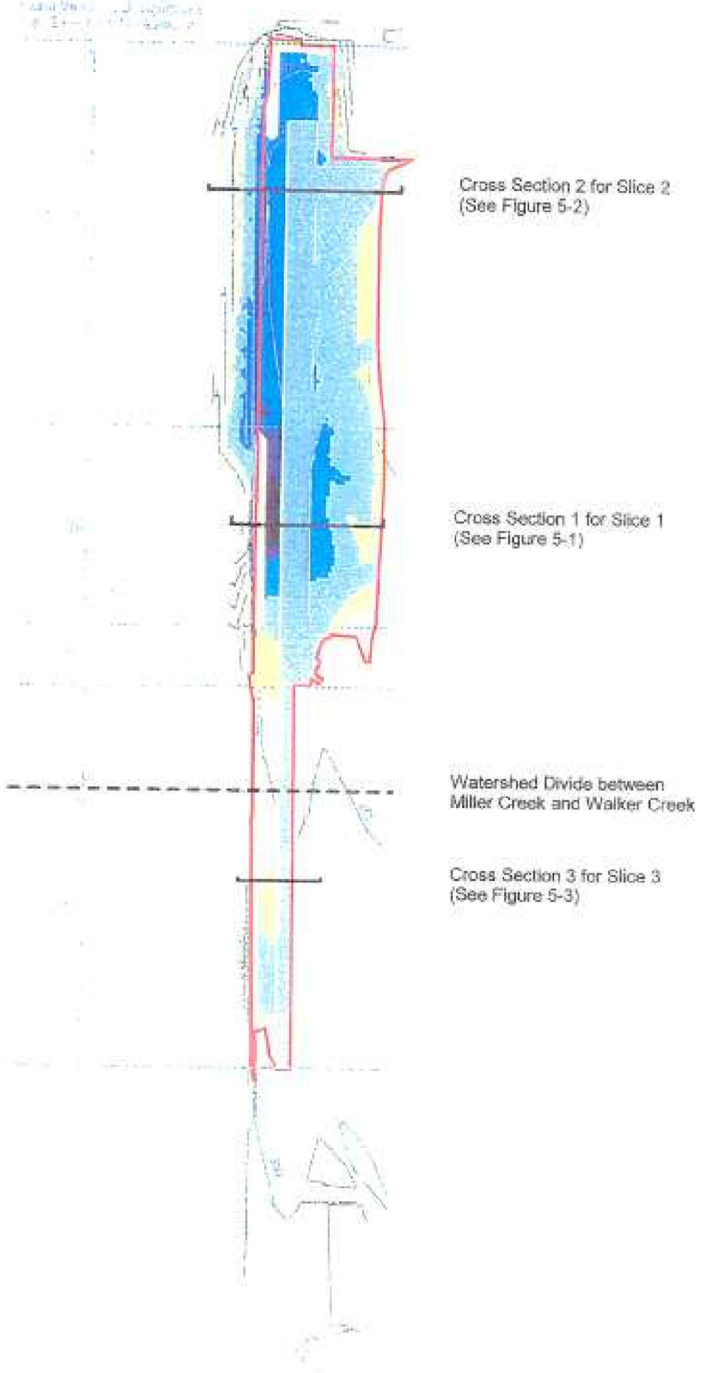
Cell ID	Distance from Outlet	Top of Till Flevation	Cell Length (ft)	Cell Type	Till Perme-ability (ft/d)	Head at Bottom of Till	Maximum Subsurface Outflow (cfd)	Specific Yield	Maximum Storage (cf)	Fill Material	Embankment Thickness (ft)	Modeled "Effective" Embankment Thickness (ft)	
1	612 5	368 7677	25	1	0 004	358 7677	28 2315	0 3	22 5	Type 2	0	-99	drain only, no overlying fill, excluded from model via zero recharge
2	587 5	366 3032	25	1	0 004	356 3032	28.2315	0 3	22.5	Type 2	0	-99	drain only, no overlying fill, excluded from model via zero recharge
3	562 5	363 9638	25	2	0 004	353 9638	62 937	0 3	48 75	Type 2	0	-99	drain only, no overlying fill, excluded from model via zero recharge
4	537 5	362 6697	25	2	0 004	352 6697	62 937	0 3	48 75	Type 2	0 8512	-99	excluded from model via zero recharge
5	512 5	361 3756	25	2	0 004	351 3756	62 937	0 3	48 75	Type 2	2 1642	-99	excluded from model via zero recharge
6	487 5	360 0815	25	2	0 004	350 0815	62 937	0 3	48 75	Type 2	3 6315	-99	runway, no recharge
7	462 5	358 7874	25	2	0 004	348 7874	62 937	0 3	48 75	Type 2	5.3445	-99	runway, no recharge
8	437 5	357 4933	25	2	0 004	347 4933	62 937	0 3	48 75	Type 2	7 0575	-99	runway, no recharge
9	412 5	356 1992	25	2	0 004	346 1992	62 937	0 3	48 75	Type 2	8 7706	-99	runway, no recharge
10	387 5	354 9051	25	2	0 004	344.9051	62.937	0 3	48 75	Type 2	10 4836	-99	runway, no recharge
11	362 5	353 611	25	2	0 004	343 611	62 937	0 3	48 75	Type 2	11 8861	-99	runway, no recharge
12	337 5	352.317	25	2	0 004	342.317	62 937	0 3	48.75	Type 2	12 8011	-99	runway, no recharge
13	312 5	351 0229	25	2	0 004	341 0229	62 937	0 3	48 75	Type 2	13.5926	-99	runway, no recharge
14	287 5	349 7288	25	2	0 004	339 7288	62 937	0 3	48 75	Type 2	14 3831	-99	runway, no recharge
15	262 5	348 4347	25	2	0 004	338 4347	62 937	0 3	48 75	Type 2	15 1737	-99	runway, no recharge
16	237 5	347 1406	25	2	0 004	337 1406	62 937	0 3	48 75	Type 2	15 7615	20	
17	212 5	345 8465	25	2	0 004	335 8465	62 937	0 3	48 75	Type 2	16 1106	20	
18	187 5	344 5524	25	2	0 004	334 5524	62 937	0 3	48 75	Type 2	16.5094	20	
19	162 5	343 2583	25	2	0 004	333 2583	62 937	0 3	48 75	Type 2	16.9061	20	
20	137 5	341 9642	25	2	0 004	331 9642	62 937	0 3	48.75	Type 2	17 3068	20	
21	112.5	340.6701	25	2	0 004	330.6701	62 937	0 3	48 75	Type 2	17.7058	20	
22	87 5	339.376	25	2	0 004	329 376	62 937	0 3	48.75	Type 2	18 1308	20	
23	62 5	338 0819	25	3	0 004	328 0819	63 6363	0 3	65 625	Type 2	19.1419	20	
24	37 5	336 7878	25	3	0 004	326 7878	63 6363	0 3	65 625	Type 2	17 3761	20	top of embankment and western edge of area receiving recharge in this cell
25	12 5	335 4937	25	3	0.004	325.4937	63 6363	0 3	65 625	Type 2	6 5615	-99	no recharge

