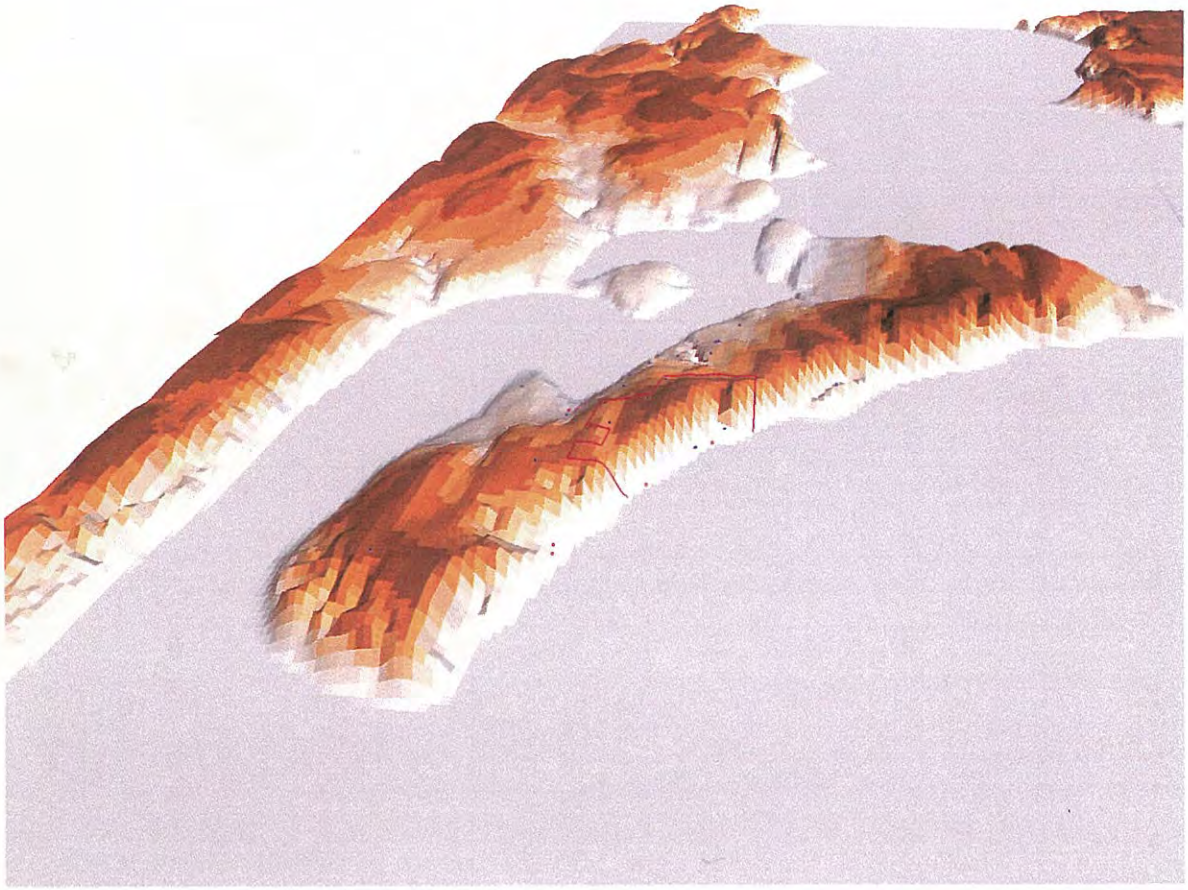
Maury Island Gravel Mine
Hydrogeologic Impact Assessment



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Group

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Maury Island Gravel Mine
Hydrogeologic Impact Assessment

Prepared for:

Washington State Department of Ecology
Northwest Regional Office
3190 160th Avenue SE
Bellevue, Washington, 98008-5452

Prepared by:
Pacific Groundwater Group
2377 Eastlake Avenue East, Suite 200
Seattle, Washington, 98102

(206) 329-0141
www.pgwg.com

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Executive Summary

Overview

Glacier Northwest, Inc., a subsidiary of Lone Star Northwest, Inc., has applied to increase the rate of gravel extraction from its mine on the eastern shore of Maury Island. Under the proposal, the rate of gravel mining would increase to a maximum of approximately 7.5 million tons annually. Mining would occur in up to 193 acres of the 235-acre site over 11 to 50 years. To assess certain hydrologic impacts associated with this expansion, the Washington State Department of Ecology retained Pacific Groundwater Group. A scope of work was developed to address the following four areas:

- Review of literature and previous studies on site soil, hydrogeology and nearshore issue
- Hydrogeologic impacts, including changes in aquifer recharge and groundwater flow conditions
- Impacts to the ecology of the nearshore marine environment
- The potential for contamination of groundwater and marine sediment

This report summarizes the results of the hydrogeologic impact assessment based on data collected through March 2000. The review of previous studies was summarized in *Document Summaries and Areas for Further Investigation, Maury Island Gravel Mining Impact Studies* (Pacific Groundwater Group, 1999b). The results of the nearshore environment assessment were summarized in *Maury Island Gravel Mining Impact Study, Nearshore Impact Assessment* (EVS Environmental Consultants, Inc., 2000). Surfacewater, sediment, and stormwater issues are summarized in *Maury Island Lone Star Gravel Mine Evaluation of Spring Water Quality, Proposed Stormwater Management Measures, and Potential Sediment Runoff Impacts* (Herrera Environmental Consultants, 2000), and *Summary of Soil Chemistry, Maury Island Gravel Mining Impact Studies (Pacific Groundwater Group, 1999c).*

The study area covers approximately 5 square miles in the central and southern portions of Maury Island. An additional area north of the study area was delineated for hydrologic modeling. The model area encompasses all but the northwestern portion of Maury Island.

The work completed for the hydrogeologic assessment included:

- Reviewing relevant technical information to identify data gaps and refine the conceptual hydrogeologic model
- Designing and implementing a field exploration program to fill important data gaps
- Analyzing groundwater recharge under existing and proposed mining conditions
- Evaluating the impacts of the proposed mine expansion on the groundwater flow system and springs using a numerical groundwater flow model

Methods

Data Review and Conceptual-Model

Relevant data and reports were reviewed to identify data gaps and provide a basis for designing a field data-collection program.

The information was also used to develop a conceptual hydrogeologic model, which is essential for assessing hydrogeologic impacts. Information from well logs was used to identify and characterize two major hydrostratigraphic units: the Principal Aquifer and a deeper aquifer system. The Principal Aquifer comprises outwash sediments of the Vashon advance (***Qva***), along with upper transitional beds. The deep aquifer comprises older, pre-Vashon sediments. The impact assessment focused on the Principal Aquifer.

Field Explorations

Field explorations were designed to fill data gaps and update the conceptual model. These explorations entailed:

- Installing five observation wells
- Conducting a well inventory and measuring water levels throughout the study area
- Accurate location and elevation measurement of 47 wells and springs using GPS methods

Two monitoring wells were installed on site (MW-1 and MW-2) and three were installed off site (MW-3, MW-4, and MW-5) to provide additional information about groundwater flow patterns and help characterize the vadose (unsaturated) zone. The depths of these wells range from 72 to 203 feet. All five monitoring wells are completed in the Principal Aquifer.

Domestic and other wells in the study area were inventoried to identify suitable locations for measuring water levels. Groundwater levels were measured in 41 wells on November 1999 and in 32 wells March 2000. Most of these wells were completed in the Principal Aquifer. The measurements were used to construct water-level contour maps for the Principal Aquifer. Groundwater flow directions were estimated from the maps.

Recharge Assessment

Changes in recharge to the Principal Aquifer were assessed using three approaches:

- A spreadsheet model was used to estimate recharge originating at the land surface for the entire model domain. This model estimates recharge through the root zone and underlying till where it is present. Input to the model included soil property, geologic, and land-cover data derived from maps, aerial photographs, and Geographic Information Systems coverages.
- Hydrus-2D, a finite-element code, was used to simulate the vertical movement of recharge between the root zone and the water table and to assess the dampening effects of unsaturated media.
- Water-level data from on-site monitoring wells was evaluated to estimate the lag time between recharge events in the wet season and responses in the Principal Aquifer. In addition, Carr & Associates' (1983) lag-time analysis was modified to better characterize the relationship between recharge and groundwater levels outside the mine.

Groundwater Flow Modeling

A numerical groundwater flow model was developed to estimate the impacts associated with mine development. This model was based on the updated conceptual hydrogeologic model. Impacts could not be quantified using a simple analytical model because hy-

drogeologic and mine development conditions were too complex.

The model features three layers representing the Principle Aquifer, an aquitard, and the underlying deep aquifer. It incorporates boundary conditions along the coast and at near-site springs. The recharge and lag-time estimates were used as model input. To verify its accuracy, the model was calibrated using measured water levels (from the field survey) and spring flows. It was then run for the preferred mine-expansion alternative to predict changes in the water levels and spring flows. Hydrogeologic conditions were simulated for the three 12-year phases of mine excavation and for site reclamation. Dr. Thomas Harter, Associate Professor of Subsurface Hydrology at the University of California, Davis, reviewed the recharge and groundwater flow models and provided comment on the modeling approaches.

Findings

Impacts to Recharge Dynamics

The results of the recharge analysis indicate that the timing and rate of recharge *in the mine area* will be impacted if up to 350 feet of gravel and sand are removed as proposed. These impacts will occur because recharge over much of the mine area is currently delayed and dampened by a thick sequence of unsaturated sediments. The removal of unsaturated materials will increase recharge in the wet season and decrease it in the dry season. A slight reduction in annual recharge is expected because the vegetative cover will be modified during mine excavation and reclamation. Another consequence of excavation is that the movement of recharge near the mine may change.

Impacts to Principal Aquifer

Because of the changes in the recharge dynamic in the mine area, small impacts to the Principal Aquifer and to springs will occur in parts of the study area. The impacts discussed below are conservative estimates, reflecting worst-case conditions.

- Water levels are predicted to decline within the mine area and immediately adjacent to the mine site. The predicted impacts are small (about 0.1 to 0.4 feet) relative to natural water-level fluctuations. Predicted impacts should not affect groundwater availability in off-site domestic wells.

- Groundwater flow directions in the Principal Aquifer are not expected to change appreciably because of the predicted mine-induced water-level declines.

- Flows in the Dockton Park and the Ferguson Springs are expected to decrease slightly—by up to 0.5 gpm—by the end of reclamation. Seasonal flow variations at these springs are expected to increase by less than 2 percent of their current flow. Long term and seasonal impacts to flows from Spring E, located along the beach face below the mine site, will be greater.

- Groundwater mounding will be localized beneath the infiltration pond that will be constructed in southeast edge of the mine floor. This mounding should not impact water levels at off-site supply wells. At least 18 feet of separation is predicted to remain between the water table and mine floor after storm events.

Impacts to Deep Aquifer Recharge

A small reduction in deep aquifer recharge will result from the groundwater-level declines in the Principal Aquifer. These reductions are on the order of 0.5 percent of pre-mining, steady-state conditions. For the entire model area, recharge to the deep aquifer is predicted to decrease by about 3 to 5 gpm, although this amount will be smaller when water levels beneath the mine are at their seasonal high. Based on model predictions, water levels and water availability in deep aquifer wells are unlikely to change because of proposed mining operations.

1.0 Introduction

The Washington State Department of Ecology contracted with Pacific Groundwater Group (PGG) to conduct a study of environmental impacts associated with increased rates of gravel mining on Maury Island. The study was mandated by the Washington State Legislature as part of ESSB 5180, signed by Governor Locke on May 14, 1999. The Maury Island Gravel Mining Impact Studies, hereafter referred to as the "Maury Island Studies," were commissioned to assess certain hydrologic impacts of mine expansion. These impacts include changes in aquifer recharge and groundwater flow conditions, changes in the ecology of the nearshore marine environment, and the potential for contamination of groundwater and marine sediment.

Glacier Northwest, Inc., a subsidiary of Lone Star Northwest, Inc., has applied to increase the rate of gravel extraction from an existing mine located on the eastern shore of Maury Island, as shown on **Figure 1-1**. Mining levels under the proposed alternative would increase to a maximum of approximately 7.5 million tons annually, with most of the material being barged to off-island markets. Mining would occur in up to 193 acres of the 235-acre site over a period of 11 to 50 years. This proposed gravel removal is currently in review under the State Environmental Policy Act (SEPA) review process. A draft Environmental Impact Statement (DEIS) for the site was prepared in July 1999 (King County, 1999).

1.1 Purpose

This report summarizes the results of the hydrogeologic impact assessment for Glacier Northwest's Maury Island mine site ("the mine site"). It is based on existing and newly collected data through March 2000. This report is the last in a series of mine-related impact assessment documents prepared for Ecology by PGG and its subconsultants, EVS Environmental Consultants and Herrera Environmental Consultants. This work was authorized under a memorandum of agreement dated September 9, 1999, signed by Ecology.

The objectives of the hydrogeologic impact assessment documented in this report were to:

- Provide an independent review of the hydrogeologic conditions at and near the Maury Island mine site
- Present additional hydrogeologic field data collected during the study
- Describe the impacts that proposed mining will have on the groundwater flow system, including impacts to nearby springs and water wells
- Document modeling approaches used to predict these impacts

This investigation involved limited interaction with Ecology regarding the overall study approach. It also involved limited review by Ecology of intermediate work products prepared by PGG. Ecology provided review and feedback at the start of the project and during the final preparation of this report. This feedback was used to revise and guide portions of the original work proposed by PGG (Pacific Groundwater Group, 1999a) and to obtain general agreement on technical issues related to the project scope and use of the project data. The ultimate goal of this process was to ensure that the project was consistent with Ecology's Request for Proposal Number ECY-RFP 9913 (Washington State Department of Ecology, 1999a) and the legislative intent of the ESSB 5180.

As with any scientific work, data collected and analyzed after March 2000 will undoubtedly provide additional insights that will help refine the interpretations presented herein. This report presents the current and most quantitative understanding of groundwater flow in the Maury Island mine area as of March 2000, the date of final data collection for this study.

1.2 Scope

This hydrogeologic impact assessment is an integral part of the Maury Island Studies. The scope of this assessment included:

- Reviewing relevant technical information for the Maury Island mine site and the surrounding area
- Identifying areas for further investigation (data gaps) in existing the groundwater studies for the site
- Conducting additional field investigations to fill important data gaps
- Analyzing groundwater recharge under existing and proposed mining conditions
- Evaluating impacts to the groundwater system that may be caused by the proposed mine expansion
- Assessing impacts to flow rates in on-site and off-site springs

The scope of work was designed to evaluate significant changes to the groundwater flow system that will occur from Glacier's proposed mine expansion. Impacts were predicted using numerical modeling techniques that incorporated both new and existing data.

1.3 Study and Model Area

The study and model areas are shown on **Figure 1-1**. The study area covers approximately 5 square miles in the central and southern portions of Maury Island. It includes all or part of Sections 20 through 22 and Sections 28 through 32 of T.22N./R.3E., and it is centered on the mine site. The northeastern extent of the study area extends to about 6,000 feet from the mine near the local hamlets of Mileta and Raeco; this boundary was chosen based on the distribution of water wells in the area. The study area is 25 percent smaller than the area bounded by the groundwater flow model, which covers an area of about 6.7 square miles. Except for the north and northeastern portions of the model area, the study and model areas are the same.

The model area includes all but the northwest corner of Maury Island. The model area was selected to include the entire island shoreline, which forms a natural hydraulic boundary to the regional groundwater flow system. Further discussion of the model area and boundary conditions is presented in Section 8.

Recharge at the island surface was assessed throughout the model area as discussed in Section 7. Hydrostratigraphic features and geologic relationships were assessed for the study area using available subsurface data. Details about the hydrogeology were provided by local well logs and by logs for new wells completed for the project. Hydrostratigraphic features of the outlying model area were defined by regional studies. Regional studies provided information about the hydrogeology of the perimeter of the model area, information that was not otherwise included in the study area.

1.4 Report Structure

The report is organized in nine sections:

- **Section 1: Introduction.** This section contains background information on the project and brief discussion of previous investigations related to the mine site.
- **Section 2: Summary of Findings.** This section presents the major findings of the hydrogeologic impact assessment, including the predicted impacts to groundwater levels, spring flows, and aquifer leakage rate.
- **Section 3: Overview of Methods.** This section presents an overview of the methods used to collect and analyze data for this report.
- **Section 4: Island Physiography.** This section gives a brief overview of the land and water features of the island, features that are relevant to the hydrogeologic impact assessment.
- **Section 5: Geologic Framework.** This section discusses the regional and local geologic features. It describes the glacial and pre-glacial deposits that form aquifers and aquitards.
- **Section 6: Groundwater Flow System.** This section identifies the pertinent aquifers and aquitards in the study area and discusses their properties. It also discusses water level trends and groundwater flow patterns in the Principal Aquifer, and includes a discussion about springs near the mine site.
- **Section 7: Recharge Assessment.** This section discusses the estimation of recharge quantities at the island land surface. It also discusses the movement of recharge to the Principal Aquifer.
- **Section 8: Estimation of Hydrogeologic Impacts.** This section presents the development and calibration of the groundwater flow model. It also discusses predictive model simulations and presents impacts to groundwater levels, flow directions, and spring flows caused by proposed mining activities.
- **Section 9: References.** This section presents references cited in this report.