Table 5-7
Summary of Effective Basin Widths for Walker and Miller Creek Flow Estimates

Basin & Slice Representation	Impermeable Area, IA (sf)	Permeable Area, PA= FS+OPA (sf)	Modeled Fill Area (MFA) = IA+PA (sf)	Slice Active Cell Count	Slice Model Cell Length (ft)	Active Slice Length (ASL, ft)	Effective Basin Width (EBW, ft)	Approx. Mapped Basin Width (MBW, ft)	Fraction of EBW
Walker Creek	277,072	452,475	729,547						
Slice 3				14	25	350	2,084	2,300	100.0%
Miller Creek	1,797,702	3,203,503	5,001,205				5,229	6,230	
Slice 1				42	25	1,050	1,600	1,600	30.6%
Slice 2				37	30	1,110	2,699	3,700	51.6%
Slice 3				14	25	350	930	930	17.8%

Note: lengths are measured east-west and widths are measured north-south.

FIGURES



Depth of Fill (feet)

☐	0 - 20
▨	21 - 40
▨	41 - 60
▨	61 - 80
▨	81 - 100
▨	101 - 120
▨	121 - 140
▨	141 - 160

Approximate Area Modeled by Hydrus and Slice (Clipped from HSPF)*

Impervious Area

"Built" Elevation Contours (25 ft interval)