Appendices A through G provide supporting technical information about the following topics:

- **Appendix A**-Field Exploration Summary
- **Appendix B**-Well Logs for Study Area
- **Appendix C**-GPS Survey Results
- **Appendix D**-Recharge Estimation for the Maury Groundwater Flow Model
- **Appendix E**-Maury Island Vadose Zone Modeling with Hydrus-2D
- **Appendix F**-Formulation of General Head Boundaries for the Maury Groundwater Flow Model
- **Appendix G**-Review Comments from Dr. Thomas Harter for Interim Modeling Reports

1.5 Previous Investigations

The geology and hydrogeology of Maury Island have been investigated extensively by other workers prior to the start of this project. These investigations are summarized below.

1.5.1 Investigations Related to Mine Expansion

Pertinent investigations focusing on the mine expansion were reviewed and summarized in *Document Summaries and Areas for Further Investigation, Maury Island Gravel Mining Impact Studies* (Pacific Groundwater Group, 1999b) as part of this project. The document summary report was used to help establish site characterization and identify areas warranting further data collection. The following documents were reviewed for the project and were used to help formulate the site conceptual model:

- Consulting reports prepared by Lone Star Northwest's consultant, Associated Earth Sciences, Inc. (AESI, 1998, 1999a, 1999b)
- A review of subsurface conditions at the Maury Island mine site prepared for an adjacent water purveyor (Rongey & Associates, 1998)
- The Draft Environmental Impact Statement ("DEIS"), prepared for the mine site by King County's project team (King County, 1999)

1.5.2 Regional Investigations by Private Consultants, Public Agencies, and Researchers

Regional geologic and hydrogeologic investigations of the Vashon-Maury Island area have been conducted by private consultants, public agencies, and academic researchers. The most pertinent regional study is an investigation of groundwater resources for Vashon-Maury Island prepared by J.R. Carr & Associates in cooperation with King County (Carr, 1983). This report, which characterizes the hydrogeology and stratigraphy of three hydrostratigraphic units in the project area, was a valuable reference for this project. Likewise, the Vashon-Maury Island Groundwater Management Plan, prepared in part by Geraghty & Miller, Inc., also served as a valuable resource (Vashon-Maury Groundwater Advisory Committee [VMGAC], 1998). The U.S. Geological Survey (USGS) conducted a regional study of geologic conditions and glacial stratigraphy in the area (Booth, 1991). This study provided valuable information about the surficial geology of greater Maury Island and the subsurface geometry of the base of the Vashon Advance outwash. Other references included:

- Robert Ritzi's master's thesis regarding the hydrogeology and water resources of Vashon-Maury Island (Ritzi, 1983)
- Soil mapping conducted for King County (USDA Soil Conservation Service, 1973)
- A regional aquifer system analysis for the Puget Sound Lowlands conducted by the USGS (Vaccaro and others, 1998)

1.6 Warranty

This work has been performed, and this report prepared, in accordance with hydrogeologic practices generally accepted at this time, in this area, for the exclusive use of the Department of Ecology, for specific application to the study area. No other warranty, express or implied, is made.

2.0 Summary of Findings

PGG assessed the hydrogeologic impacts of the proposed mine excavation both on site and over the entire study area. This assessment focused on the Principal Aquifer, which comprises the lower Vashon advance (***Qva***) and upper transitional beds. It also includes an assessment of impacts to the deep aquifer, which comprises pre-Vashon sediments.

This impact assessment entailed evaluating changes in recharge dynamics, which could affect water levels, flow directions, and spring flows in the Principal Aquifer. These effects were assessed using a numerical groundwater flow model that was centered on the mine site.

Predicted hydrogeologic impacts are summarized in **Table 2-1**.

2.1 Impacts to Recharge Dynamics

The timing and rate of recharge movement through the vadose zone to the water table will be impacted by the proposed removal of up to 350 feet of gravel and sand at the mine. The changes in recharge were assessed using an in-house, proprietary recharge spreadsheet model ("the spreadsheet model") and Hydrus-2D. The results of this analysis are summarized below.

- Although the recharge occurring at land surface varies seasonally, the thick sequences of unsaturated sediments dampen this seasonality and reduce the variability of recharge between the surface and the water table over the annual cycle.
- The removal of unsaturated materials by mining will increase the rate of recharge in the wet season and decrease it in the dry season.
- A slight reduction in annual recharge is expected because the vegetative cover will be altered during mine excavation and reclamation.
- The removal of local perching horizons, such as shallow till, may alter recharge patterns near the mine. Recharge may be redistributed in cases where significant lateral movement occurs along these horizons before the recharge reaches the water table.

*The analysis of recharge dynamics is presented in Section 7 and **Appendices D and E**.*

2.2 Impacts to Principal Aquifer

Small impacts to the Principal Aquifer will occur because of the changes in the recharge dynamics in the mine area. These impacts were assessed using a numerical flow model. The assumptions used for this model produce a conservative, worst-case estimate of impacts to water levels, flow directions, and spring flows in the Principal Aquifer, as discussed below. Water-level impacts in the Principal Aquifer caused by the proposed infiltration pond are also discussed below.

The model results are conservative because the finished grade of the excavated area was assumed to be uniform and contain less unsaturated material than will occur under actual conditions. Consequently, the model did not account for the dampening effects of variable thicknesses of unsaturated sediments that will remain in place at the mine.

2.2.1 Changes in Water Levels

Water-level declines are predicted to occur within the mine area and immediately adjacent to the mine site. The predicted impacts are small relative to naturally occurring water-level fluctuations. These changes should not affect groundwater availability in the existing off-site domestic supply wells.

2.2.1.1 On-Site

- Natural seasonal water-level fluctuations are as much as 2 feet in on-site observation wells based on available hydrograph data.
- Average annual groundwater levels are predicted to decline by up to 0.6 feet beneath the mine site. The average annual levels illustrate the long-term water-level trends in an aquifer in the absence of seasonal variations.
- Seasonal water-level fluctuations are predicted to increase by up to ± 2.4 feet beneath the mine site. Seasonal water-level fluctuations describe the maximum changes above and below the annual average as a result of the recharge pulses.
- The total water-level impacts are the sum of long-term declines and maximum seasonal impacts. Therefore, water level impacts at the mine site may be as much as -3 feet during seasonal low water and +1.8 feet during seasonal high water relative to steady state, pre-mining conditions. Similarly, off-site water level impacts may be as much as -0.2 feet during seasonal low water and a net-zero water level change during seasonal high water.

2.2.1.2 Off-Site

- Natural seasonal water-level fluctuations are up to about 3.6 feet in off-site water wells, based on limited available data. In most off-site wells, mine-induced groundwater level declines will be significantly smaller than natural seasonal water-level variations.
- Average annual groundwater levels are predicted to decline by less than 0.1 feet at the closest domestic supply wells.
- Seasonal water-level fluctuations are predicted to increase by up to about ± 0.1 feet at the closest domestic supply wells
- Seasonal maximum water-level declines of up to 0.2 feet are predicted at the closest domestic supply well.

Changes in groundwater levels are discussed in Section 8.4.

2.2.2 Changes in Flow Direction

Groundwater flow directions in the Principal Aquifer are not expected to change appreciably because of the predicted mine-induced water-level declines, as discussed below.

2.2.2.1 On-Site

- Predicted water level declines of up to 0.6 feet at the mine will create only localized changes to the hydraulic gradients and the resultant groundwater flow directions near the mine.
- Seasonal variations of up to ± 2.4 feet would cause additional variation in local

hydraulic gradients surrounding the mine site; however, these changes would average out over the annual cycle to approximate pre-mining groundwater flow directions and are not expected to change regional-scale groundwater flow patterns.

2.2.2.2 *Off-Site*

- Water-level changes predicted outside the mine site (on the order of less than a few tenths of feet) are small relative to the head drop of over 50 feet that occurs beneath the mine due to natural hydraulic gradients. This small difference in water levels will cause insignificant changes in groundwater flow directions outside the mine.
- Because predicted water-level changes decrease rapidly between the mine and surrounding portions of the Principal Aquifer, significant changes in groundwater flow directions are unlikely beyond the immediate vicinity of the mine.

Changes in groundwater flow directions are discussed in Section 8.4.3.1.

2.2.3 Changes in Spring Flows

2.2.3.1 *Dockton and Ferguson Springs*

Average annual flows are expected to decrease in the two Dockton Park Springs and in a nearby spring owned by Paul Ferguson. Seasonal flow variations in the springs are expected to increase. The predicted impacts are as follows:

- Average annual flow rates are predicted to decline by up to 0.5 gpm (1 to 2 percent of current flow) by the end of reclamation.
- The maximum seasonal variability of flow rates is predicted to increase by between ± 0.1 and ± 0.5 gpm. These impacts will cause larger seasonal fluctuations to occur above and below the decreased annual average rate.
- Using these predictions, the worst-case impact could be a seasonal reduction in flow by as much as 1 gpm during typical low-flow periods and flow increases of less than 0.1 gpm during high-flow periods.
- Changes to spring flow should be measured against existing average annual flow and seasonal variations in spring flow. Spring owners currently do not measure these flows.

2.2.3.2 *Spring E*

Flows from Spring E, located along the beach face below the mine site, will be impacted more than the flow at Dockton springs, as discussed below.

- Average annual discharge is predicted to decrease by about 0.7 gpm (2 percent of the current flow) by the end of reclamation.
- Maximum seasonal variation of spring discharge is predicted to increase by up to ± 20 percent, a range of about 6 gpm about the average annual.

Changes in spring flows are discussed in Section 8.4.3.2.

2.2.4 Impacts to Water Levels by Infiltration Pond

An infiltration/detention pond will be constructed in the mine floor near the southeast edge of the pit. Groundwater mounding or a local rise in the groundwater table beneath the pond is predicted. The mounding should not impact water levels at off-site supply wells. Based on a model of 2 consecutive days of ¾-inch per day precipitation, predicted impacts are as follows:

2.2.4.1 On-Site

- Water levels beneath the pond will increase by up to 2.1 feet at the end of the modeled storm event.
- At least 18 feet of separation will remain between the water table and pond bottom after the modeled storm event.
- Water levels will drop to near pre-storm levels within several weeks of the event.

2.2.4.2 Off-Site

- Water levels at the mine boundaries are predicted to increase by less than 0.1 feet because of the simulated infiltration event.
- Water levels will not change appreciably in the nearest domestic wells.

These predictions are based on the preliminary infiltration pond layout presented in the DEIS and on estimated values of storm runoff. The mine owners should further analyze groundwater mounding once the pond design and stormwater management plans are complete.

The effects of the infiltration pond are discussed in Section 8.4.3.4.

2.3 Impact to Deep Aquifer Recharge Rate

A small reduction in deep aquifer recharge is predicted due to the long-term groundwater declines in the Principal Aquifer, as discussed below.

- Modeled reductions in flow rates to the deep aquifer are on the order of 0.5 percent of pre-mining, steady-state conditions.
- A reduction of 600 to 900 cubic feet per day (cfd), or 3 to 5 gpm is predicted for the entire model area.
- A smaller reduction in deep aquifer recharge is expected when water levels beneath the mine are at their seasonal high.

Impacts to deep aquifer recharge are discussed in Section 8.4.3.3.

3.0 Overview of Methods

The methods used to collect and analyze data for the hydrogeologic impact assessment are based on the proposal submitted to Ecology in July 1999 (Pacific Groundwater Group, 1999a). They were designed to provide a better understanding of the hydrogeologic conditions in the study area.

3.1 Review of Existing Data

PGG compiled and reviewed relevant data and reports for the project to facilitate analysis of site impacts. These data included:

- Previous studies of geology, groundwater hydrology, and soil contamination on Maury Island
- The Draft EIS for the proposed mine (King County, 1999)
- Relevant studies done in similar project areas in the Pacific Northwest

These data were used to guide the collection of additional field data and were the starting point for development of the conceptual site model.

3.2 Develop Conceptual Hydrogeologic Model

A conceptual hydrogeologic model was developed to evaluate impacts to the groundwater system by proposed mining. The model encompassed the mine site, the study area, and surrounding portions of the island. It was developed using data from domestic wells, springs, and technical reports. Major hydrostratigraphic units (regionally significant, laterally continuous water-bearing zones) were identified from the literature and were further characterized using available well logs. Data collected from the field exploration program and water level survey were incorporated into the model to refine it.

The conceptual model was used as the basis for evaluating groundwater recharge and for developing a numerical groundwater flow model. The results of the flow model were then used to refine the conceptual model and improve the understanding of groundwater flow on Maury Island.

3.3 Aquifer Exploration and Characterization

An aquifer exploration program was conducted to better characterize hydrogeologic conditions at the mine site and surrounding portions of the study area. Five additional wells—two on site and three off site—were completed to:

- Identify groundwater flow directions, especially off-site
- Better define the location of a mid-island groundwater flow divide in the Principal Aquifer
- Evaluate the sedimentary texture and stratigraphy of the unsaturated zone
- Assess the occurrence of perched zones above the Principal Aquifer
- Collect intact soil samples for assessing soil moisture properties

Well sites were selected based on the conceptual model, the distribution of existing wells, and access constraints. The two on-site wells (MW-1 and MW-2) were installed adjacent to existing wells so that vertical gradients in the Principal Aquifer could be assessed and geologic information could be compared. The locations of the off-site wells

(MW-3 through MW-5) optimized the distribution of water-level data and provided geologic data for previously unexplored areas of the island. The off-site locations were also selected where anticipated depths would be smaller. **Figure 1-1** presents the location of the new wells.

Site access for drilling and well installations required negotiation with private and public property owners. PGG assisted Ecology in procuring access to the well sites, helped prioritize the sites, and provided technical support for negotiations.

Drilling was conducted over a 2-week period starting in early November 1999. Six-inch diameter wells were completed using air-rotary methods. During drilling, lined split-spoon or undisturbed Shelby-tube samples were collected and logged to evaluate stratigraphy and soil moisture properties (by laboratory test). This information was used in recharge assessment presented in Section 7. Because each boring was logged using up to six split-spoon samples rather than air-rotary cutting returns alone, perched water zones could be easily identified. The drilling, sampling, and completion of the new wells is described in detail in **Appendix A**. Information on these wells is summarized in **Table 3-1**.

3.4 Well Inventory

A well inventory was conducted to identify wells nearest the proposed mine and to select well locations for measuring groundwater levels. To identify potential wells, driller's and geologic logs were compiled from the previous consulting reports and from Ecology's files. Each well was assigned a hydrostratigraphic completion interval based on the completion depth and geologic information.

For ease of reference and to provide continuity between previous reports, ID numbers were assigned to wells included in the initial groundwater characterization report (AESI, 1999a). The well IDs were used in the characterization and groundwater flow model. **Figure 1-1** presents the locations and ID numbers of wells used in this study. **Table 3-2** summarizes information for these wells, including survey coordinates, log availability, total depth, completion interval, and water levels. Well logs for domestic and public supply wells that were field checked are included in **Appendix B.**

Wells were located in the field based on information specified on the well log, along with a door-to-door field survey. Statewide Drilling Company, a contractor used for many domestic wells, provided information about wells not reported in Ecology files or in past consulting reports. Well owners were contacted to obtain permission for measuring the elevation and water level at their wellhead. A mail-in survey response was requested from well owners who could not be contacted directly during the door-to-door survey or by phone. Considerable effort was required to field locate wells during the fall 1999 survey since reported well locations were often inaccurate.

The Maury Island community was also notified of the well survey in the *Project Startup Fact Sheet* for the Maury Island Studies (Washington State Department of Ecology, 1999b). This notification provided an opportunity for well owners to contact Ecology with location and access information for their wells.

The coordinates and elevation of each well were measured using Global Positioning System (GPS) technology. This technique is accurate to the nearest $1/10^{th}$ of a foot, a

level of accuracy that could not be achieved using a USGS quadrangle (accurate to ± 20 feet at best). In areas where GPS technology was not possible because of overhead tree cover, buildings, etc., traditional leveling methods were used to survey wellhead elevations. W&H Pacific, a licensed surveyor in Washington State, performed all survey work. All GPS data were corrected to local geodetic benchmarks and are referenced to NAD 83/91 (horizontal) and NAVD 88 (vertical) datums. A complete survey report from W&H Pacific is presented in **Appendix C**.

3.5 Water Level Survey and Groundwater Flow Direction Analysis

Groundwater levels were measured in selected wells to help define flow directions, particularly outside the mine area. The groundwater flow directions derived from this survey are representative because they are based on accurate well locations, wellhead elevations, and careful water level measurements. Results of the water-level survey were also used to calibrate the groundwater flow model presented in Section 8 of this report.

3.5.1 Methods

Water levels were measured in wells with known completion depths and open-ended casings or single perforated/screened intervals. This constraint allowed wells to be assigned to a particular hydrostratigraphic interval and ensured that the water level reflected head in one discrete aquifer, instead of a composite head for several water-bearing zones. Well-completion logs were therefore critical for the selection of wells used for water-level contouring.

Water levels were measured using electric water level sounder in over 95 percent of the wells. These measurements are reported to the nearest $1/100^{th}$ of a foot and are considered to be accurate to the nearest $1/10^{th}$ of a foot. A chalked stainless steel engineering tape was used to measure depth to groundwater in small-diameter wells (e.g., drive points and piezometers) and in wells with restricted annular space or limited-access wellhead covers. Tape and chalk methods are also reported to the nearest $1/100^{th}$ of a foot and are considered to be accurate to the nearest $1/10^{th}$ of a foot. Water levels were measured during non-pumping periods.