N

0 1000 Feet

1:12,000

Figure 2-1

Site Features for
Hydrus-Slice Modeling

SeaTac Third Runway
Embankment Fill Modeling
JE0106

Pacific Groundwater Group

Figure 4-1 - Hydrus Model Output for Miller Creek Fill - Water Years 1991 - 1994

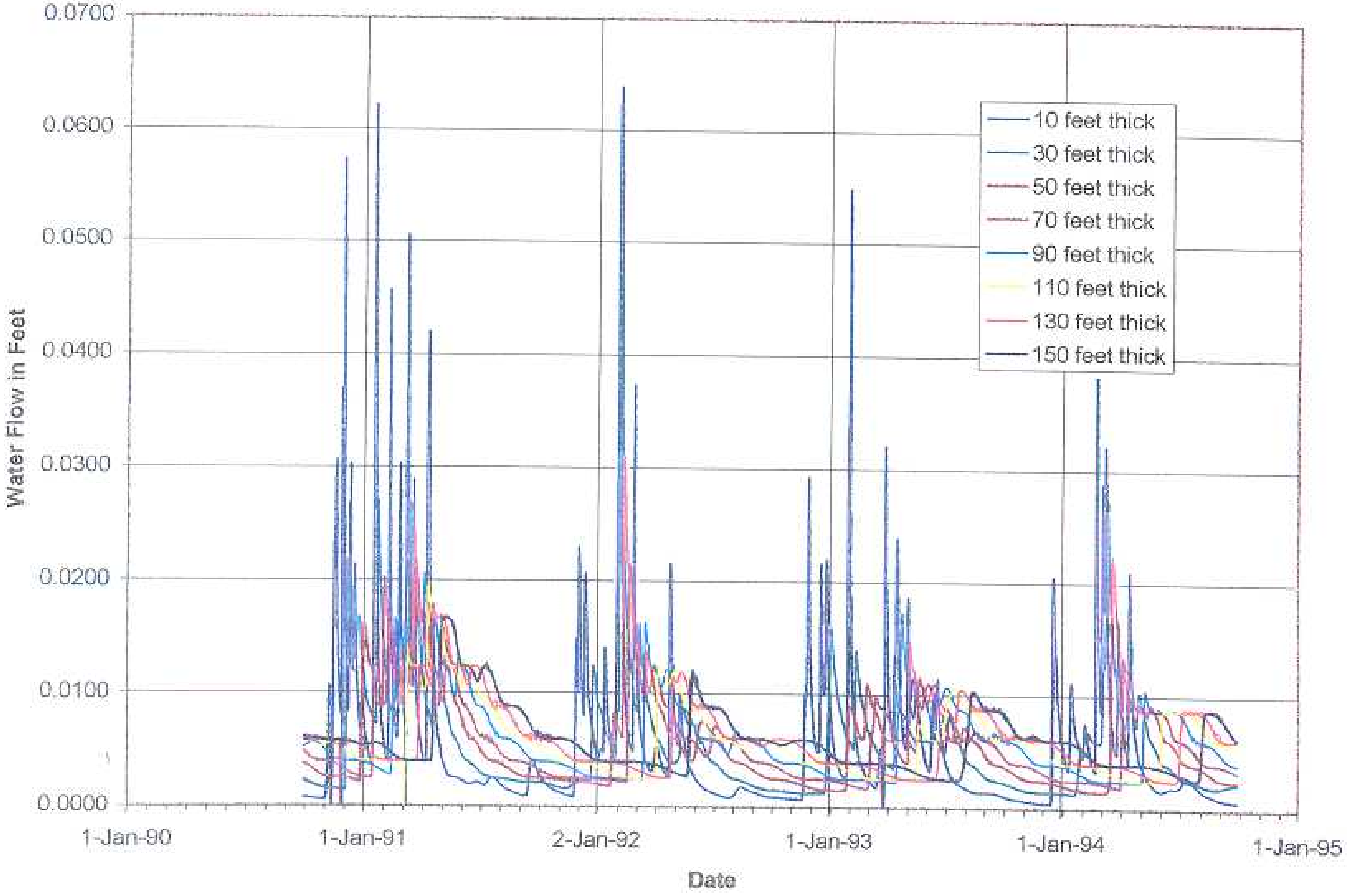
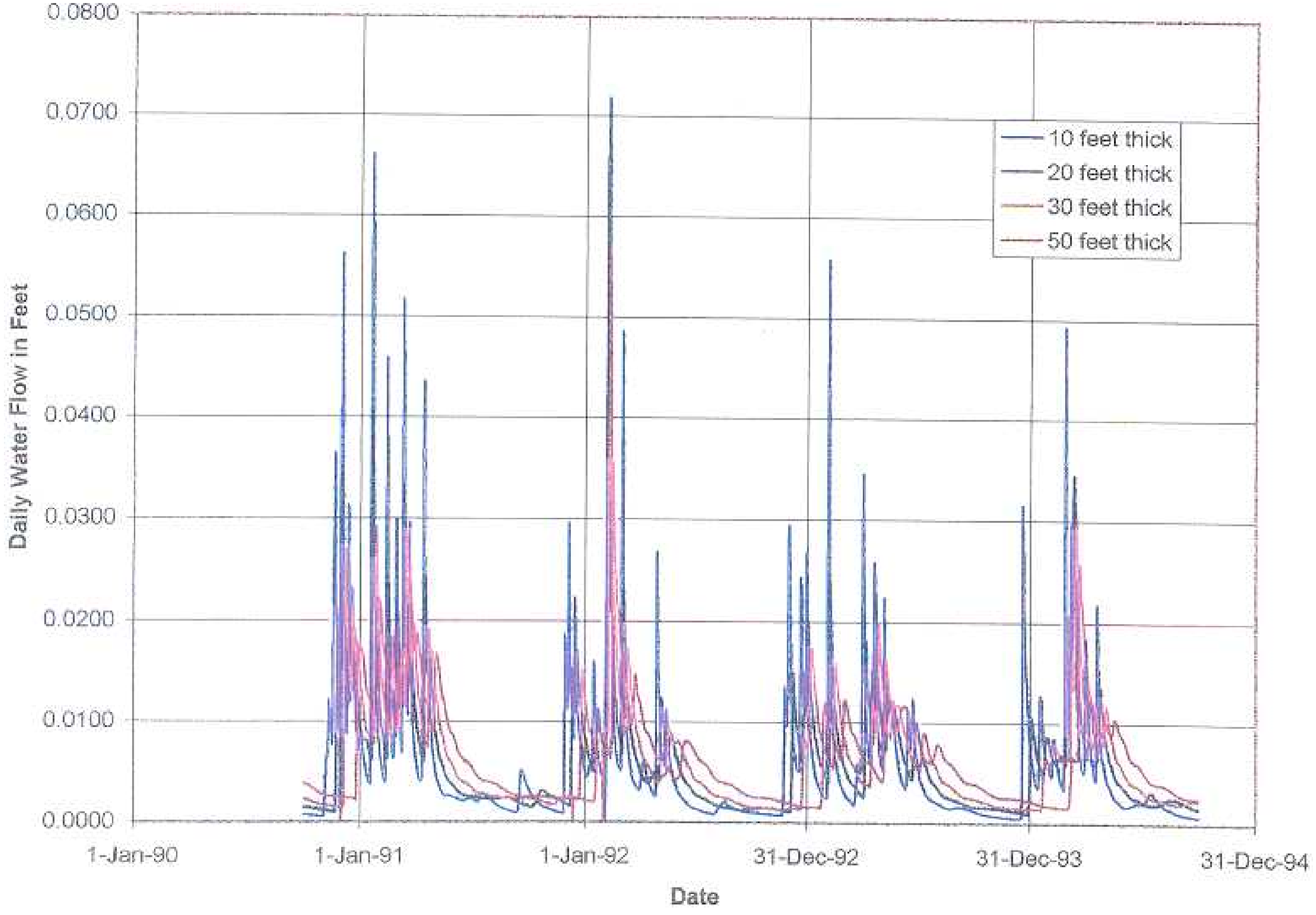
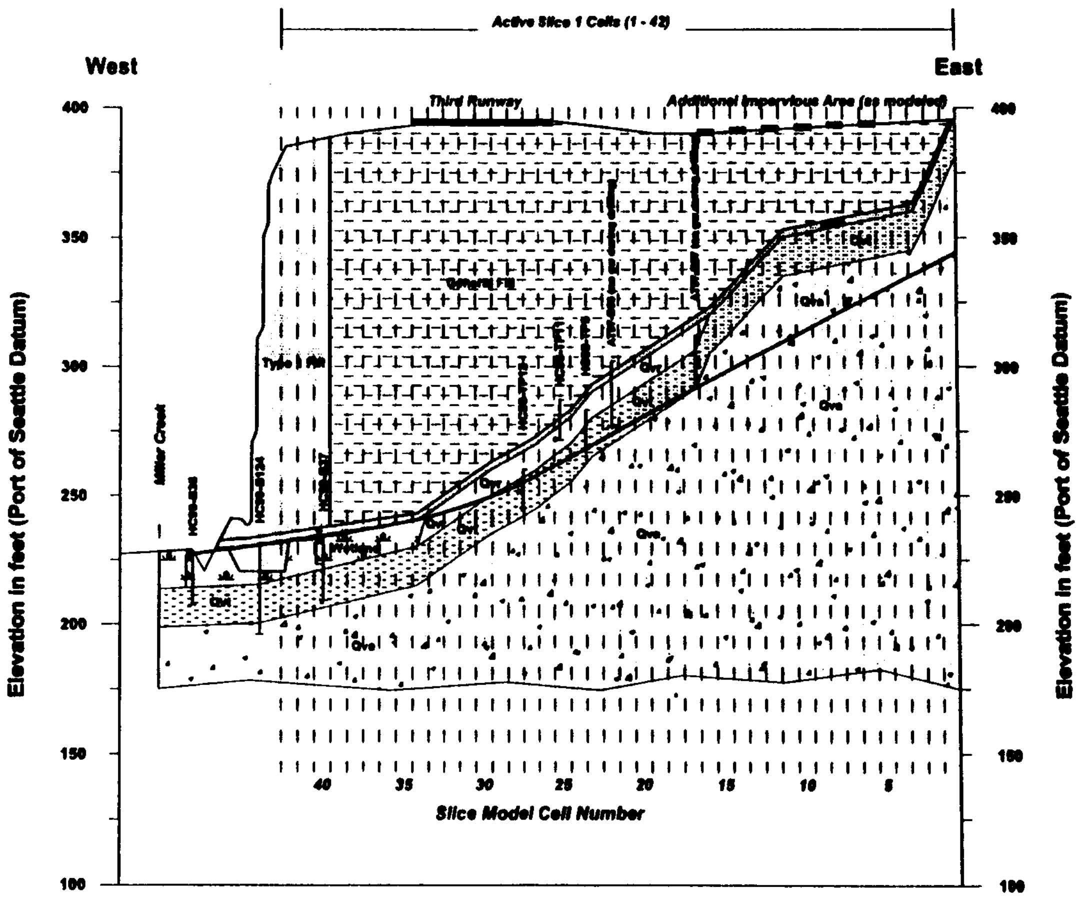


Figure 4-2 - Hydrus Model Output for Walker Creek Fill - Water Years 1991 - 1994





LEGEND

▼ Groundwater Elevation

● Groundwater Seepage Elevation

—▽— Conceptual Water Table

General Fill

Type 1 Fill

Wetland

Qvr - Vashon Recessional Outwash

Qvt - Vashon Till

Qva - Vashon Advance Outwash

Well with high and low water level and identifier

Horizontal Scale in Feet

0 100 200

0 25 50

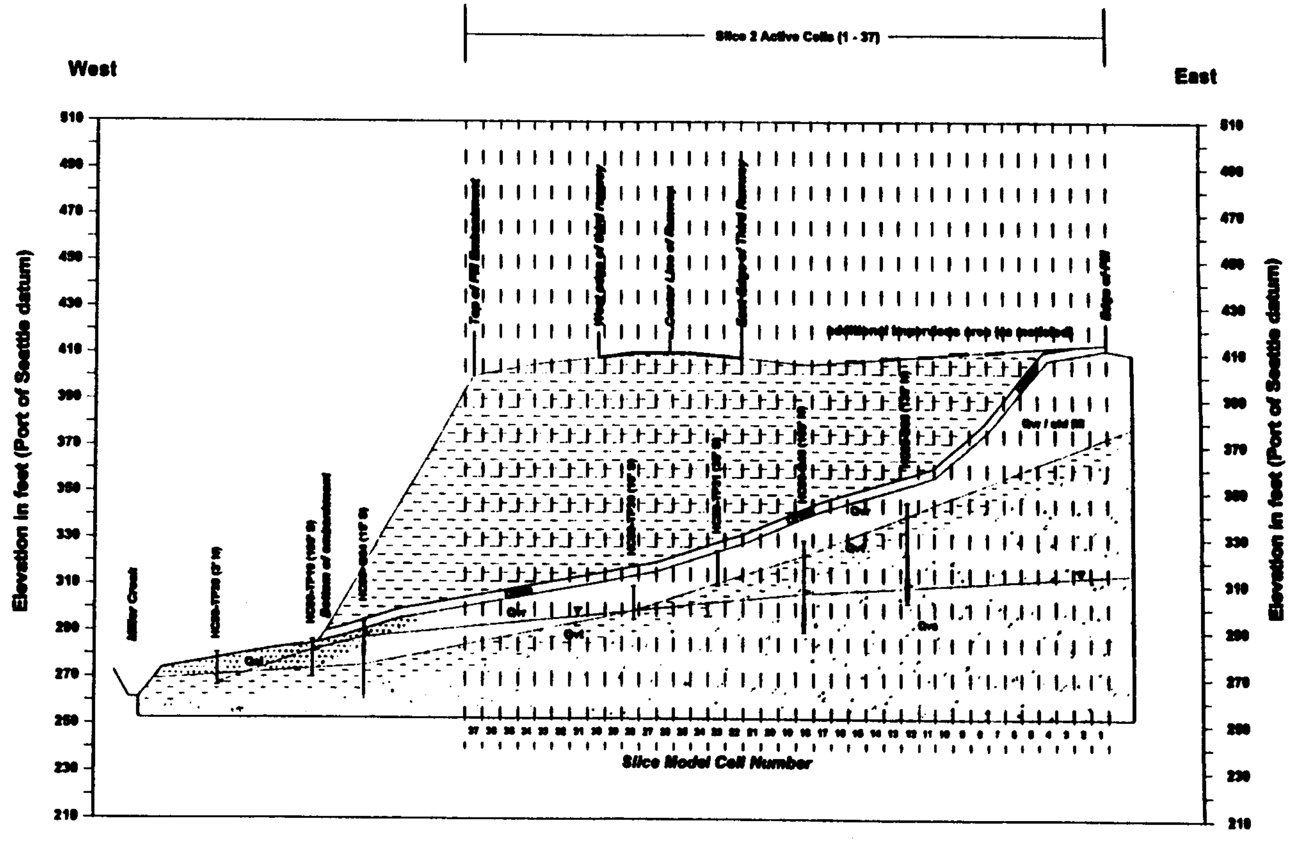
Vertical Scale in Feet

FIGURE 5-1

Simplified Cross Section for Slice 1

SeaTac Third Runway
Embankment Fill Modeling

Pacific Groundwater Group



LEGEND

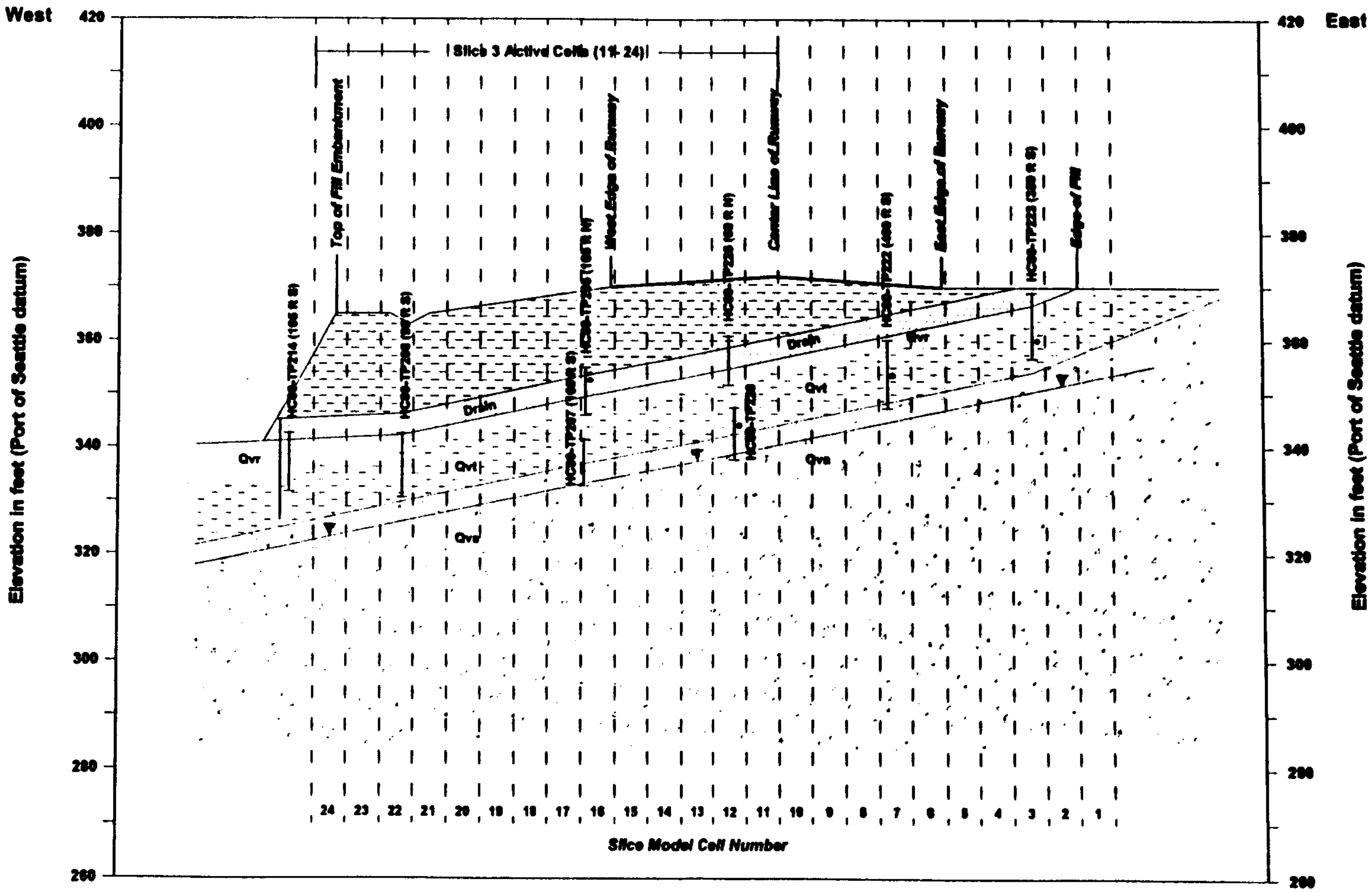
- ▼ Groundwater Elevation
- ● Groundwater Seepage Elevation
- ▼ Conceptual Water Table
- General Fill
- Qvr - Vashon Recessional Outwash
- Qvt - Vashon Till
- Qva - Vashon Advance Outwash
- Qal - Recent Alluvium
- Well with high and low water level and identifier