3.5.2 Fall 1999 and Spring 2000 Surveys

Water levels were measured in a total of 21 wells completed in the Principal Aquifer and 18 wells completed in the deep aquifer system during the fall 1999 survey. The fall 1999 survey was conducted between November 22 and November 24, 1999. Water levels are presented in **Table 3-2**. Water levels in five wells could not be measured because of difficulty in lowering an electronic sounder to depths greater than 300 feet in wells without a sounding tube. For these wells, water levels reported at the time of drilling ("ATD" measurements) are listed.

Water levels were again measured in a total of 32 wells during the spring 2000 survey. The spring 2000 survey was conducted on March 29, 2000. Water levels were measured mostly in the Principal Aquifer wells because this aquifer is the focus of the hydrogeologic impact assessment. These measurements were used to assess water level

changes occurring since the fall 1999 measurements.

Water-level elevations were calculated by subtracting the depth to water from the wellhead elevation. Data for the November 1999 and March 2000 events are presented in **Table 3-2**.

3.5.3 Analysis of Water-Level Contours

The calculated water-level elevations were used to construct water-level contour maps for the Principal Aquifer for both measurement events. Water level elevations were posted over the study-area base map and contoured by hand. The contours considered regional local hydrographic features such as springs and the island shoreline, and geologic contacts. Groundwater flow directions in the Principal Aquifer were estimated from the maps based on the assumption that groundwater typically flows at right angles to water level contours. Section 6.1 discusses the water-level contour maps and groundwater flow patterns.

Water-level contour maps were not prepared for the deep aquifer because these wells are likely completed in a variety of water-bearing zones that are likely to be laterally discontinuous. Water levels in deep aquifer wells were used during design of the groundwater flow model (Section 8.1).

3.6 Hydrogeologic Impact Assessment

Hydrogeologic impacts were assessed using site-specific models that simulate recharge processes and regional groundwater flow. Recharge processes were evaluated using field data and quantitative models to estimate recharge rates and downward movement of water from the land surface to the Principal Aquifer. A groundwater flow model was developed and calibrated using the estimated recharge, aquifer properties, and measured groundwater levels. The flow model was used to predict the impacts of altered recharge patterns associated with the proposed mining and reclamation alternative.

3.6.1 Evaluation of Groundwater Recharge Dynamics

Three methods were used to assess recharge dynamics:

- A spreadsheet model to estimate recharge originating at the land surface and moving through the shallow subsurface
- A time-lag analysis of on-site water-level data
- A finite-element code (Hydrus-2D) for simulating flow in variably saturated media from the shallow subsurface to the regional water table

3.6.1.1 Recharge Spreadsheet Model

Existing climatic, soil property, geologic, and land-cover data were used as input to a proprietary, spreadsheet model of recharge processes. This model simulates recharge processes that occur at the surface—through the root zone and underlying till (where present). It uses a daily soil moisture balance to account for precipitation, runoff, evapotranspiration, and percolation through the root zone and underlying till. Maps, aerial photographs, and GIS coverages were used to identify portions of the island with differing combinations of land-cover, soil type, and/or surficial geology. The recharge model is

discussed in Section 7.1. Supporting documentation is provided in **Appendix D**.

3.6.1.2 Time-Lag Analysis

Time-series water level data were reviewed to evaluate the lag between recharge and aquifer response during high-recharge months in the rainy season. Twelve months of water-level data from existing on-site monitoring wells were assessed. In addition, the time-lag analysis from Carr & Associates (1983) was modified to better characterize the relationship between recharge and groundwater levels in the Principal Aquifer outside the mine site. This analysis is detailed in Section 7.2.

3.6.1.3 Hydrus-2D Model

Because the time-lag analysis could not adequately describe the dynamics of recharge processes between the land surface and the Principal Aquifer, a simplified numerical model of the vadose zone was developed using Hydrus-2D (Simunek, 1999). This model was used to evaluate the movement, time lags, and dampening of seasonal recharge as it passes through the unsaturated sediments between land surface and the Principal Aquifer. The model considered:

- Grain-size analyses and/or soil moisture retention curves from soil samples obtained during well installation
- Soil property data reported in the existing site characterization reports
- Estimates of the magnitude and timing of seepage through the root zone and beneath the till as developed in the spreadsheet model.

The Hydrus-2D model was used in combination with the spreadsheet model and time-lag analysis to estimate recharge to the Principal Aquifer under current and proposed mining conditions. The recharge assessment is presented in Section 7.2. Supporting model documentation is provided in **Appendix E**.

Findings of the unsaturated flow evaluation were used to better define recharge lag times for the groundwater flow model discussed below.

3.6.2 Development of Calibrated Groundwater Flow Model

A numerical model of groundwater flow was developed to estimate the hydrogeologic impacts of the proposed mine development. A simple analytical model could not be used because hydrogeologic and mine development conditions were too complex. These conditions include spatially/temporally varying recharge, aquifer discharge to marine water bodies, and springs located along aquifer margins, the presence of a deep aquifer and a phased mine development and reclamation schedule.

3.6.2.1 Model Development

The flow model was based on the updated conceptual model. It features three layers representing the Principal Aquifer, an aquitard, and the underlying deep aquifer. It also incorporates boundary conditions along the coast and at near-site springs. The groundwater flow model was constructed using a graphical users interface (GUI), which promotes highly efficient setup, operation, and visualization of model structure and results. "MODFLOW," a finite-difference model for groundwater flow developed by the USGS

(McDonald and Harbaugh, 1988) was used with the "Groundwater Vistas" GUI developed by Environmental Simulations, Ltd. The model employs the maximum simplicity required to accurately portray the groundwater flow system.

Details of the groundwater flow model design and structure are presented in Section 8 and **Appendix F**.

3.6.2.2 Model Calibration and Predictive Simulations

The model was calibrated using the November 1999 water-level data, measured and reported spring flows, and water-level data collected from on-site wells. The recharge and lag time estimates were also used as model input. Model calibration is presented in Section 8.2.

Once calibrated, the model was used to predict changes in groundwater levels and discharges from near-site springs under three 12-year phases of mine excavation and subsequent site reclamation. Results of the predictive modeling are presented in Section 8.4. Limitations of the model predictions and underlying model assumptions are discussed in Section 8.5.

3.6.2.3 Model Review

An outside expert Dr. Thomas Harter, Associate Professor of Subsurface Hydrology at the University of California, Davis, reviewed the Maury Island models to ensure that they were scientifically sound and technically unbiased. He provided comment on the modeling approaches along with written input for three milestones in the hydrogeologic assessment task:

- Upon completion of recharge and unsaturated flow modeling
- After design and steady-state calibration of the groundwater flow model
- Upon completion of predictive modeling

Dr. Harter's comments are presented in **Appendix G** of this report.

4.0 Maury Island Physiography

Physiographic features of Maury Island have been described in detail by previous investigators (Carr (1983), Ritzi (1983), VMGAC, (1998), Booth (1991), AESI (1998, 1999)). The brief discussion that follows is an overview of physiographic features that are important for understanding and developing hydrologic models for the project.

4.1 Relief

Elevation in the study area ranges from about 380 feet at the center of the island in the mine site to sea level along the perimeter of the island. The land surface topography is relatively flat within the higher elevation areas with gradual slopes dipping to the north-northwest towards Dockton and Quartermaster Harbor. Steep bluffs rising from Puget Sound bound the southeastern margin of the study area. These bluffs extend from Manzanita at the southwest end of the island to Point Robinson at the island's eastern tip. The top of these bluffs generally forms the crest of the topographic divide that runs the length of the island.

4.2 Climate

Maury Island typically experiences cool dry summers and mild wet winters. The factors responsible for Maury Island climate have been described in detail in prior reports (see Carr, 1983). For the purpose of this analysis, available data were compiled and analyzed to estimate monthly values of precipitation, and minimum and maximum temperatures.

Historic climatic data collection on Maury and Vashon Islands has been relatively spotty. Carr (1983) summarizes data collection from seven rain gages on the islands and presents an isohyetal map for the 1981-82 water year. Two of the seven gages were located on Maury Island, and most of the gages had records less than 12 years in duration. The Vashon-Maury Island Ground Water Management Plan included precipitation monitoring and generation of an isohyetal map for 1989 through 1991 (VMGAC, 1998). Nine gages were monitored over the 3-year period, two of which were on Maury Island.

Comparison of the two isohyetal maps showed contradictory precipitation distributions on Maury Island. Carr's map showed almost 6 inches higher precipitation on the southwest end of Maury Island with respect to the northeast end (41.2 vs. 35.6 in/yr). In contrast, the Ground Water Management Plan (GWMP) showed almost 5 inches higher precipitation on the northeast end of the Island (43.8 vs. 39.1 in/yr).

PGG analyzed both sets of data, as well as long-term climatic data from SeaTac International Airport (located 8 miles northeast of central Maury Island) to derive representative, long-term monthly precipitation and temperature values for Maury Island. For the purpose of this analysis, precipitation and temperature were assumed uniformly distributed across the island. For precipitation, a ratio of 1.05 was estimated between the King County Water District (KCWD) #19 gage on Vashon Island and central Maury Island. This ratio was based on the GWMP isohyetal map, as it represented three rather than the one-year of collected data shown in Carr's report. In addition, a regression equation was developed to relate monthly precipitation at KCWD #19 to SeaTac airport, based on nine years of overlapping data. The equation (KCWD = 1.27 x SeaTac) had a correlation coefficient of 0.95. Based on

these two relationships, monthly precipitation at Maury Island is estimated to be 20 percent higher than SeaTac Airport.

Long-term (1961-1990) values of monthly precipitation at SeaTac Airport were used to derive synthetic monthly values of long-term precipitation on Maury Island. Long-term annual precipitation measured at Seatac Airport was 37.2 inches, compared to a synthesized value of 44.6 inches for Maury Island. **Figure 4-1** presents the monthly averages for Maury Island as well as monthly precipitation over two years preceding the groundwater level monitoring period used to calibrate the groundwater flow model. The plot shows that the majority of precipitation is concentrated in the months of October through March. Unusually high precipitation in the winter/spring of 1998-1999 directly precedes the one-year groundwater level monitoring period beginning in February of 1999.

Temperatures on Maury Island (in degrees Fahrenheit) range from the lower 50's to the lower 70's in the summer, and from the lower 30's to the lower 50's in the winter. A more detailed discussion of Maury Island temperatures is presented in **Appendix D**.

4.3 Hydrographic Features

Major hydrographic features in the study area consist of adjacent marine water bodies and localized springs discharging to the ground surface at the island's perimeter. Hydrographic features are shown in **Figure 1-1**. Streams and other surface water features did not exist in the mine site or in immediately adjacent areas during field reconnaissance conducted during this study. Ephemeral streams are shown to exist to the north of the mine site shown in Sections 20 and 21 of T.22N/R3E based on the USGS 1:24,000 topographic map.

The study area is bounded by Quartermaster Harbor to the northwest and the East Passage of Puget Sound to the southeast. These saltwater bodies receive groundwater discharge from the aquifers beneath Maury Island. Because hydraulic continuity exists between Maury Island aquifers/aquitards and these saltwater bodies, groundwater elevations tend to approach sea level beneath coastal areas especially in the Principal Aquifer.

Springs exist at various locations along the steep bluffs that surround Maury Island. Springs represent groundwater discharging from the Principal Aquifer or from localized perched groundwater zones above the Principal Aquifer. They are localized discharge features and generally have only hearsay flow yield and construction information where developed as potable water supplies.

Only springs located immediately adjacent to the mine site and receiving discharge from the Principal Aquifer were modeled in this study, as these features generally have supporting hydrogeologic data. Springs fed by perched groundwater were not modeled in this study because the extent of perched aquifers is not known and because supporting characterization of perched groundwater conditions is beyond the scope of this study.

Springs adjacent to the mine site are summarized in **Table 4-1**. Approximate spring locations are shown on **Figure 1-1**. The Dockton Water Association maintains two springs for public water supply immediately south of Dockton Park. In this report, the east and west Dockton Park springs are designated as Springs 50s and 51s, respectively. A spring maintained by Paul Ferguson, hereafter referred to as the Ferguson

Spring (or Spring 48s on report figures) is located about 350 feet northeast of the Dockton Park springs. Two undeveloped springs exist along the beach area below the Glacier Northwest mine site. The springs are designated as Springs A and E based on initial spring descriptions by Rongey & Associates (1998) and subsequent characterization of on-site spring conditions conducted as part of these impact studies (Herrera, 2000). On-site springs are not currently used for water supply. Spring E discharges directly onto the beach face south of the mine dock. To the north of the dock, Spring A discharges at a slightly higher elevation on the steep, vegetated slope above the beach face, suggesting that it is fed by a localized perched groundwater horizon above the Principal Aquifer.

Two privately owned springs designated as Springs 52s and 54s exist in the Shore Acres area southwest of the mine site. These springs serve backup water systems to individual residences that are otherwise connected to the Sandy Shores water system. They are located at elevations of about 100 and 80 feet, respectively and have unknown completion and source details. The elevations of these springs suggest hydraulic continuity with perched groundwater above the Principal Aquifer. These springs are cross gradient from the mine site.

The Dockton Water Association maintains a spring-fed public water supply called Hake Spring on the south side of SW 268th Street. It is designated as Spring 49s in this report. Hake spring is located about 3,600 feet west of the mine site and is completed at an elevation of approximately 180 feet. The spring is located cross-gradient from the mine and is likely recharged by precipitation occurring on the south-central end of the island outside the mine area. For these reasons, Hake Spring is not vulnerable to activities on the mine site and was not considered in the impact assessments.

4.4 Land Cover

Land cover over most of Maury Island consists of either forest or grassland, with sparsely vegetated sand and gravel in the mine areas. PGG generated GIS coverage of these three land-cover types by digitizing associated areas identified on aerial 7.5-minute orthophotos taken by the USGS in the summer of 1990 (USGS, 1990). Forested areas occupy approximately 87 percent of the island, and typically comprise a patchy mixture of coniferous and deciduous trees. Grassy areas, including areas of low-density residential development (e.g. Dockton and Gold Beach) cover approximately 11 percent of the island. Existing mines cover the remainder, with impermeable surfaces such as paved roads and parking areas occuring over an extremely small percentage of island. Section 7 of this report presents the application of land coverage to the recharge analysis.

5.0 Geologic Conditions

5.1 Overview

For purposes of this study, the sediments encountered on Maury Island can be characterized as either glacial or interglacial. Sediments that are glacial in origin were deposited by a series of glaciers that once occupied Puget Sound. Interglacial sediments were deposited between glacial episodes, when glaciers did not occupy the region. The entire sequence of glacial and interglacial deposits is as much as 3,600 feet thick in the Puget Sound Lowland (Woodward and others, 1995). These deposits are at least 500 feet thick on Vashon-Maury Island based on the deepest wells completed near the mine site (VMGAC, 1998). The deeper glacial stratigraphy has not been defined due to lack of deep exploratory borings. A USGS map of the area indicates that unconsolidated deposits extend to at least 700 feet below sea level at Maury Island (Buchanan-Banks and others, 1995).

Previous investigators have presented significant research and discussion of the glacial geology and stratigraphy of Maury and Vashon Islands (see AESI (1998, 1999), Booth (1991), Carr (1983), Ritzi (1983), VMGAC (1998)). These studies provide the foundation for geologic interpretations presented in this report. The following is a brief history of glacial and interglacial deposition responsible for units observed in the study area.

5.1.1 Glacial Deposition

Geologic features over most of Maury Island are largely the result of a series of glaciations that occurred in Pleistocene time, which began about 2 million years ago and ended about 10,000 years ago. During this epoch, the Puget lobe of the Cordilleran glacier occupied the Puget Sound Lowland at least six times. These glacial episodes have been referred to as the Orting, the Stuck, the Salmon Springs, the Double Bluff, the Possession, and the Fraser glaciations (Easterbrook, 1994). According to Easterbrook, they span more than 1.7 million years. The glacial episodes were separated by long interglacial periods (Woodward and others, 1995). The youngest and best understood of these glacial episodes, the Vashon Stade of the Fraser Glaciation, ended 13,650 (± 550) years ago in Seattle (Booth and Goldstein, 1994), and probably culminated about 15,000 years ago in the Maury Island area.

5.1.2 Glacial Drift Sequence

Glacial drift is sedimentary material that has been transported and deposited by glacial ice or by meltwater derived from the ice. Each glacial episode is characterized by a "drift sequence." If complete, this sequence, from bottom to top, would typically consist of advance outwash, till, and recessional outwash. Melt-water streams issue from the front and margins of advancing and retreating glaciers. These streams or stream systems leave behind outwash deposits, which contain mostly sand and/or gravel. Because the glaciers are constantly moving in response to climatic and other changes, the outwash deposits cover extensive areas. The Vashon Stade outwash sand and gravel deposits are the target source of Glacier's proposed Maury Island mine and other aggregate mines on the south side of Maury Island.

5.1.2.1 *Advance and Recessional Outwash*

Advance outwash is deposited from streams and rivers issuing from the glacier as it advances. These processes are responsible for the extensive sand and gravel deposits that exist on Maury Island. Recessional outwash, on the other hand, is deposited by streams and rivers issuing from the glacier as it retreats. Recessional outwash is similar to advance outwash in its composition and method of deposition, with one major difference: it has not been overridden by advancing ice. Therefore, it is less compact and dense than advance outwash, which has been overridden by several thousand feet of ice. Very little recessional outwash was deposited on Maury Island during the last glacial retreat.