Horizontal Scale in Feet
0 100 200
0 25 50
Vertical Scale in Feet

FIGURE 5-2
Simplified Cross Section for Slice 2

SeaTac Third Runway
Embankment Fill Modeling

Pacific
Groundwater
Group



LEGEND

▼ Groundwater Elevation
● Groundwater Seepage Elevation
▽ Conceptual Water Table

▨ General Fill
☐ Qvr - Vashon Recessional Outwash
▨ Qvt - Vashon Till
▨ Qva - Vashon Advance Outwash

HC98-999 Well with high and low water level and identifier

Horizontal Scale in Feet
0 40 80
0 10 20
Vertical Scale in Feet

FIGURE 6-3
Simplified Cross Section for Slice 3

SeaTac Third Runway
Embankment Fill Modeling

Pacific Groundwater Group

Figure 5-4 Slice 1 Model Output for Test Period

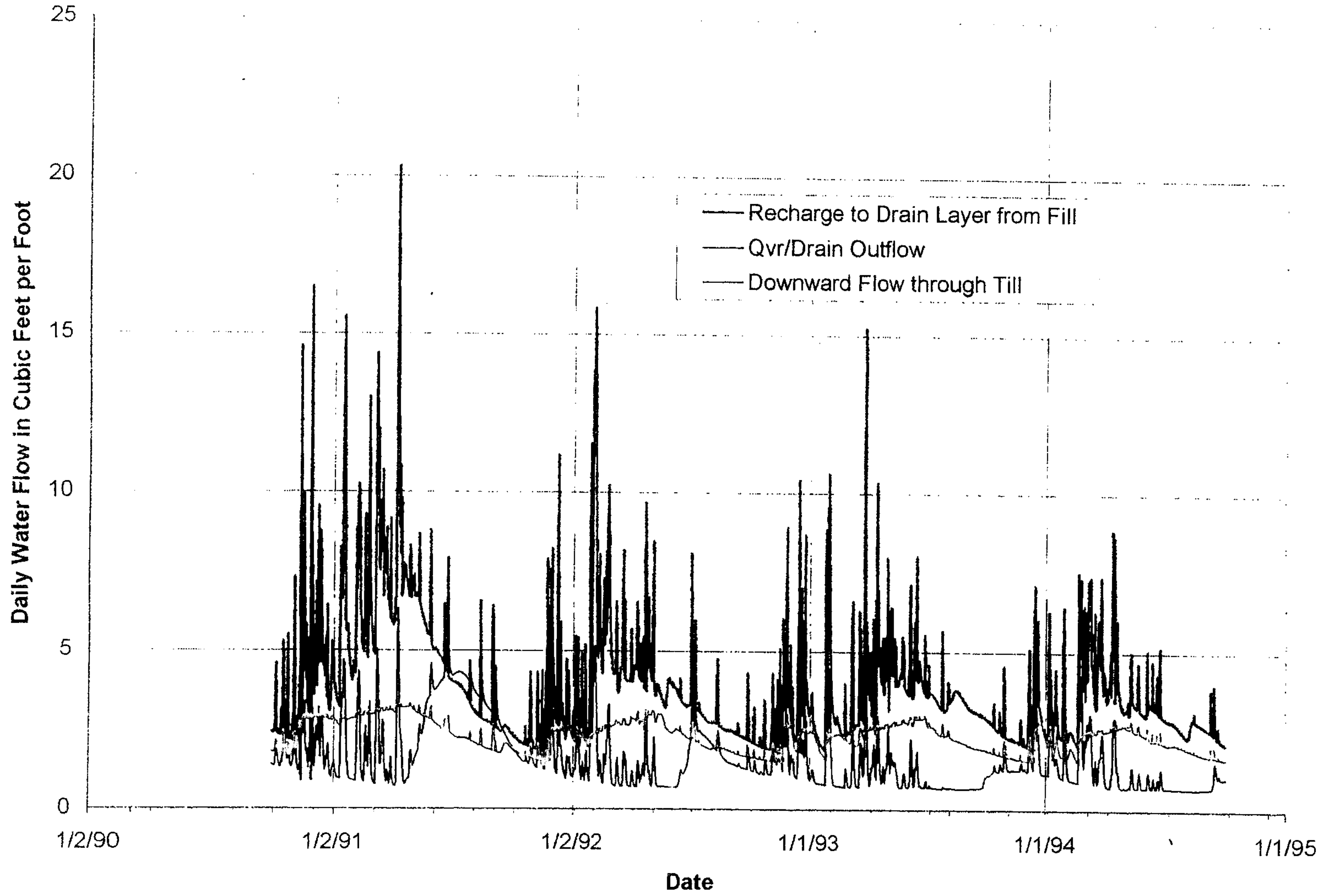