5.1.2.2 *Till*

Till is generally a dense, poorly sorted mixture of silt, sand, angular gravel, and boulders. One type of till—"lodgement till"—has been "smeared" along the bottom of a glacier as it flows. It is typically very dense because it has been overridden by several thousand feet of glacial ice. However, some till is deposited beneath blocks of standing (non-flowing) ice left by a retreating glacier. This type of till, referred to as "ablation till," is significantly less dense than lodgement till because it has not been overridden by the weight of an entire glacier. Lodgement till is the dominant till type deposited on the Maury Island mine site (AESI, 1999a). Till is not present over much of the site due to prior mining activity.

5.1.2.3 *Interglacial Deposits*

Interglacial deposits on Maury Island are commonly characterized by fine-grained sediments (fine sand, silt, and clay) of lacustrine (lake) or fluvial (river) origin, but may occasionally contain coarser-grained sediments of fluvial origin. Interglacial sediments were deposited in low energy environments such as proglacial lakes or floodplains that proceeded the advancing glacial ice masses. Interglacial sediments underlie the Vashon-age outwash deposits on Maury Island. These sediments have limited surficial exposure in the study area compared to the overlying advance outwash deposits, with exposures occurring mainly at the perimeter of the island. Contact with the overlying advance outwash is gradational, forming "transitional beds" beneath the outwash unit (Booth, 1991). The transitional beds are typically silts and sandy silts formed by lowland ponding just prior to the arrival of glacial ice. The transitional beds coarsen upwards into fine sands of the advance outwash deposited by proglacial streams flowing from the advancing ice.

5.2 Vashon Deposits (Qvr, Qvt, Qva)

More is known about the Vashon drift than about deposits associated with earlier glaciations, since surface exposures of Vashon sediments are more abundant and because wells penetrate these sediments. The Vashon glacier is believed to have covered the entire Puget Sound Lowland. Deposits associated with the Vashon glaciation include:

- Vashon recessional outwash (***Qvr***)
- Vashon till (***Qvt***)
- Vashon advance outwash (***Qva***)

These units are described below. Surface contact patterns for these units as mapped by Booth (1991) are shown on **Figure 5-1**. This

figure also includes the interpretive mapping of surficial geologic contacts between ***Qva*** and ***Qvt*** at the mine site as provided by AESI (1999a).

5.2.1 Vashon Recessional Outwash (*Qvr*)

Vashon recessional outwash (***Qvr***) deposits crop out at only one location in the study area **(Figure 5-1)** in the northeast corner of the mine site. The ***Qvr*** was likely deposited by streams that issued from the Vashon glacier as they shifted in response to climatic changes. The unit consists predominantly of stratified, sand and gravel with silty sand and rare silty clay. These deposits are generally relatively thin and discontinuous because they have been eroded and dissected by streams. The ***Qvr*** is not considered to be a significant unit in the study area because of its limited occurrence.

5.2.2 Vashon Till (*Qvt*)

Vashon till (***Qvt***) blankets most of the Maury Island study area above elevations of 200 to 300 feet (**Figure 5-1**). It consists of brown to brown-gray, poorly sorted, gravelly, silty sand with cobbles. Most of the unit was deposited along the bottom of the Vashon glacier; under a considerable thickness of ice; as such, it mantles the existing topography and it is typically dense. Till is commonly described by well drillers as "hardpan." The ***Qvt*** varies substantially in thickness, ranging from 0 to over 11-1/2 feet on the mine site (AESI, 1999a) and at most about 30 feet thick over parts of Maury Island (Booth, 1991).

The distribution of ***Qvt*** is defined by the mapping of Booth (1991) and by on-site test pits and borings conducted by AESI (1999a). These mapping efforts were re-evaluated and combined to describe the distribution of till used in PGG's recharge analysis. Although minor interpretive changes were made to AESI's surficial geologic interpretations, the till-outwash contact defined by AESI was considered representative of the surficial conditions of the mine site.

5.2.3 Vashon Advance Outwash (*Qva*)

The Vashon advance outwash (***Qva***) is the source of sand and gravel for the mine. It has nearly the same amount of surficial exposure as till on the island. The ***Qva*** exists beneath most of the study area as shown in **Figure 5-1**. It is the predominant geologic unit exposed at the mine site and on the steep bluffs that surround much of the island. It consists of well-bedded sandy gravel in its upper section and grades downward to a more common brown to gray, variably silty, stratified medium to fine-grained sand with occasional silty interbeds. The ***Qva*** unit gradually becomes finer downward to silty sand and sandy silt at the base of the deposit within the transitional beds. Primarily the lower, finer grained section of the ***Qva*** (and transitional beds) is typically saturated on Maury Island. These saturated sediments form the Principal Aquifer (see Section 6.1). The ***Qva*** was encountered in the five borings completed during this study as described in **Appendix A** and in all exploratory borings completed previously at the mine site (AESI, 1999a).

Interbeds of silt occur within the ***Qva*** above the regional water table. The grain size of these interbeds ranges from sandy silt to clayey silt. Silt interbeds range in thickness from about 1 to 5 feet in on-site wells and about 6 to 20 feet off-site wells. They occur more commonly in the lower, finer-grained

section of the ***Qva*** at depths of about 10 to 20 feet above the regional water table. They reflect the fining downward sequence that occurs within the lower portions of the ***Qva*** as it fines into transitional deposits. Individual interbeds have limited aerial distribution and could not be correlated between wells. Where a high permeability contrast exists with overlying sediments, interbeds can act as localized perching horizons as observed in Wells OBW-6 and OBW-7 (AESI, 1999a).

Thickness of the ***Qva*** varies considerably over the study area. Its thickness is greatest in the mine area where subsurface explorations do not penetrate the bottom of the deposit. The bottom of wells OBW-1, OBW-2, and OBW-7 installed by AESI (1999a) penetrate what is interpreted by PGG to be fine-grained ***Qva*** to depths of 300, 340, and 300 feet, respectively (bottom elevations of –6, 0, and 12 feet). These are the deepest explorations at the mine site and are completed in material ranging from fine sand with occasional gravel (OBW-7) to sandy silt and very fine sand with occasional gravel (OBW-1 and OBW-2). The ***Qva*** thickness in the mine area is therefore greater than about 340 feet assuming negligible thickness of ***Qvt*** and ***Qvr***.

The fine sands and silty sands observed at the bottom of AESI explorations are likely to be fine-grained advance outwash with a fining downward trend toward transitional beds. From the standpoint of regional groundwater flow, these sediments are considered part of the Principal Aquifer rather than part of the underlying aquitard unit. For this reason, PGG considers these fine-grain units to be part of the ***Qva*** and not part of the "pre-Vashon non-glacial deposits" described in corresponding well logs (AESI, 1998, 1999a). Deeper explorations would be required to define the absolute bottom depth of these water-bearing fine sands beneath the mine site.

Five explorations completed for this study were also completed in the finer-grained, lower section of the ***Qva***. These explorations were drilled to depths necessary for completing observation wells in the Principal Aquifer. ***Qva*** sediments encountered at the bottom of these borings ranged from saturated fine-to-medium sand with varying quantities of silt in MW-2, MW-3, and MW-5 to silt and very fine sand at MW-4 and MW-1. These materials were water-bearing and produced sufficient water for well completions. Project explorations show that the basal ***Qva*** section is typically saturated and may contain significant thicknesses of fine-grained sediments. These materials, which include sediments that could be considered as transitional beds by textural description alone (equivalent to the "pre-Vashon interglacial" designation of AESI's logs), are part of the Principal Aquifer.

The approximate elevation of the base of the ***Qva*** was estimated using driller's logs and from previous mapping and subsurface interpretations by Booth (1991). A structural contour map of the base of the ***Qva*** is shown in **Figure 5-2**. The contour map describes a broad, shallow, sub-sea level trough structure at the base of the ***Qva***. This trough includes fine-grained, saturated sediments penetrated by on-site wells and new off-site wells. According to Booth (1991), the sub-sea level portion of this structure likely marks a pre-Fraser arm of Puget Sound. The mine site is located roughly at the center of trough. The axis of the ***Qva*** trough extends from Dockton Park (including Dockton Springs) to the southeast though the mine site. The trough is narrowest at Dockton Park and widens along the southeast shore of the island to include Gold Beach and Sandy Shores. The ***Qva*** trough occurs where

discussed in Section 7.1. Supporting documentation is provided in **Appendix D**.

3.6.1.2 Time-Lag Analysis

Time-series water level data were reviewed to evaluate the lag between recharge and aquifer response during high-recharge months in the rainy season. Twelve months of water-level data from existing on-site monitoring wells were assessed. In addition, the time-lag analysis from Carr & Associates (1983) was modified to better characterize the relationship between recharge and groundwater levels in the Principal Aquifer outside the mine site. This analysis is detailed in Section 7.2.

3.6.1.3 Hydrus-2D Model

Because the time-lag analysis could not adequately describe the dynamics of recharge processes between the land surface and the Principal Aquifer, a simplified numerical model of the vadose zone was developed using Hydrus-2D (Simunek, 1999). This model was used to evaluate the movement, time lags, and dampening of seasonal recharge as it passes through the unsaturated sediments between land surface and the Principal Aquifer. The model considered:

- Grain-size analyses and/or soil moisture retention curves from soil samples obtained during well installation
- Soil property data reported in the existing site characterization reports
- Estimates of the magnitude and timing of seepage through the root zone and beneath the till as developed in the spreadsheet model.

The Hydrus-2D model was used in combination with the spreadsheet model and time-lag analysis to estimate recharge to the Principal Aquifer under current and proposed mining conditions. The recharge assessment is presented in Section 7.2. Supporting model documentation is provided in **Appendix E**.

Findings of the unsaturated flow evaluation were used to better define recharge lag times for the groundwater flow model discussed below.

3.6.2 Development of Calibrated Groundwater Flow Model

A numerical model of groundwater flow was developed to estimate the hydrogeologic impacts of the proposed mine development. A simple analytical model could not be used because hydrogeologic and mine development conditions were too complex. These conditions include spatially/temporally varying recharge, aquifer discharge to marine water bodies, and springs located along aquifer margins, the presence of a deep aquifer and a phased mine development and reclamation schedule.

3.6.2.1 Model Development

The flow model was based on the updated conceptual model. It features three layers representing the Principal Aquifer, an aquitard, and the underlying deep aquifer. It also incorporates boundary conditions along the coast and at near-site springs. The groundwater flow model was constructed using a graphical users interface (GUI), which promotes highly efficient setup, operation, and visualization of model structure and results. "MODFLOW," a finite-difference model for groundwater flow developed by the USGS

(McDonald and Harbaugh, 1988) was used with the "Groundwater Vistas" GUI developed by Environmental Simulations, Ltd. The model employs the maximum simplicity required to accurately portray the groundwater flow system.

Details of the groundwater flow model design and structure are presented in Section 8 and **Appendix F**.

3.6.2.2 Model Calibration and Predictive Simulations

The model was calibrated using the November 1999 water-level data, measured and reported spring flows, and water-level data collected from on-site wells. The recharge and lag time estimates were also used as model input. Model calibration is presented in Section 8.2.

Once calibrated, the model was used to predict changes in groundwater levels and discharges from near-site springs under three 12-year phases of mine excavation and subsequent site reclamation. Results of the predictive modeling are presented in Section 8.4. Limitations of the model predictions and underlying model assumptions are discussed in Section 8.5.

3.6.2.3 Model Review

An outside expert Dr. Thomas Harter, Associate Professor of Subsurface Hydrology at the University of California, Davis, reviewed the Maury Island models to ensure that they were scientifically sound and technically unbiased. He provided comment on the modeling approaches along with written input for three milestones in the hydrogeologic assessment task:

- Upon completion of recharge and unsaturated flow modeling
- After design and steady-state calibration of the groundwater flow model
- Upon completion of predictive modeling

Dr. Harter's comments are presented in **Appendix G** of this report.

4.0 Maury Island Physiography

Physiographic features of Maury Island have been described in detail by previous investigators (Carr (1983), Ritzi (1983), VMGAC, (1998), Booth (1991), AESI (1998, 1999)). The brief discussion that follows is an overview of physiographic features that are important for understanding and developing hydrologic models for the project.

4.1 Relief

Elevation in the study area ranges from about 380 feet at the center of the island in the mine site to sea level along the perimeter of the island. The land surface topography is relatively flat within the higher elevation areas with gradual slopes dipping to the north-northwest towards Dockton and Quartermaster Harbor. Steep bluffs rising from Puget Sound bound the southeastern margin of the study area. These bluffs extend from Manzanita at the southwest end of the island to Point Robinson at the island's eastern tip. The top of these bluffs generally forms the crest of the topographic divide that runs the length of the island.

4.2 Climate

Maury Island typically experiences cool dry summers and mild wet winters. The factors responsible for Maury Island climate have been described in detail in prior reports (see Carr, 1983). For the purpose of this analysis, available data were compiled and analyzed to estimate monthly values of precipitation, and minimum and maximum temperatures.

Historic climatic data collection on Maury and Vashon Islands has been relatively spotty. Carr (1983) summarizes data collection from seven rain gages on the islands and presents an isohyetal map for the 1981-82 water year. Two of the seven gages were located on Maury Island, and most of the gages had records less than 12 years in duration. The Vashon-Maury Island Ground Water Management Plan included precipitation monitoring and generation of an isohyetal map for 1989 through 1991 (VMGAC, 1998). Nine gages were monitored over the 3-year period, two of which were on Maury Island.

Comparison of the two isohyetal maps showed contradictory precipitation distributions on Maury Island. Carr's map showed almost 6 inches higher precipitation on the southwest end of Maury Island with respect to the northeast end (41.2 vs. 35.6 in/yr). In contrast, the Ground Water Management Plan (GWMP) showed almost 5 inches higher precipitation on the northeast end of the Island (43.8 vs. 39.1 in/yr).

PGG analyzed both sets of data, as well as long-term climatic data from SeaTac International Airport (located 8 miles northeast of central Maury Island) to derive representative, long-term monthly precipitation and temperature values for Maury Island. For the purpose of this analysis, precipitation and temperature were assumed uniformly distributed across the island. For precipitation, a ratio of 1.05 was estimated between the King County Water District (KCWD) #19 gage on Vashon Island and central Maury Island. This ratio was based on the GWMP isohyetal map, as it represented three rather than the one-year of collected data shown in Carr's report. In addition, a regression equation was developed to relate monthly precipitation at KCWD #19 to SeaTac airport, based on nine years of overlapping data. The equation (KCWD = 1.27 x SeaTac) had a correlation coefficient of 0.95. Based on

these two relationships, monthly precipitation at Maury Island is estimated to be 20 percent higher than SeaTac Airport.

Long-term (1961-1990) values of monthly precipitation at SeaTac Airport were used to derive synthetic monthly values of long-term precipitation on Maury Island. Long-term annual precipitation measured at Seatac Airport was 37.2 inches, compared to a synthesized value of 44.6 inches for Maury Island. **Figure 4-1** presents the monthly averages for Maury Island as well as monthly precipitation over two years preceding the groundwater level monitoring period used to calibrate the groundwater flow model. The plot shows that the majority of precipitation is concentrated in the months of October through March. Unusually high precipitation in the winter/spring of 1998-1999 directly precedes the one-year groundwater level monitoring period beginning in February of 1999.

Temperatures on Maury Island (in degrees Fahrenheit) range from the lower 50's to the lower 70's in the summer, and from the lower 30's to the lower 50's in the winter. A more detailed discussion of Maury Island temperatures is presented in **Appendix D**.

4.3 Hydrographic Features

Major hydrographic features in the study area consist of adjacent marine water bodies and localized springs discharging to the ground surface at the island's perimeter. Hydrographic features are shown in **Figure 1-1**. Streams and other surface water features did not exist in the mine site or in immediately adjacent areas during field reconnaissance conducted during this study. Ephemeral streams are shown to exist to the north of the mine site shown in Sections 20 and 21 of T.22N/R3E based on the USGS 1:24,000 topographic map.

The study area is bounded by Quartermaster Harbor to the northwest and the East Passage of Puget Sound to the southeast. These saltwater bodies receive groundwater discharge from the aquifers beneath Maury Island. Because hydraulic continuity exists between Maury Island aquifers/aquitards and these saltwater bodies, groundwater elevations tend to approach sea level beneath coastal areas especially in the Principal Aquifer.

Springs exist at various locations along the steep bluffs that surround Maury Island. Springs represent groundwater discharging from the Principal Aquifer or from localized perched groundwater zones above the Principal Aquifer. They are localized discharge features and generally have only hearsay flow yield and construction information where developed as potable water supplies.

Only springs located immediately adjacent to the mine site and receiving discharge from the Principal Aquifer were modeled in this study, as these features generally have supporting hydrogeologic data. Springs fed by perched groundwater were not modeled in this study because the extent of perched aquifers is not known and because supporting characterization of perched groundwater conditions is beyond the scope of this study.

Springs adjacent to the mine site are summarized in **Table 4-1**. Approximate spring locations are shown on **Figure 1-1**. The Dockton Water Association maintains two springs for public water supply immediately south of Dockton Park. In this report, the east and west Dockton Park springs are designated as Springs 50s and 51s, respectively. A spring maintained by Paul Ferguson, hereafter referred to as the Ferguson

Spring (or Spring 48s on report figures) is located about 350 feet northeast of the Dockton Park springs. Two undeveloped springs exist along the beach area below the Glacier Northwest mine site. The springs are designated as Springs A and E based on initial spring descriptions by Rongey & Associates (1998) and subsequent characterization of on-site spring conditions conducted as part of these impact studies (Herrera, 2000). On-site springs are not currently used for water supply. Spring E discharges directly onto the beach face south of the mine dock. To the north of the dock, Spring A discharges at a slightly higher elevation on the steep, vegetated slope above the beach face, suggesting that it is fed by a localized perched groundwater horizon above the Principal Aquifer.

Two privately owned springs designated as Springs 52s and 54s exist in the Shore Acres area southwest of the mine site. These springs serve backup water systems to individual residences that are otherwise connected to the Sandy Shores water system. They are located at elevations of about 100 and 80 feet, respectively and have unknown completion and source details. The elevations of these springs suggest hydraulic continuity with perched groundwater above the Principal Aquifer. These springs are cross gradient from the mine site.

The Dockton Water Association maintains a spring-fed public water supply called Hake Spring on the south side of SW 268th Street. It is designated as Spring 49s in this report. Hake spring is located about 3,600 feet west of the mine site and is completed at an elevation of approximately 180 feet. The spring is located cross-gradient from the mine and is likely recharged by precipitation occurring on the south-central end of the island outside the mine area. For these reasons, Hake Spring is not vulnerable to activities on the mine site and was not considered in the impact assessments.

4.4 Land Cover

Land cover over most of Maury Island consists of either forest or grassland, with sparsely vegetated sand and gravel in the mine areas. PGG generated GIS coverage of these three land-cover types by digitizing associated areas identified on aerial 7.5-minute orthophotos taken by the USGS in the summer of 1990 (USGS, 1990). Forested areas occupy approximately 87 percent of the island, and typically comprise a patchy mixture of coniferous and deciduous trees. Grassy areas, including areas of low-density residential development (e.g. Dockton and Gold Beach) cover approximately 11 percent of the island. Existing mines cover the remainder, with impermeable surfaces such as paved roads and parking areas occuring over an extremely small percentage of island. Section 7 of this report presents the application of land coverage to the recharge analysis.

5.0 Geologic Conditions

5.1 Overview

For purposes of this study, the sediments encountered on Maury Island can be characterized as either glacial or interglacial. Sediments that are glacial in origin were deposited by a series of glaciers that once occupied Puget Sound. Interglacial sediments were deposited between glacial episodes, when glaciers did not occupy the region. The entire sequence of glacial and interglacial deposits is as much as 3,600 feet thick in the Puget Sound Lowland (Woodward and others, 1995). These deposits are at least 500 feet thick on Vashon-Maury Island based on the deepest wells completed near the mine site (VMGAC, 1998). The deeper glacial stratigraphy has not been defined due to lack of deep exploratory borings. A USGS map of the area indicates that unconsolidated deposits extend to at least 700 feet below sea level at Maury Island (Buchanan-Banks and others, 1995).

Previous investigators have presented significant research and discussion of the glacial geology and stratigraphy of Maury and Vashon Islands (see AESI (1998, 1999), Booth (1991), Carr (1983), Ritzi (1983), VMGAC (1998)). These studies provide the foundation for geologic interpretations presented in this report. The following is a brief history of glacial and interglacial deposition responsible for units observed in the study area.

5.1.1 Glacial Deposition

Geologic features over most of Maury Island are largely the result of a series of glaciations that occurred in Pleistocene time, which began about 2 million years ago and ended about 10,000 years ago. During this epoch, the Puget lobe of the Cordilleran glacier occupied the Puget Sound Lowland at least six times. These glacial episodes have been referred to as the Orting, the Stuck, the Salmon Springs, the Double Bluff, the Possession, and the Fraser glaciations (Easterbrook, 1994). According to Easterbrook, they span more than 1.7 million years. The glacial episodes were separated by long interglacial periods (Woodward and others, 1995). The youngest and best understood of these glacial episodes, the Vashon Stade of the Fraser Glaciation, ended 13,650 (± 550) years ago in Seattle (Booth and Goldstein, 1994), and probably culminated about 15,000 years ago in the Maury Island area.

5.1.2 Glacial Drift Sequence

Glacial drift is sedimentary material that has been transported and deposited by glacial ice or by meltwater derived from the ice. Each glacial episode is characterized by a "drift sequence." If complete, this sequence, from bottom to top, would typically consist of advance outwash, till, and recessional outwash. Melt-water streams issue from the front and margins of advancing and retreating glaciers. These streams or stream systems leave behind outwash deposits, which contain mostly sand and/or gravel. Because the glaciers are constantly moving in response to climatic and other changes, the outwash deposits cover extensive areas. The Vashon Stade outwash sand and gravel deposits are the target source of Glacier's proposed Maury Island mine and other aggregate mines on the south side of Maury Island.

5.1.2.1 *Advance and Recessional Outwash*

Advance outwash is deposited from streams and rivers issuing from the glacier as it advances. These processes are responsible for the extensive sand and gravel deposits that exist on Maury Island. Recessional outwash, on the other hand, is deposited by streams and rivers issuing from the glacier as it retreats. Recessional outwash is similar to advance outwash in its composition and method of deposition, with one major difference: it has not been overridden by advancing ice. Therefore, it is less compact and dense than advance outwash, which has been overridden by several thousand feet of ice. Very little recessional outwash was deposited on Maury Island during the last glacial retreat.

5.1.2.2 *Till*

Till is generally a dense, poorly sorted mixture of silt, sand, angular gravel, and boulders. One type of till—"lodgement till"—has been "smeared" along the bottom of a glacier as it flows. It is typically very dense because it has been overridden by several thousand feet of glacial ice. However, some till is deposited beneath blocks of standing (non-flowing) ice left by a retreating glacier. This type of till, referred to as "ablation till," is significantly less dense than lodgement till because it has not been overridden by the weight of an entire glacier. Lodgement till is the dominant till type deposited on the Maury Island mine site (AESI, 1999a). Till is not present over much of the site due to prior mining activity.

5.1.2.3 *Interglacial Deposits*

Interglacial deposits on Maury Island are commonly characterized by fine-grained sediments (fine sand, silt, and clay) of lacustrine (lake) or fluvial (river) origin, but may occasionally contain coarser-grained sediments of fluvial origin. Interglacial sediments were deposited in low energy environments such as proglacial lakes or floodplains that proceeded the advancing glacial ice masses. Interglacial sediments underlie the Vashon-age outwash deposits on Maury Island. These sediments have limited surficial exposure in the study area compared to the overlying advance outwash deposits, with exposures occurring mainly at the perimeter of the island. Contact with the overlying advance outwash is gradational, forming "transitional beds" beneath the outwash unit (Booth, 1991). The transitional beds are typically silts and sandy silts formed by lowland ponding just prior to the arrival of glacial ice. The transitional beds coarsen upwards into fine sands of the advance outwash deposited by proglacial streams flowing from the advancing ice.

5.2 Vashon Deposits (Qvr, Qvt, Qva)

More is known about the Vashon drift than about deposits associated with earlier glaciations, since surface exposures of Vashon sediments are more abundant and because wells penetrate these sediments. The Vashon glacier is believed to have covered the entire Puget Sound Lowland. Deposits associated with the Vashon glaciation include:

- Vashon recessional outwash (***Qvr***)
- Vashon till (***Qvt***)
- Vashon advance outwash (***Qva***)

These units are described below. Surface contact patterns for these units as mapped by Booth (1991) are shown on **Figure 5-1**. This

figure also includes the interpretive mapping of surficial geologic contacts between ***Qva*** and ***Qvt*** at the mine site as provided by AESI (1999a).

5.2.1 Vashon Recessional Outwash (*Qvr*)

Vashon recessional outwash (***Qvr***) deposits crop out at only one location in the study area **(Figure 5-1)** in the northeast corner of the mine site. The ***Qvr*** was likely deposited by streams that issued from the Vashon glacier as they shifted in response to climatic changes. The unit consists predominantly of stratified, sand and gravel with silty sand and rare silty clay. These deposits are generally relatively thin and discontinuous because they have been eroded and dissected by streams. The ***Qvr*** is not considered to be a significant unit in the study area because of its limited occurrence.

5.2.2 Vashon Till (*Qvt*)

Vashon till (***Qvt***) blankets most of the Maury Island study area above elevations of 200 to 300 feet (**Figure 5-1**). It consists of brown to brown-gray, poorly sorted, gravelly, silty sand with cobbles. Most of the unit was deposited along the bottom of the Vashon glacier; under a considerable thickness of ice; as such, it mantles the existing topography and it is typically dense. Till is commonly described by well drillers as "hardpan." The ***Qvt*** varies substantially in thickness, ranging from 0 to over 11-1/2 feet on the mine site (AESI, 1999a) and at most about 30 feet thick over parts of Maury Island (Booth, 1991).

The distribution of ***Qvt*** is defined by the mapping of Booth (1991) and by on-site test pits and borings conducted by AESI (1999a). These mapping efforts were re-evaluated and combined to describe the distribution of till used in PGG's recharge analysis. Although minor interpretive changes were made to AESI's surficial geologic interpretations, the till-outwash contact defined by AESI was considered representative of the surficial conditions of the mine site.

5.2.3 Vashon Advance Outwash (*Qva*)

The Vashon advance outwash (***Qva***) is the source of sand and gravel for the mine. It has nearly the same amount of surficial exposure as till on the island. The ***Qva*** exists beneath most of the study area as shown in **Figure 5-1**. It is the predominant geologic unit exposed at the mine site and on the steep bluffs that surround much of the island. It consists of well-bedded sandy gravel in its upper section and grades downward to a more common brown to gray, variably silty, stratified medium to fine-grained sand with occasional silty interbeds. The ***Qva*** unit gradually becomes finer downward to silty sand and sandy silt at the base of the deposit within the transitional beds. Primarily the lower, finer grained section of the ***Qva*** (and transitional beds) is typically saturated on Maury Island. These saturated sediments form the Principal Aquifer (see Section 6.1). The ***Qva*** was encountered in the five borings completed during this study as described in **Appendix A** and in all exploratory borings completed previously at the mine site (AESI, 1999a).

Interbeds of silt occur within the ***Qva*** above the regional water table. The grain size of these interbeds ranges from sandy silt to clayey silt. Silt interbeds range in thickness from about 1 to 5 feet in on-site wells and about 6 to 20 feet off-site wells. They occur more commonly in the lower, finer-grained

section of the ***Qva*** at depths of about 10 to 20 feet above the regional water table. They reflect the fining downward sequence that occurs within the lower portions of the ***Qva*** as it fines into transitional deposits. Individual interbeds have limited aerial distribution and could not be correlated between wells. Where a high permeability contrast exists with overlying sediments, interbeds can act as localized perching horizons as observed in Wells OBW-6 and OBW-7 (AESI, 1999a).

Thickness of the ***Qva*** varies considerably over the study area. Its thickness is greatest in the mine area where subsurface explorations do not penetrate the bottom of the deposit. The bottom of wells OBW-1, OBW-2, and OBW-7 installed by AESI (1999a) penetrate what is interpreted by PGG to be fine-grained ***Qva*** to depths of 300, 340, and 300 feet, respectively (bottom elevations of –6, 0, and 12 feet). These are the deepest explorations at the mine site and are completed in material ranging from fine sand with occasional gravel (OBW-7) to sandy silt and very fine sand with occasional gravel (OBW-1 and OBW-2). The ***Qva*** thickness in the mine area is therefore greater than about 340 feet assuming negligible thickness of ***Qvt*** and ***Qvr***.

The fine sands and silty sands observed at the bottom of AESI explorations are likely to be fine-grained advance outwash with a fining downward trend toward transitional beds. From the standpoint of regional groundwater flow, these sediments are considered part of the Principal Aquifer rather than part of the underlying aquitard unit. For this reason, PGG considers these fine-grain units to be part of the ***Qva*** and not part of the "pre-Vashon non-glacial deposits" described in corresponding well logs (AESI, 1998, 1999a). Deeper explorations would be required to define the absolute bottom depth of these water-bearing fine sands beneath the mine site.

Five explorations completed for this study were also completed in the finer-grained, lower section of the ***Qva***. These explorations were drilled to depths necessary for completing observation wells in the Principal Aquifer. ***Qva*** sediments encountered at the bottom of these borings ranged from saturated fine-to-medium sand with varying quantities of silt in MW-2, MW-3, and MW-5 to silt and very fine sand at MW-4 and MW-1. These materials were water-bearing and produced sufficient water for well completions. Project explorations show that the basal ***Qva*** section is typically saturated and may contain significant thicknesses of fine-grained sediments. These materials, which include sediments that could be considered as transitional beds by textural description alone (equivalent to the "pre-Vashon interglacial" designation of AESI's logs), are part of the Principal Aquifer.

The approximate elevation of the base of the ***Qva*** was estimated using driller's logs and from previous mapping and subsurface interpretations by Booth (1991). A structural contour map of the base of the ***Qva*** is shown in **Figure 5-2**. The contour map describes a broad, shallow, sub-sea level trough structure at the base of the ***Qva***. This trough includes fine-grained, saturated sediments penetrated by on-site wells and new off-site wells. According to Booth (1991), the sub-sea level portion of this structure likely marks a pre-Fraser arm of Puget Sound. The mine site is located roughly at the center of trough. The axis of the ***Qva*** trough extends from Dockton Park (including Dockton Springs) to the southeast though the mine site. The trough is narrowest at Dockton Park and widens along the southeast shore of the island to include Gold Beach and Sandy Shores. The ***Qva*** trough occurs where

fine-grained outwash sediments have their lowest base elevation (below sea level). The absolute base elevation of the trough cannot be determined from existing exploration data because borings do not penetrate the entire ***Qva*** section in this area. On the flanks of the trough where ***Qva*** sediments are thinner, the base of the ***Qva*** rises to elevations of about 120 to 140 feet. Schematic geologic cross sections drawn through the ***Qva*** trough are presented in **Figures 5-3 and 5-4**.

5.3 Undifferentiated Pre-Vashon Deposits (Qpvu)

Pre-Vashon deposits were formed during earlier interglacial and glacial periods in the Puget Sound region. Deposition occurred in lacustrine and alluvial environments prior to about 20,000 years before present. For the purpose of hydrogeologic impact evaluations presented in this report, pre-Vashon units are not differentiated. They are described only in context to their relative stratigraphic positions and the conceptual geologic framework used to construct the groundwater flow model. The units that are combined in the undifferentiated Pre-Vashon deposits (***Qpvu***) include the "transitional beds" and the older interglacial deposits as described by Booth (1991). Surface outcrop patterns for the combined ***Qpvu*** are shown on **Figure 5-1**.

No project explorations were conducted in pre-Vashon units. More detailed discussion of individual pre-Vashon units is presented in Booth (1991) and VMGAC (1998).

Undifferentiated pre-Vashon deposits (***Qpvu***) underlie the ***Qva*** outwash. A gradational contact exists between the base of the ***Qva*** and the underlying "transitional beds" that form upper part of the ***Qpvu***. The transitional beds primarily comprise silt with varying amounts of very fine to fine sand. The textural (and hydraulic) difference between upper transitional beds and fine-grained silty sands of the lower ***Qva*** are very small. Thickness of transitional beds beneath the mine site can not be determined from existing explorations because these borings generally only penetrate the ***Qva*** and upper transitional beds and not the deeper pre-Vashon aquitard units. Because of the gradational contact between ***Qva*** and upper ***Qpvu*** deposits, distinction of transitional beds from boring logs is not exact.

Below the transitional beds are massive to thinly laminated clays and silts deposited during interglacial periods approximately 20,000 to 60,000 years before present. These ***Qpvu*** deposits, which commonly referred to as to "Olympia beds" (Booth, 1991), form a regionally extensive aquitard beneath the Principal Aquifer. Clays and silts of the Olympia beds were not encountered in explorations at the mine site. Silts and clays of this unit are encountered in the deeper private water wells drilled on the flanks of the ***Qva*** trough to the southwest and northeast of the mine site.

Thin horizons of water-bearing sand and gravel occur occasionally below sea level in the ***Qpvu***. The lateral extent and hydraulic continuity of these horizons between wells is not known. Fluvial channels within the proglacial environment or pre-Fraser glacial advances deposited these granular materials. These materials form the deep aquifer beneath Maury Island. Clays and silts of the ***Qpvu*** Olympia beds form a confining aquitard above these sand and gravel horizons. **Figures 5-3 and 5-4** present schematic geologic cross sections showing the upper surface of the ***Qpvu*** and the range of well completion depths in this unit.

fine-grained outwash sediments have their lowest base elevation (below sea level). The absolute base elevation of the trough cannot be determined from existing exploration data because borings do not penetrate the entire ***Qva*** section in this area. On the flanks of the trough where ***Qva*** sediments are thinner, the base of the ***Qva*** rises to elevations of about 120 to 140 feet. Schematic geologic cross sections drawn through the ***Qva*** trough are presented in **Figures 5-3 and 5-4**.

5.3 Undifferentiated Pre-Vashon Deposits (Qpvu)

Pre-Vashon deposits were formed during earlier interglacial and glacial periods in the Puget Sound region. Deposition occurred in lacustrine and alluvial environments prior to about 20,000 years before present. For the purpose of hydrogeologic impact evaluations presented in this report, pre-Vashon units are not differentiated. They are described only in context to their relative stratigraphic positions and the conceptual geologic framework used to construct the groundwater flow model. The units that are combined in the undifferentiated Pre-Vashon deposits (***Qpvu***) include the "transitional beds" and the older interglacial deposits as described by Booth (1991). Surface outcrop patterns for the combined ***Qpvu*** are shown on **Figure 5-1**.

No project explorations were conducted in pre-Vashon units. More detailed discussion of individual pre-Vashon units is presented in Booth (1991) and VMGAC (1998).