Figure 5-5 - Slice 2 Model Output for Test Period

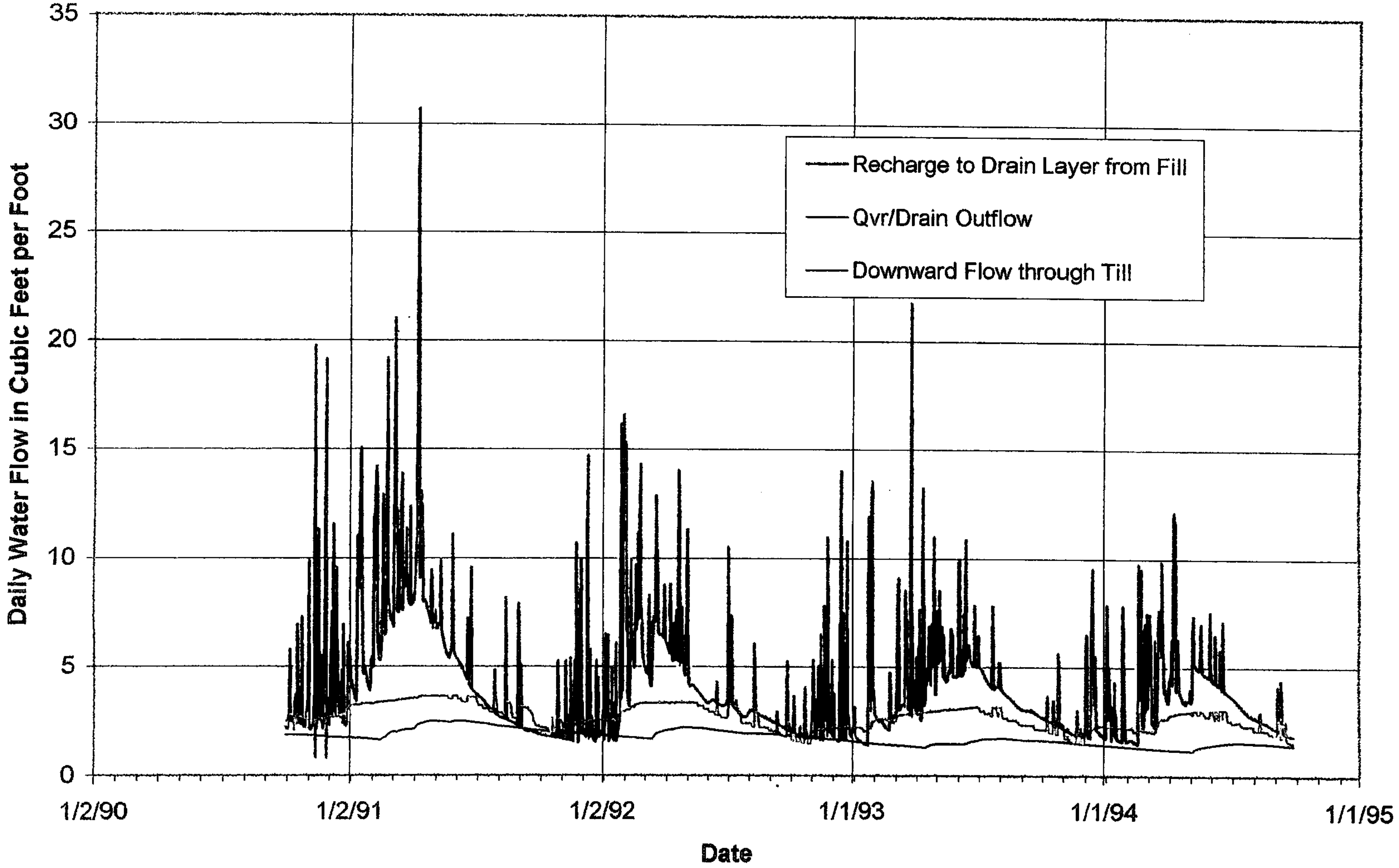


Figure 5-6 - Slice 3 Model Output for Test Period

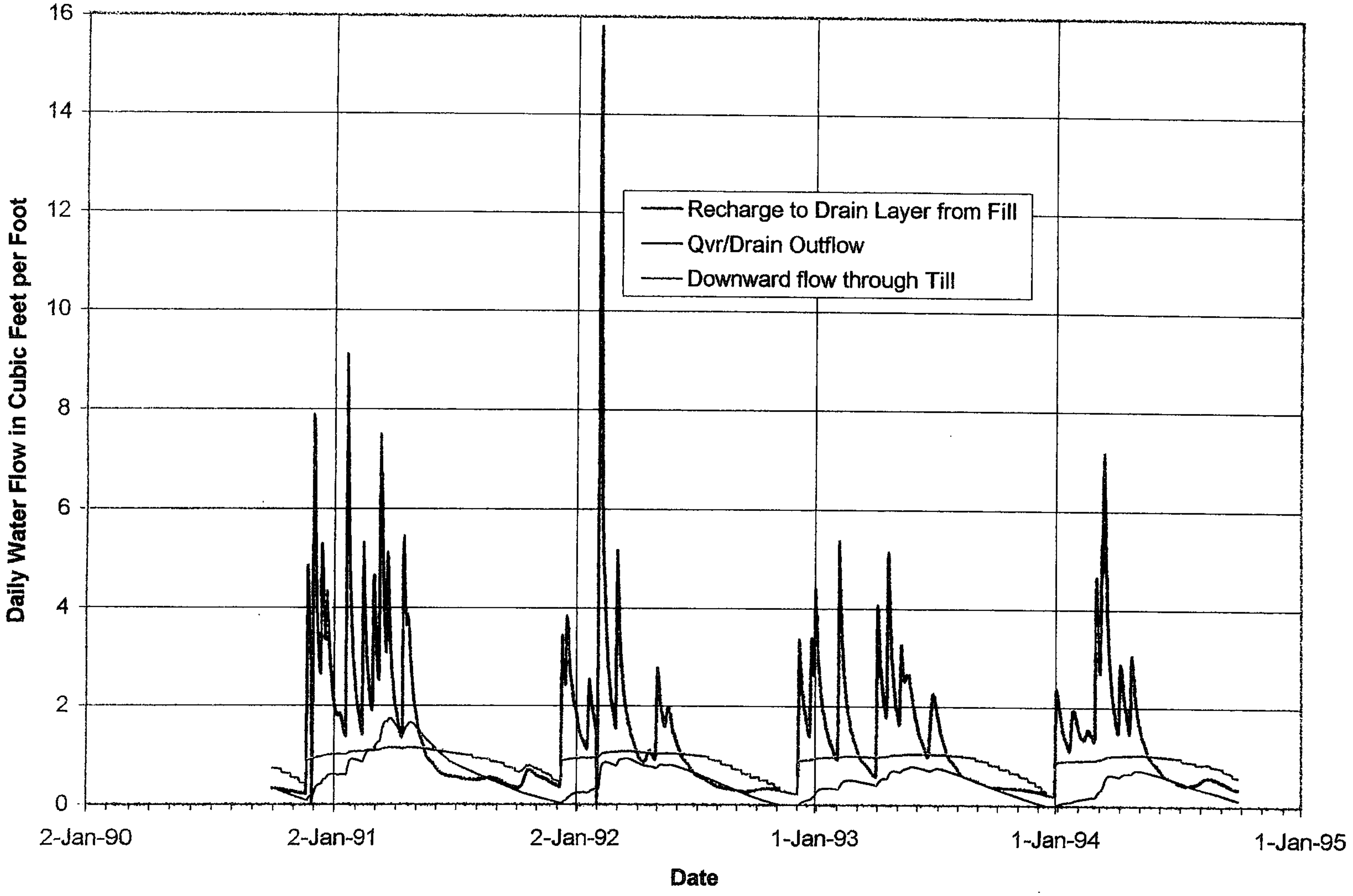


Figure 5-7 - Walker Creek Fill Inflow and Outflow for Test Period

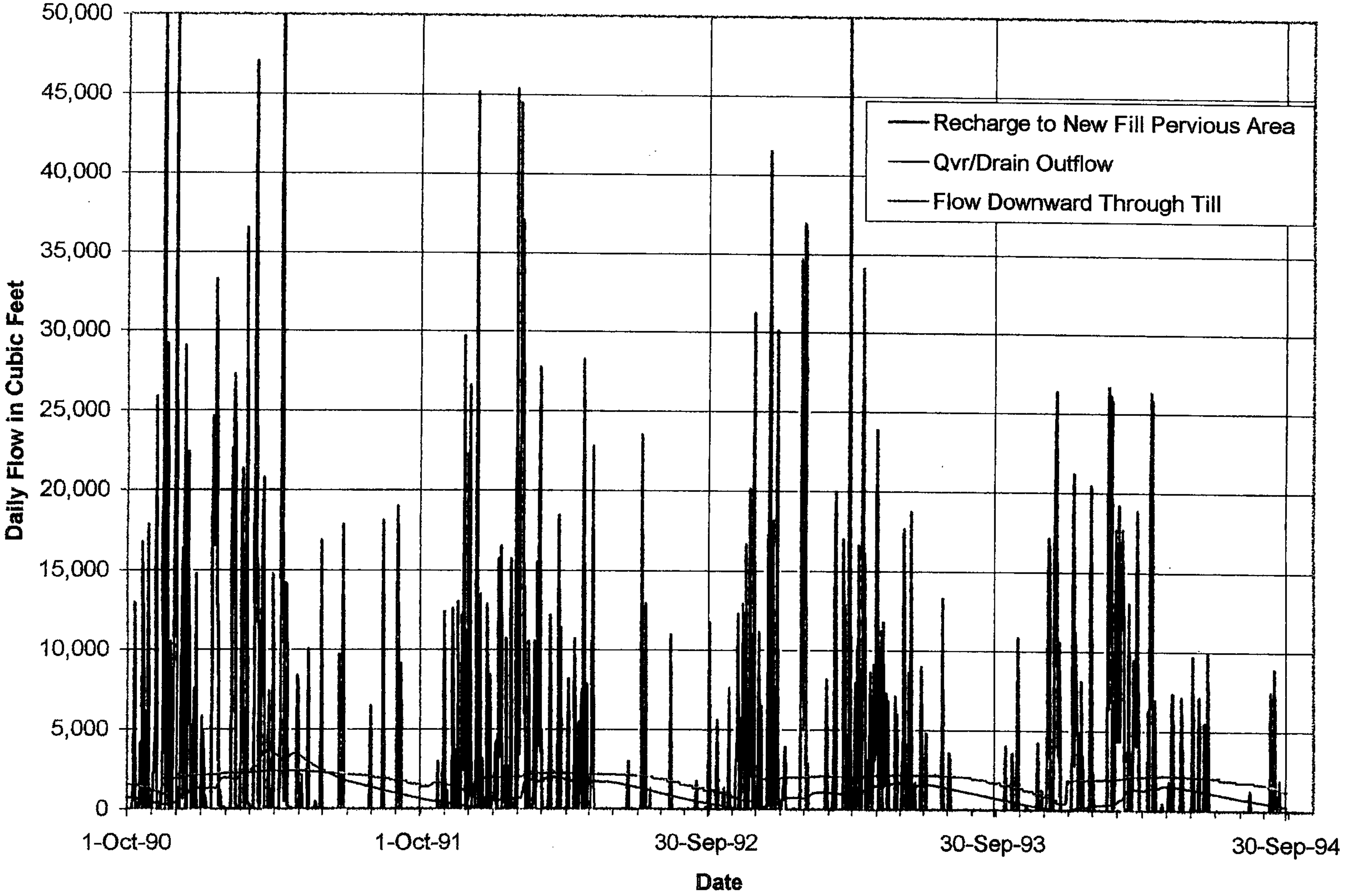


Figure 5-8 - Miller Creek Fill Inflow and Outflow for Test Period