Undifferentiated pre-Vashon deposits (***Qpvu***) underlie the ***Qva*** outwash. A gradational contact exists between the base of the ***Qva*** and the underlying "transitional beds" that form upper part of the ***Qpvu***. The transitional beds primarily comprise silt with varying amounts of very fine to fine sand. The textural (and hydraulic) difference between upper transitional beds and fine-grained silty sands of the lower ***Qva*** are very small. Thickness of transitional beds beneath the mine site can not be determined from existing explorations because these borings generally only penetrate the ***Qva*** and upper transitional beds and not the deeper pre-Vashon aquitard units. Because of the gradational contact between ***Qva*** and upper ***Qpvu*** deposits, distinction of transitional beds from boring logs is not exact.

Below the transitional beds are massive to thinly laminated clays and silts deposited during interglacial periods approximately 20,000 to 60,000 years before present. These ***Qpvu*** deposits, which commonly referred to as to "Olympia beds" (Booth, 1991), form a regionally extensive aquitard beneath the Principal Aquifer. Clays and silts of the Olympia beds were not encountered in explorations at the mine site. Silts and clays of this unit are encountered in the deeper private water wells drilled on the flanks of the ***Qva*** trough to the southwest and northeast of the mine site.

Thin horizons of water-bearing sand and gravel occur occasionally below sea level in the ***Qpvu***. The lateral extent and hydraulic continuity of these horizons between wells is not known. Fluvial channels within the proglacial environment or pre-Fraser glacial advances deposited these granular materials. These materials form the deep aquifer beneath Maury Island. Clays and silts of the ***Qpvu*** Olympia beds form a confining aquitard above these sand and gravel horizons. **Figures 5-3 and 5-4** present schematic geologic cross sections showing the upper surface of the ***Qpvu*** and the range of well completion depths in this unit.

4.0 Maury Island Physiography

Physiographic features of Maury Island have been described in detail by previous investigators (Carr (1983), Ritzi (1983), VMGAC, (1998), Booth (1991), AESI (1998, 1999)). The brief discussion that follows is an overview of physiographic features that are important for understanding and developing hydrologic models for the project.

4.1 Relief

Elevation in the study area ranges from about 380 feet at the center of the island in the mine site to sea level along the perimeter of the island. The land surface topography is relatively flat within the higher elevation areas with gradual slopes dipping to the north-northwest towards Dockton and Quartermaster Harbor. Steep bluffs rising from Puget Sound bound the southeastern margin of the study area. These bluffs extend from Manzanita at the southwest end of the island to Point Robinson at the island's eastern tip. The top of these bluffs generally forms the crest of the topographic divide that runs the length of the island.

4.2 Climate

Maury Island typically experiences cool dry summers and mild wet winters. The factors responsible for Maury Island climate have been described in detail in prior reports (see Carr, 1983). For the purpose of this analysis, available data were compiled and analyzed to estimate monthly values of precipitation, and minimum and maximum temperatures.

Historic climatic data collection on Maury and Vashon Islands has been relatively spotty. Carr (1983) summarizes data collection from seven rain gages on the islands and presents an isohyetal map for the 1981-82 water year. Two of the seven gages were located on Maury Island, and most of the gages had records less than 12 years in duration. The Vashon-Maury Island Ground Water Management Plan included precipitation monitoring and generation of an isohyetal map for 1989 through 1991 (VMGAC, 1998). Nine gages were monitored over the 3-year period, two of which were on Maury Island.

Comparison of the two isohyetal maps showed contradictory precipitation distributions on Maury Island. Carr's map showed almost 6 inches higher precipitation on the southwest end of Maury Island with respect to the northeast end (41.2 vs. 35.6 in/yr). In contrast, the Ground Water Management Plan (GWMP) showed almost 5 inches higher precipitation on the northeast end of the Island (43.8 vs. 39.1 in/yr).

PGG analyzed both sets of data, as well as long-term climatic data from SeaTac International Airport (located 8 miles northeast of central Maury Island) to derive representative, long-term monthly precipitation and temperature values for Maury Island. For the purpose of this analysis, precipitation and temperature were assumed uniformly distributed across the island. For precipitation, a ratio of 1.05 was estimated between the King County Water District (KCWD) #19 gage on Vashon Island and central Maury Island. This ratio was based on the GWMP isohyetal map, as it represented three rather than the one-year of collected data shown in Carr's report. In addition, a regression equation was developed to relate monthly precipitation at KCWD #19 to SeaTac airport, based on nine years of overlapping data. The equation (KCWD = 1.27 x SeaTac) had a correlation coefficient of 0.95. Based on

these two relationships, monthly precipitation at Maury Island is estimated to be 20 percent higher than SeaTac Airport.

Long-term (1961-1990) values of monthly precipitation at SeaTac Airport were used to derive synthetic monthly values of long-term precipitation on Maury Island. Long-term annual precipitation measured at Seatac Airport was 37.2 inches, compared to a synthesized value of 44.6 inches for Maury Island. **Figure 4-1** presents the monthly averages for Maury Island as well as monthly precipitation over two years preceding the groundwater level monitoring period used to calibrate the groundwater flow model. The plot shows that the majority of precipitation is concentrated in the months of October through March. Unusually high precipitation in the winter/spring of 1998-1999 directly precedes the one-year groundwater level monitoring period beginning in February of 1999.

Temperatures on Maury Island (in degrees Fahrenheit) range from the lower 50's to the lower 70's in the summer, and from the lower 30's to the lower 50's in the winter. A more detailed discussion of Maury Island temperatures is presented in **Appendix D**.

4.3 Hydrographic Features

Major hydrographic features in the study area consist of adjacent marine water bodies and localized springs discharging to the ground surface at the island's perimeter. Hydrographic features are shown in **Figure 1-1**. Streams and other surface water features did not exist in the mine site or in immediately adjacent areas during field reconnaissance conducted during this study. Ephemeral streams are shown to exist to the north of the mine site shown in Sections 20 and 21 of T.22N/R3E based on the USGS 1:24,000 topographic map.

The study area is bounded by Quartermaster Harbor to the northwest and the East Passage of Puget Sound to the southeast. These saltwater bodies receive groundwater discharge from the aquifers beneath Maury Island. Because hydraulic continuity exists between Maury Island aquifers/aquitards and these saltwater bodies, groundwater elevations tend to approach sea level beneath coastal areas especially in the Principal Aquifer.

Springs exist at various locations along the steep bluffs that surround Maury Island. Springs represent groundwater discharging from the Principal Aquifer or from localized perched groundwater zones above the Principal Aquifer. They are localized discharge features and generally have only hearsay flow yield and construction information where developed as potable water supplies.

Only springs located immediately adjacent to the mine site and receiving discharge from the Principal Aquifer were modeled in this study, as these features generally have supporting hydrogeologic data. Springs fed by perched groundwater were not modeled in this study because the extent of perched aquifers is not known and because supporting characterization of perched groundwater conditions is beyond the scope of this study.

Springs adjacent to the mine site are summarized in **Table 4-1**. Approximate spring locations are shown on **Figure 1-1**. The Dockton Water Association maintains two springs for public water supply immediately south of Dockton Park. In this report, the east and west Dockton Park springs are designated as Springs 50s and 51s, respectively. A spring maintained by Paul Ferguson, hereafter referred to as the Ferguson

Spring (or Spring 48s on report figures) is located about 350 feet northeast of the Dockton Park springs. Two undeveloped springs exist along the beach area below the Glacier Northwest mine site. The springs are designated as Springs A and E based on initial spring descriptions by Rongey & Associates (1998) and subsequent characterization of on-site spring conditions conducted as part of these impact studies (Herrera, 2000). On-site springs are not currently used for water supply. Spring E discharges directly onto the beach face south of the mine dock. To the north of the dock, Spring A discharges at a slightly higher elevation on the steep, vegetated slope above the beach face, suggesting that it is fed by a localized perched groundwater horizon above the Principal Aquifer.

Two privately owned springs designated as Springs 52s and 54s exist in the Shore Acres area southwest of the mine site. These springs serve backup water systems to individual residences that are otherwise connected to the Sandy Shores water system. They are located at elevations of about 100 and 80 feet, respectively and have unknown completion and source details. The elevations of these springs suggest hydraulic continuity with perched groundwater above the Principal Aquifer. These springs are cross gradient from the mine site.

The Dockton Water Association maintains a spring-fed public water supply called Hake Spring on the south side of SW 268th Street. It is designated as Spring 49s in this report. Hake spring is located about 3,600 feet west of the mine site and is completed at an elevation of approximately 180 feet. The spring is located cross-gradient from the mine and is likely recharged by precipitation occurring on the south-central end of the island outside the mine area. For these reasons, Hake Spring is not vulnerable to activities on the mine site and was not considered in the impact assessments.

4.4 Land Cover

Land cover over most of Maury Island consists of either forest or grassland, with sparsely vegetated sand and gravel in the mine areas. PGG generated GIS coverage of these three land-cover types by digitizing associated areas identified on aerial 7.5-minute orthophotos taken by the USGS in the summer of 1990 (USGS, 1990). Forested areas occupy approximately 87 percent of the island, and typically comprise a patchy mixture of coniferous and deciduous trees. Grassy areas, including areas of low-density residential development (e.g. Dockton and Gold Beach) cover approximately 11 percent of the island. Existing mines cover the remainder, with impermeable surfaces such as paved roads and parking areas occuring over an extremely small percentage of island. Section 7 of this report presents the application of land coverage to the recharge analysis.

5.0 Geologic Conditions

5.1 Overview

For purposes of this study, the sediments encountered on Maury Island can be characterized as either glacial or interglacial. Sediments that are glacial in origin were deposited by a series of glaciers that once occupied Puget Sound. Interglacial sediments were deposited between glacial episodes, when glaciers did not occupy the region. The entire sequence of glacial and interglacial deposits is as much as 3,600 feet thick in the Puget Sound Lowland (Woodward and others, 1995). These deposits are at least 500 feet thick on Vashon-Maury Island based on the deepest wells completed near the mine site (VMGAC, 1998). The deeper glacial stratigraphy has not been defined due to lack of deep exploratory borings. A USGS map of the area indicates that unconsolidated deposits extend to at least 700 feet below sea level at Maury Island (Buchanan-Banks and others, 1995).

Previous investigators have presented significant research and discussion of the glacial geology and stratigraphy of Maury and Vashon Islands (see AESI (1998, 1999), Booth (1991), Carr (1983), Ritzi (1983), VMGAC (1998)). These studies provide the foundation for geologic interpretations presented in this report. The following is a brief history of glacial and interglacial deposition responsible for units observed in the study area.

5.1.1 Glacial Deposition

Geologic features over most of Maury Island are largely the result of a series of glaciations that occurred in Pleistocene time, which began about 2 million years ago and ended about 10,000 years ago. During this epoch, the Puget lobe of the Cordilleran glacier occupied the Puget Sound Lowland at least six times. These glacial episodes have been referred to as the Orting, the Stuck, the Salmon Springs, the Double Bluff, the Possession, and the Fraser glaciations (Easterbrook, 1994). According to Easterbrook, they span more than 1.7 million years. The glacial episodes were separated by long interglacial periods (Woodward and others, 1995). The youngest and best understood of these glacial episodes, the Vashon Stade of the Fraser Glaciation, ended 13,650 (± 550) years ago in Seattle (Booth and Goldstein, 1994), and probably culminated about 15,000 years ago in the Maury Island area.

5.1.2 Glacial Drift Sequence

Glacial drift is sedimentary material that has been transported and deposited by glacial ice or by meltwater derived from the ice. Each glacial episode is characterized by a "drift sequence." If complete, this sequence, from bottom to top, would typically consist of advance outwash, till, and recessional outwash. Melt-water streams issue from the front and margins of advancing and retreating glaciers. These streams or stream systems leave behind outwash deposits, which contain mostly sand and/or gravel. Because the glaciers are constantly moving in response to climatic and other changes, the outwash deposits cover extensive areas. The Vashon Stade outwash sand and gravel deposits are the target source of Glacier's proposed Maury Island mine and other aggregate mines on the south side of Maury Island.

5.1.2.1 *Advance and Recessional Outwash*

Advance outwash is deposited from streams and rivers issuing from the glacier as it advances. These processes are responsible for the extensive sand and gravel deposits that exist on Maury Island. Recessional outwash, on the other hand, is deposited by streams and rivers issuing from the glacier as it retreats. Recessional outwash is similar to advance outwash in its composition and method of deposition, with one major difference: it has not been overridden by advancing ice. Therefore, it is less compact and dense than advance outwash, which has been overridden by several thousand feet of ice. Very little recessional outwash was deposited on Maury Island during the last glacial retreat.

5.1.2.2 *Till*

Till is generally a dense, poorly sorted mixture of silt, sand, angular gravel, and boulders. One type of till—"lodgement till"—has been "smeared" along the bottom of a glacier as it flows. It is typically very dense because it has been overridden by several thousand feet of glacial ice. However, some till is deposited beneath blocks of standing (non-flowing) ice left by a retreating glacier. This type of till, referred to as "ablation till," is significantly less dense than lodgement till because it has not been overridden by the weight of an entire glacier. Lodgement till is the dominant till type deposited on the Maury Island mine site (AESI, 1999a). Till is not present over much of the site due to prior mining activity.

5.1.2.3 *Interglacial Deposits*

Interglacial deposits on Maury Island are commonly characterized by fine-grained sediments (fine sand, silt, and clay) of lacustrine (lake) or fluvial (river) origin, but may occasionally contain coarser-grained sediments of fluvial origin. Interglacial sediments were deposited in low energy environments such as proglacial lakes or floodplains that proceeded the advancing glacial ice masses. Interglacial sediments underlie the Vashon-age outwash deposits on Maury Island. These sediments have limited surficial exposure in the study area compared to the overlying advance outwash deposits, with exposures occurring mainly at the perimeter of the island. Contact with the overlying advance outwash is gradational, forming "transitional beds" beneath the outwash unit (Booth, 1991). The transitional beds are typically silts and sandy silts formed by lowland ponding just prior to the arrival of glacial ice. The transitional beds coarsen upwards into fine sands of the advance outwash deposited by proglacial streams flowing from the advancing ice.

5.2 Vashon Deposits (Qvr, Qvt, Qva)

More is known about the Vashon drift than about deposits associated with earlier glaciations, since surface exposures of Vashon sediments are more abundant and because wells penetrate these sediments. The Vashon glacier is believed to have covered the entire Puget Sound Lowland. Deposits associated with the Vashon glaciation include:

- Vashon recessional outwash (***Qvr***)
- Vashon till (***Qvt***)
- Vashon advance outwash (***Qva***)

These units are described below. Surface contact patterns for these units as mapped by Booth (1991) are shown on **Figure 5-1**. This

figure also includes the interpretive mapping of surficial geologic contacts between ***Qva*** and ***Qvt*** at the mine site as provided by AESI (1999a).

5.2.1 Vashon Recessional Outwash (*Qvr*)

Vashon recessional outwash (***Qvr***) deposits crop out at only one location in the study area **(Figure 5-1)** in the northeast corner of the mine site. The ***Qvr*** was likely deposited by streams that issued from the Vashon glacier as they shifted in response to climatic changes. The unit consists predominantly of stratified, sand and gravel with silty sand and rare silty clay. These deposits are generally relatively thin and discontinuous because they have been eroded and dissected by streams. The ***Qvr*** is not considered to be a significant unit in the study area because of its limited occurrence.

5.2.2 Vashon Till (*Qvt*)

Vashon till (***Qvt***) blankets most of the Maury Island study area above elevations of 200 to 300 feet (**Figure 5-1**). It consists of brown to brown-gray, poorly sorted, gravelly, silty sand with cobbles. Most of the unit was deposited along the bottom of the Vashon glacier; under a considerable thickness of ice; as such, it mantles the existing topography and it is typically dense. Till is commonly described by well drillers as "hardpan." The ***Qvt*** varies substantially in thickness, ranging from 0 to over 11-1/2 feet on the mine site (AESI, 1999a) and at most about 30 feet thick over parts of Maury Island (Booth, 1991).

The distribution of ***Qvt*** is defined by the mapping of Booth (1991) and by on-site test pits and borings conducted by AESI (1999a). These mapping efforts were re-evaluated and combined to describe the distribution of till used in PGG's recharge analysis. Although minor interpretive changes were made to AESI's surficial geologic interpretations, the till-outwash contact defined by AESI was considered representative of the surficial conditions of the mine site.

5.2.3 Vashon Advance Outwash (*Qva*)

The Vashon advance outwash (***Qva***) is the source of sand and gravel for the mine. It has nearly the same amount of surficial exposure as till on the island. The ***Qva*** exists beneath most of the study area as shown in **Figure 5-1**. It is the predominant geologic unit exposed at the mine site and on the steep bluffs that surround much of the island. It consists of well-bedded sandy gravel in its upper section and grades downward to a more common brown to gray, variably silty, stratified medium to fine-grained sand with occasional silty interbeds. The ***Qva*** unit gradually becomes finer downward to silty sand and sandy silt at the base of the deposit within the transitional beds. Primarily the lower, finer grained section of the ***Qva*** (and transitional beds) is typically saturated on Maury Island. These saturated sediments form the Principal Aquifer (see Section 6.1). The ***Qva*** was encountered in the five borings completed during this study as described in **Appendix A** and in all exploratory borings completed previously at the mine site (AESI, 1999a).

Interbeds of silt occur within the ***Qva*** above the regional water table. The grain size of these interbeds ranges from sandy silt to clayey silt. Silt interbeds range in thickness from about 1 to 5 feet in on-site wells and about 6 to 20 feet off-site wells. They occur more commonly in the lower, finer-grained

section of the ***Qva*** at depths of about 10 to 20 feet above the regional water table. They reflect the fining downward sequence that occurs within the lower portions of the ***Qva*** as it fines into transitional deposits. Individual interbeds have limited aerial distribution and could not be correlated between wells. Where a high permeability contrast exists with overlying sediments, interbeds can act as localized perching horizons as observed in Wells OBW-6 and OBW-7 (AESI, 1999a).

Thickness of the ***Qva*** varies considerably over the study area. Its thickness is greatest in the mine area where subsurface explorations do not penetrate the bottom of the deposit. The bottom of wells OBW-1, OBW-2, and OBW-7 installed by AESI (1999a) penetrate what is interpreted by PGG to be fine-grained ***Qva*** to depths of 300, 340, and 300 feet, respectively (bottom elevations of –6, 0, and 12 feet). These are the deepest explorations at the mine site and are completed in material ranging from fine sand with occasional gravel (OBW-7) to sandy silt and very fine sand with occasional gravel (OBW-1 and OBW-2). The ***Qva*** thickness in the mine area is therefore greater than about 340 feet assuming negligible thickness of ***Qvt*** and ***Qvr***.

The fine sands and silty sands observed at the bottom of AESI explorations are likely to be fine-grained advance outwash with a fining downward trend toward transitional beds. From the standpoint of regional groundwater flow, these sediments are considered part of the Principal Aquifer rather than part of the underlying aquitard unit. For this reason, PGG considers these fine-grain units to be part of the ***Qva*** and not part of the "pre-Vashon non-glacial deposits" described in corresponding well logs (AESI, 1998, 1999a). Deeper explorations would be required to define the absolute bottom depth of these water-bearing fine sands beneath the mine site.

Five explorations completed for this study were also completed in the finer-grained, lower section of the ***Qva***. These explorations were drilled to depths necessary for completing observation wells in the Principal Aquifer. ***Qva*** sediments encountered at the bottom of these borings ranged from saturated fine-to-medium sand with varying quantities of silt in MW-2, MW-3, and MW-5 to silt and very fine sand at MW-4 and MW-1. These materials were water-bearing and produced sufficient water for well completions. Project explorations show that the basal ***Qva*** section is typically saturated and may contain significant thicknesses of fine-grained sediments. These materials, which include sediments that could be considered as transitional beds by textural description alone (equivalent to the "pre-Vashon interglacial" designation of AESI's logs), are part of the Principal Aquifer.

The approximate elevation of the base of the ***Qva*** was estimated using driller's logs and from previous mapping and subsurface interpretations by Booth (1991). A structural contour map of the base of the ***Qva*** is shown in **Figure 5-2**. The contour map describes a broad, shallow, sub-sea level trough structure at the base of the ***Qva***. This trough includes fine-grained, saturated sediments penetrated by on-site wells and new off-site wells. According to Booth (1991), the sub-sea level portion of this structure likely marks a pre-Fraser arm of Puget Sound. The mine site is located roughly at the center of trough. The axis of the ***Qva*** trough extends from Dockton Park (including Dockton Springs) to the southeast though the mine site. The trough is narrowest at Dockton Park and widens along the southeast shore of the island to include Gold Beach and Sandy Shores. The ***Qva*** trough occurs where

fine-grained outwash sediments have their lowest base elevation (below sea level). The absolute base elevation of the trough cannot be determined from existing exploration data because borings do not penetrate the entire ***Qva*** section in this area. On the flanks of the trough where ***Qva*** sediments are thinner, the base of the ***Qva*** rises to elevations of about 120 to 140 feet. Schematic geologic cross sections drawn through the ***Qva*** trough are presented in **Figures 5-3 and 5-4**.

5.3 Undifferentiated Pre-Vashon Deposits (Qpvu)

Pre-Vashon deposits were formed during earlier interglacial and glacial periods in the Puget Sound region. Deposition occurred in lacustrine and alluvial environments prior to about 20,000 years before present. For the purpose of hydrogeologic impact evaluations presented in this report, pre-Vashon units are not differentiated. They are described only in context to their relative stratigraphic positions and the conceptual geologic framework used to construct the groundwater flow model. The units that are combined in the undifferentiated Pre-Vashon deposits (***Qpvu***) include the "transitional beds" and the older interglacial deposits as described by Booth (1991). Surface outcrop patterns for the combined ***Qpvu*** are shown on **Figure 5-1**.

No project explorations were conducted in pre-Vashon units. More detailed discussion of individual pre-Vashon units is presented in Booth (1991) and VMGAC (1998).

Undifferentiated pre-Vashon deposits (***Qpvu***) underlie the ***Qva*** outwash. A gradational contact exists between the base of the ***Qva*** and the underlying "transitional beds" that form upper part of the ***Qpvu***. The transitional beds primarily comprise silt with varying amounts of very fine to fine sand. The textural (and hydraulic) difference between upper transitional beds and fine-grained silty sands of the lower ***Qva*** are very small. Thickness of transitional beds beneath the mine site can not be determined from existing explorations because these borings generally only penetrate the ***Qva*** and upper transitional beds and not the deeper pre-Vashon aquitard units. Because of the gradational contact between ***Qva*** and upper ***Qpvu*** deposits, distinction of transitional beds from boring logs is not exact.

Below the transitional beds are massive to thinly laminated clays and silts deposited during interglacial periods approximately 20,000 to 60,000 years before present. These ***Qpvu*** deposits, which commonly referred to as to "Olympia beds" (Booth, 1991), form a regionally extensive aquitard beneath the Principal Aquifer. Clays and silts of the Olympia beds were not encountered in explorations at the mine site. Silts and clays of this unit are encountered in the deeper private water wells drilled on the flanks of the ***Qva*** trough to the southwest and northeast of the mine site.

Thin horizons of water-bearing sand and gravel occur occasionally below sea level in the ***Qpvu***. The lateral extent and hydraulic continuity of these horizons between wells is not known. Fluvial channels within the proglacial environment or pre-Fraser glacial advances deposited these granular materials. These materials form the deep aquifer beneath Maury Island. Clays and silts of the ***Qpvu*** Olympia beds form a confining aquitard above these sand and gravel horizons. **Figures 5-3 and 5-4** present schematic geologic cross sections showing the upper surface of the ***Qpvu*** and the range of well completion depths in this unit.

fine-grained outwash sediments have their lowest base elevation (below sea level). The absolute base elevation of the trough cannot be determined from existing exploration data because borings do not penetrate the entire ***Qva*** section in this area. On the flanks of the trough where ***Qva*** sediments are thinner, the base of the ***Qva*** rises to elevations of about 120 to 140 feet. Schematic geologic cross sections drawn through the ***Qva*** trough are presented in **Figures 5-3 and 5-4**.

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6.0 Groundwater Flow System

6.1 Overview

The Maury Island groundwater flow system consists of three primary groundwater flow regimes, interconnected by low permeability aquitards or significant thicknesses of unsaturated sediments. These flow regimes include a perched subflow zone above the ***Qvt***, the Principal Aquifer in the ***Qva*** and upper transitional beds, and the deep aquifer in the ***Qpvu***. The perched subflow zone occurs locally and may be seasonally dependent. The Principal and deep aquifers are regionally significant groundwater systems that supply water to the majority of wells and springs in the study area. Previous investigators including AESI (1998, 1999a), Carr (1983), Terra (1999), Ritzi (1983), and VMGAC (1998) provide valuable characterization and description of the study area flow regimes.

Understanding of the groundwater flow regimes is important for constructing a representative numerical flow model, and thereby providing a reliable assessment of hydrogeologic impacts caused by proposed mine development. The following is an overview of the three groundwater flow regimes incorporated in the hydrogeologic impact assessments (Section 8).

6.1.1 Perched Subflow Network above *Qvt*

Perched conditions occur when the rate of recharge to surficial soils above the till exceeds the ability of the till to conduct water downward to underlying layers. Saturated conditions have been observed locally above the lodgment till horizon (***Qvt***) that mantles the north-northwestern portion of the mine site (AESI, 1999a). Perched subflow occurs when saturation above the till flows laterally, and is most likely to occur where the till surface is sloping. Field observations reported by AESI (1999a) and Terra (1999) suggest that lateral flow at the mine site is highly localized due to heterogeneities in the till. Furthermore, no surface discharge of a perched subflow zone was observed near the study areas. Although not observed by past site investigators, it is possible that seasonal perched subflow will cause shallow groundwater atop the ***Qvt*** to move laterally before entering the underlying advance outwash. The significance of such perched subflow on the regional recharge patterns was considered in the recharge evaluation presented in Section 7 and **Appendix D** of this report.

It should be noted that limited data collection, field characterization, and monitoring studies have been conducted in the perched subflow zone by past investigations. Additionally, no field characterization of the perched subflow system was conducted as part of this study. Estimates of flow rates and water movement in this zone are therefore based on assumed values within ranges based on best professional judgement.

6.1.2 Principal Aquifer in *Qva* and Transitional Beds

The uppermost aquifer of regional significance in the study area is the Principal Aquifer. The Principal Aquifer is unconfined and occurs in the lower section of ***Qva*** sediments and permeable upper portions of the underlying transitional beds. Transitional beds are typically saturated and are in direct contact with overlying ***Qva*** sediments. The ***Qva*** and upper transitional bed sediments that comprise the Principal Aquifer are capable of

producing domestic well yields of 2 to 10 gpm. The Principal Aquifer is recharged by precipitation at the land surface infiltrating through the root zone and flowing through the ***Qvt*** (where present), and then through the underlying unsaturated ***Qva*** profile. Recharge to the Principal Aquifer occurs throughout the study area, including all but the shoreline areas of the subject mine site. Groundwater discharges from the Principal Aquifer to Puget Sound and Quartermaster Harbor in areas where the marine beach face intersects the aquifer in the ***Qva*** trough (Section 5.2.3). The Principal Aquifer also drains vertically (leakage) into the underlying ***Qpvu*** interglacial sediments, although leakage through these aquitard materials is expected to be relatively small and is difficult to quantify (Carr, 1983). Discharge from the Principal Aquifer also occurs by wells and by groundwater seeps and springs located at or near beach level on the island perimeter.

The occurrence of the Principal Aquifer along portions of Quartermaster Harbor near Dockton Park is defined by the geologic contact of ***Qva*** (and/or upper transitional bed) sediments with older ***Qpvu*** interglacial sediments (**Figure 5-1**). With the exception of upper transitional bed sediments, the outcrop of ***Qpvu*** interglacial sediments defines the lateral boundary of the Principal Aquifer. The aquifer therefore truncates against the ***Qpvu*** contact where ***Qva*** sediments onlap the older interglacial sediments.

The geometry of the Principal Aquifer over most of the study area is defined by the erosional surface of the underlying ***Qpvu*** interglacial sediments. The upper erosional surface of the ***Qpvu*** forms a trough that is filled ***Qva*** sediments (and transitional bed sediments). The ***Qva*** trough structure is shown in plan view in **Figure 5-2** and in cross sections presented in **Figures 5-3 and 5-4**. The Principal Aquifer geometry roughly follows the configuration of this structural surface, with the aquifer base occurring at higher elevations on the flanks of the trough to the northeast and southwest of the mine site. Along the highest elevation flanks of the trough, where wells are generally completed in the deep aquifer, the ***Qva*** has a base elevation above sea level and generally has insufficient saturated thickness and/or permeability to provide reliable quantities of groundwater. This condition occurs at many of the wells drilled at higher elevations in the study area such as Well Numbers 16, 17, 20, 30, 31, 32 and 42 (**Figure 1-1**). In these areas, the Principal Aquifer is not considered reliable as a completion zone for domestic water supply wells (Larry Johnson, 1999, personal communication). The aquifer base occurs below sea level along the axis of the trough between Dockton Park and the island's southeast shoreline, including an area extending from north of Gold Beach through the mine site to Summerhurst.

The Principal Aquifer occurs to the north of the mine site as demonstrated by logs of domestic supply wells 4b, 18, 21, 22, and 47. These wells, in conjunction with wells MW-4 and MW-5 drilled for this study, serve as the basis for defining the aquifer geometry outside of the mine site. The Principal Aquifer is not used for water well completions to the east of this area, presumably due to insufficient saturated thickness encountered while drilling (see Well Numbers 16, 17, 20, 30, and 42). The Principal Aquifer also thins significantly to the southwest of the mine site as defined by Well Numbers 31 and 32. Similar to wells completed on the higher elevation areas to the northeast of the mine site, these wells were drilled through and completed below the ***Qva*** sediments presumably for lack of significant water in ***Qva*** materials.

The hydraulic properties of the Principal Aquifer on Maury Island have not been characterized by field testing. However, the properties of glacial advance outwash materials have been extensively studied in other locations and have been published in the literature. A recent USGS publication summarizes the results of various studies reporting horizontal hydraulic conductivity of various aquifers in the Puget Sound (Vaccaro et al, 1998). It states:

> "The units that consist principally of sand have average conductivity values of about 15 to 50 feet per day (ft/d)... Hydraulic conductivity values less than about 15 ft/d indicate a fine grained equivalent of the sand units (probably silty sand), and values less than about 10 ft/d indicate that the fine-grained equivalent contains more silt and probably has 1-10 percent clay content."

Specifically for ***Qva*** deposits, the USGS reports mean hydraulic conductivity values ranging from 5 to 100 ft/d. Porosity values for sands typically range from 25 to 50 percent (Freeze and Cherry, 1979), and representative values of specific yield are reported to range from 23 to 28 percent (Todd, 1980). Increased silt contents will result in decreased values of specific yield.

6.1.3 Aquitard in Interglacial Sediments

The ***Qpvu*** interglacial sediments form a regionally extensive aquitard that underlies the Principal Aquifer. This aquitard separates the Principal Aquifer from the underlying deep aquifer on Maury Island, thereby limiting vertical flow between the two aquifers. No wells have penetrated the aquitard on the mine site. The spatial distribution of this unit is interpreted from well logs for off-site wells presented in **Appendix B** and by surficial geologic mapping (Booth, 1991). The ***Qpvu*** aquitard is encountered in the relatively deep wells drilled to the southwest (e.g., Well Numbers 31 and 32) and northeast (e.g., Wells Numbers 16, 17, 20) of the mine site. Clay layers in the ***Qpvu*** aquitard range in thickness from about 30 and 180 feet based on driller's logs for these wells.

Given the interbedded nature of the interglacial sediments, horizontal hydraulic conductivity values are expected to be significantly higher than vertical hydraulic conductivity values. In the horizontal dimension, groundwater flow will follow interconnected sandy layers and lenses where available. Thus, horizontal hydraulic conductivity will be largely influenced by the properties of silty sands. In the vertical dimension, groundwater flow will have to cross layered and laminated clay and silt deposits, and will thus be largely influenced by the associated finer grained sediments. The USGS cites one study which reports conductivity values for interglacial silty clay ranging from 0.00007 to 0.003 ft/d (Vacarro et al, 1998). Relative to other values reported in the literature, these appear to be somewhat low. Freeze and Cherry (1979) report hydraulic conductivity values for silt that range from 0.0003 to 3 ft/d.

6.1.4 Deep Aquifer in *Qpvu*

A laterally discontinuous, deep aquifer system exists in the ***Qpvu*** sediments at selected locations on Maury Island. A total of 19 wells penetrate water-bearing ***Qpvu*** sediments in the study area (**Table 3-2**). The deep aquifer system is confined and is overlain and underlain by fine-grained ***Qpvu*** aquitard materials. Recharge to the deep aquifer system is by slow drainage or leakage through the overlying ***Qpvu*** aquitard materials from the Principal Aquifer.

The deep aquifer occurs below sea level at elevations ranging from about –30 to –360 feet below mean sea level, and is frequently referred to as the "sub sea-level aquifer." It ranges in thickness from about 2 to 60 feet and is extremely heterogeneous, with aquifer materials ranging from fine sand to gravel to clayey gravel at various locations. Many of the public supply wells in the study area are completed below sea level in the deep aquifer (e.g., Well Numbers 20, 31, 32) as shown schematically on **Figure 5-3**. However, variations in aquifer depth, thickness, and character suggest that the deep aquifer may not be a laterally continuous water-bearing unit within the ***Qpvu***. Instead, wells completed within the ***Qpvu*** materials likely tap different lenses or local zones of water-bearing material.

Stratigraphic correlation of water-bearing zones between deep aquifer wells is difficult, and associated maps of groundwater levels are highly interpretive and variable (Carr, 1983). A subset of wells in the deep aquifer, completed beneath an elevation of 80 feet below sea level, do show generally consistent water-level elevations ranging from about 5 to 27 feet above sea level. This subset was used to represent deep aquifer heads during design of the groundwater flow model, as discussed in Section 8.1.

6.2 Groundwater Flow Patterns

An understanding of groundwater flow patterns is important for evaluating hydrogeologic impacts of the proposed mine to the Principal Aquifer and for developing a representative groundwater flow model to predict these impacts. Hydraulically distinct flow fields exist in the Principal Aquifer and the deep aquifer systems. Methods used to for evaluating groundwater flow paths in the Principal Aquifer are presented in Sections 3.4 and 3.5. Results of water level monitoring used to assess flow patterns in the island aquifers are presented below. A summary of water level data used to assess flow patterns is presented in **Table 3-2**.

6.2.1 Wells Available for Measurement

Wells available for water level measurements are generally not distributed evenly within the study area (**Figure 1-1**). Off-site wells completed in the Principal Aquifer exist primarily to the northwest and north of the mine site. These domestic wells serve residential properties along Dockton Road SW. Using off-site and on-site wells, flow directions in the Principal Aquifer are well defined to the north-northwest of the mine and in the mine area itself. No wells are known to be completed in the Principal Aquifer to the south and southwest of the mine site. For purposes of estimating groundwater flow directions in the Principal Aquifer in this area, water levels were estimated at Well Numbers 31 (Sandy Shores) and 32 (Hillcrest) using saturated conditions and/or water levels noted at the time of drilling ("ATD") in well logs. Water levels for these wells are considered approximate but are suitable for defining regional flow conditions given a lack of more detailed subsurface information. Water levels in the Principal Aquifer to the east of the mine site are defined only by Well Numbers 34 and 35 (Gold Beach wells). Other wells located to the east and northeast of the mine site are completed in the deep aquifer and no Principal Aquifer water level data are available in this area.

Fewer wells were available for measuring hydraulic head in the deep aquifer. Most of the deep aquifer wells are located at least 2,000 to 3,000 feet north and/or northeast of the mine site. Two deep wells were available

for measurement to the southwest of the mine site. Water level sounder access was not possible in some of the deeper wells. ATD water levels were used as an estimate of hydraulic head conditions at inaccessible wells.

6.2.2 Interpretation of November 1999 Data

Figure 6-1 presents water level contours and groundwater flow directions in the Principal Aquifer for November 1999. Because groundwater flows to both Puget Sound and to Quartermaster Harbor through the ***Qva*** trough, there are two dominant flow directions in the Principal Aquifer. The primary component of flow is toward Puget Sound, with flow beneath the mine site occurring primarily to the southeast. A more localized component of groundwater flow exists to the northwest of the mine where flow is toward Quartermaster Harbor at Dockton Park. A groundwater flow divide exists roughly parallel to the axis of the island. The divide is located immediately northwest of the mine site and trends from southwest to northeast. The divide results in groundwater beneath the mine site flowing toward Puget Sound. Groundwater occurring to the northwest side of this divide near the mine site flows towards Quartermaster Harbor and Dockton Springs.

Measured groundwater levels in the Principal Aquifer are highest to the north of the site where water table elevations range from about 80 to 90 feet. The elevation of the water level divide between the mine site and Dockton Springs is at an elevation of between 57 and 60 feet based on surrounding measurements. Water levels decrease rapidly towards sea level towards Dockton Park and along the southeast shoreline of the island where the Principal Aquifer intersects marine waters.

The groundwater levels on the island create a wide range of relatively steep horizontal hydraulic gradients ranging from 0.005 to the north of the mine to 0.03 beneath the mine. Measured vertical gradients range from +0.008 at the well pair OBW-5 & MW-1 to –0.2 at the well pair OBW-9 and MW-2. These gradients suggest that a component of downward flow is occurring through in the Principal Aquifer at the downgradient edge of the mine site. Downward flow is typical of a recharge area.

Groundwater in the Principal Aquifer generally flows toward the ***Qva*** trough and marine waters that bound the aquifer. Water levels in the aquifer are likely controlled, at least in part, by the bottom elevation of the ***Qva*** sediments, both within the trough and on the surrounding higher elevation flanks. Groundwater moves from the areas of high water levels to the low water levels at the outlet of the trough.

Hydraulic head values for deep aquifer wells measured in November 1999 range from an elevation of 85 feet in a relatively shallow ***Qpvu*** completion to an elevation of 5 feet in deeper completions. **Figure 6-2** presents a plot of head versus the completion depth of wells completed in the ***Qpvu***. It shows the range of completion elevations for these wells and shows that heads generally decrease at deeper completion elevations. This head distribution shows an overall downward hydraulic gradient in the ***Qpvu***. Head measurements in these wells are valuable for looking at seasonal head changes at individual wells but have limited value for describing regional groundwater flow patterns between wells. The variability of head values in ***Qpvu*** well completions suggests a complex flow system with multiple water-bearing zones that may or may not be hy-

draulically interconnected. A meaningful equipotential map could not be produced using wells completed in the ***Qpvu***. This is because wells are completed over a wide range of elevations and in a variety of water-bearing zones, most of which are likely to be laterally discontinuous.

6.2.3 Interpretation of March 2000 Data

Figure 6-3 presents groundwater flow directions in the Principal Aquifer for March 2000. Except for a small shift in the groundwater divide near wells MW-3 and OBW-6, flow directions in the Principal Aquifer are nearly identical to those described by the November 1999 measurement event. The flow field is dominated by flow towards Puget Sound over much of the study area with flow towards Quartermaster Harbor at Dockton Park to the northwest of the mine site. Water levels in the Principal Aquifer are generally lower in March 2000 compared to November 1999 measurements. Water level changes range from an increase of about 3.6 feet at wells 34 and 35 (Gold Beach) to a decrease of -8.9 feet at MW-3. However, typical water level changes observed between the two measurement dates are on the order of 0.2 to 0.7 feet. Excluding the Gold Beach wells, the average water level decrease for the 20 measured Principal Aquifer wells is 0.97 feet. Water level data for the March 2000 measurement event are summarized in **Table 3-2**.

Seasonal water level declines of over two feet were observed in only two wells. The water level in Well OBW-6 dropped by about 2.8 feet. This change is similar in magnitude to the rise observed in the previous year's monitoring data. A water level drop of 8.9 feet occurred at Well MW-3. Long-term water level monitoring at MW-3 is needed to assess the significance of this decline. These changes cause the mid-island groundwater divide to shift slightly southeast towards the mine site as shown in **Figure 6-3**. This causes a slightly larger groundwater capture zone for the Dockton Spring area.

A rise in Principal Aquifer water levels was observed only at the two Gold Beach wells (Wells 34 and 35). These wells are screened at considerably lower elevations than other Principal Aquifer wells. They are completed in coarse sand and gravel compared to more typical fine sand completion zones in other Principal Aquifer wells to the south. These and other factors, such as possible seasonal pumping recovery and/or the hydraulic effects of landslide structures near the Gold Beach wells as (described by Rongey & Associates (1998)), may all contribute to the observed water level rise. The exact cause of this water level rise while other Principal Aquifer wells experienced a decline can not be explained from existing data.

Water level changes observed in deep aquifer wells range from a rise of 1.1 feet in Well 10 to a drop of 1.75 feet in Well 32. Water level elevations increased in eight ***Qpvu*** wells located to the north of the mine site with an average change of about 0.5 feet. The two deep wells available for measurement to the south of the site showed declines of –0.52 feet at Well 31 and –1.75 feet at Well 32. Seasonal water level trends can not be determined from these measurements without more frequent, long-term monitoring data.

6.3 Groundwater-Level Trends

Groundwater-level monitoring data for Maury Island are relatively scarce. Carr (1983) reports monthly (or weekly) moni-

toring of groundwater levels in ten wells on Maury Island during the 1981-1982 water year. Three of these wells were shallow dug wells, three were completed in the Principal Aquifer, and four were completed in the deep aquifer. Unfortunately, these monitoring data were not available for analysis. AESI has been monitoring groundwater levels in seven observation wells surrounding the proposed mine site from February 1999 through present (see wells OBW-1, 2, 5, 6, 7, 8, and 9 on **Figure 6-4**). Three of the wells are fitted with automatic dataloggers, while the other four are monitored monthly with hand measurements. **Figure 6-4** presents the water-level trends measured in these wells over the one-year period of record supplied by AESI.

Groundwater level trends among the seven observation wells show both similarities and inconsistencies. **Figure 6-4** shows an overall rising trend in five of the seven wells: OBW-1, OBW-2, OBW-6, OBW-7, and (to some degree) OBW-5. The rising trend partly obscures observation of a typical seasonal rising/falling fluctuation and is likely related to the unusually high precipitation preceding the monitoring period (see SeaTac rainfall data on the same Figure and discussion in Section 4.2). Although a seasonal rising/falling fluctuation can be discerned superimposed on the rising trend in most of these wells, the degree to which this fluctuation is "representative" of an average year is uncertain. Despite this uncertainty, the magnitude and timing of 1999 seasonal rise and fall of the water table can be extracted from individual well hydrographs via comparison to an assumed linearly rising water-level trend (where present). **Table 6-1** summarizes the year-long linear trends and relative seasonal fluctuations extracted from **Figure 6-4**.

Observed 1999 water-level fluctuations generally did not exceed 1.5 feet in magnitude, and varied in the timing of high and low water levels. Close to the coast, wells OBW-7, OBW-8 and OBW-9 showed high water levels in winter and low water levels in summer/fall. Towards the interior of the island, wells OBW-1, OBW-5 and OBW-6 showed high water levels in summer and low water levels in winter. Well OBW-2, also located in the island interior, was anomalous in that it showed no obvious seasonal high and low water level, suggesting that seasonal variations are likely to be small. Seasonal trends were masked at this location by a year-long water-level rise. The variable timing of 1999 highs and lows reflects the complexity of recharge dynamics in the groundwater flow system. More detailed discussion of the recharge dynamics is provided in Section 7.

6.4 Springs Near the Mine Site

Springs adjacent to the mine site are summarized in **Table 4-1**. The Dockton Water Association ("DWA") maintains two springs for public water supply immediately south of Dockton Park (**Figure 1-1**). DWA's Park East spring (ID number 50s) consists of a coiled, perforated collection lateral buried into the hill slope to the east of the spring house. It is reported to have a yield of 25 gpm (personal communication, Robert Colombo, October 20, 1999). DWA's Park West spring (ID number 51s) consists of ten shallow drive points completed in the shallow sediments to the west of the spring house. It is reported to have a yield of 35 gpm (personal communication, Robert Colombo October 20, 1999). Seasonal variability of spring yields is reported to be minimal although DWA does not routinely measure flow rates in either spring. A privately owned spring maintained by Paul

Ferguson, hereafter referred to as the Ferguson spring (ID number 48s) is located about 350 feet northeast of the Park West spring. The Ferguson spring supplies water to a small community water system that serves three lots located northeast of the Park. It is reported to consist of a buried, horizontal collector but lacks formal construction details (personal communication, Bob Seabold, February 6, 1999). The yield of the Ferguson spring is not known but is assumed to be similar to that of the Park East spring given its nearby location and similar elevation. Recharge to springs 48s, 50s, and 51s occurs from the upland area to the south through southeast of Dockton, likely including parts of the mine site during certain times of the year.

Two undeveloped springs exist along the beach area below the mine site. The springs are designated as Springs A and E based on initial spring designations by Rongey & Associates (1998) and subsequent characterization conducted by Herrera Environmental Consultants as part of the impact studies (Herrera, 2000). Spring locations are shown on **Figure 1-1**. These springs are not developed as water supplies and currently drain naturally onto the beach face. Flow rates and water quality of the springs were characterized in an earlier phase of the mining impact studies (Herrera, 2000). The spring yields range from about 15 to 33 gpm as measured in October and November 1999. Spring A discharges from the Principal Aquifer onto the upper beach face. Spring E discharges from a slightly higher elevation on the hill slope behind the beach face, suggesting that it discharges from a localized perched horizon above the Principal Aquifer. Recharge to these springs occurs from the mine site and upgradient portions of the island.

Two privately owned springs designated as Springs 52s and 54s exist in the Shore Acres area southwest of the mine site. These springs serve backup water systems to individual residences that are served by the Sandy Shores water system as their main water supply. They are located at elevations of about 100 and 80 feet, respectively, and have unknown completion and source details. The elevations of these springs suggest hydraulic continuity with perched groundwater above the Principal Aquifer. Recharge to these springs is expected to occur from the upland area to the west-northwest and not from the mine site. These springs are cross-gradient from the mine site. Because these springs likely originate from a perched flow system and for lack of site-specific hydrogeologic and flow data, these springs could not be assessed in the groundwater flow model.

The seasonal variability of discharge rates for springs near the mine site is not known. Discharges may change seasonally but are not documented in existing literature or system operating records. Extended hydrologic monitoring with dedicated equipment would be necessary to characterize seasonal fluctuations in spring flow. In the absence of long-term monitoring data, instantaneous flow measurements and operator reports of historical spring yields were used to describe discharge rates at each spring location.

7.0 Recharge Assessment

Recharge on Maury Island originates on the land surface from rainfall percolating into the soils. A relatively small portion of incident rainfall runs off the land surface as storm flow, but the majority enters the root zone to recharge underlying aquifers or be taken up by plants. In some cases, till immediately underlies the root zone and causes infiltrated water to accumulate in a shallow perched aquifer. Field observation on the island indicate that till generally occurs at a depth of 2 to 3 feet and that seasonally saturated conditions above the till generally do not cause ponding at the land surface.

Groundwater in the shallow perched aquifer slowly percolates downward through the till at a rate controlled by the till's permeability. Perched groundwater can also flow down slope in the subsurface along the top of the till. Water passing through the bottom of the till will continue to flow downward to the underlying water table in the Principal Aquifer. In areas where till is absent, water passing through the root zone similarly flows downward to the underlying water table. Where localized perched zones within the outwash section exist, water may move laterally to the edge of the perching horizon before it moves downward again to the water table.

Recharge from the land surface must travel downwards through up to several hundred feet of unsaturated ***Qva*** sediments before reaching the water table. This unsaturated thickness is typically referred to as the "vadose zone", and can significantly alter the timing of when shallow recharge reaches the water table. In western Washington, alternating wet and dry seasons create a seasonal recharge pulse at the land surface. Recharge is highest during winter, and falls to zero during the summer months when plant water requirements exceed available rainfall.

As the pulse moves downward through the vadose zone, the soil tends to absorb a portion of the pulse while letting the remainder drain through. During the dry months, a portion of this storage is slowly released and continues to flow downward towards the water table. This process results in a "dampening" or "spreading" of the recharge pulse. While average *annual* recharge does not vary as a function of depth, the seasonal variation of recharge rate decreases with depth. In addition, time is needed for downward propagation of the recharge pulse. The time lag required for the wettest portion of the pulse to reach the water table increases with depth to water.

Depth to groundwater in the Maury Island study area is typically less than 100 feet along the coast, averages 200 feet in the island's interior, reaches 300 feet beneath the proposed mine site and can exceed 350 feet northeast of the site. The variable distribution of depth to water across the island results in a variable distribution of lag time and degree of dampening for the recharge pulse to reach the water table. Thus at any given time, recharge is reaching the water table at different rates at different locations on the study area. This variation adds complexity to the dynamics of recharge and the resulting fluctuation in groundwater levels. The following two sections describe how recharge was estimated at or near the land surface, and present an analysis of the dampening and lagging of the recharge pulse as a function of depth.

7.1 Estimation of Recharge Originating at the Land Surface

7.1.1 Overview of Methods

Recharge from the land surface was estimated with a combination of Geographic Information Systems (GIS) analysis and a proprietary spreadsheet model developed by PGG. GIS analysis was used to characterize the spatial distribution of factors that significantly influence the recharge process. Soil types, land cover, and the presence/absence of shallow till were compiled from existing data and unique combinations thereof were assigned to individual "recharge classes." The spreadsheet model was then used to estimate monthly and annual recharge for each recharge class. The model performed a daily water-balance calculation, but was run based on average monthly values for precipitation and ambient air temperature. Along with climatic data, information regarding plant water demand, soil hydraulic properties, surface runoff, and depth to till (where present) were used to perform the daily water balance. For areas with shallow till, recharge was represented as the flux of water seeping through the bottom of the till. For areas without till, recharge was represented as downward flux at the bottom of the root zone.

The spatial distribution of land-cover was divided into three categories (grass, forest, and mine) and entered into GIS by hand digitizing from 1990 USGS aerial photographs ("orthophotoquads"). Water requirements for grass were used to represent meadows, lawns, and low-density developed areas. Water requirements for coniferous and deciduous trees were averaged to represent the Fir-Madrona forest. Mine areas were represented with two-thirds grass cover and one-third barren cover (no vegetation). The spatial distribution of soils was hand-digitized from U.S. Soil Conservation Service soils maps, but ultimately was not needed because hydraulic properties differed so little between dominant soil types. The presence/absence of till was based on surficial geology maps of the island (Booth, 1991) and the site (AESI, 1999a) as shown on **Figure 5-1**.

Additional recharge classes were developed to represent conditions during phased mine build-out and reclamation. During each 12-year excavation phase, a mine cell was represented by barren soil with no underlying till. Soon after excavation, a mine cell was represented as grass cover with no underlying till. After reclamation, the entire mine was represented by 100 percent coniferous forest with no underlying till.

The recharge model was run for the eight unique combinations of land cover and till occurrence discussed above. Where till was present, the model allowed shallow groundwater to accumulate above the till and slowly percolate downward based on an assumed till permeability. The model could also be used to track lateral flow in the perched aquifer, however separate analysis showed this "perched subflow" term to hold relatively little significance in the overall recharge water balance. A detailed description of the method for estimating recharge and the perched subflow analysis is presented in **Appendix D**.

7.1.2 Results

Figure 7-1 presents the average monthly values of recharge estimated at the bottom of the root zone (with till absent) and at the bottom of the till (where present). The model predictions show little difference

among recharge classes grouped by the presence/absence of till. Model results presented in **Appendix D** suggest that this similarity occurs despite differences in potential evapotranspiration (PET) between land-cover classes. Differences in root zone depth may compensate for differences in PET. In addition, model predictions show little difference in annual recharge between till covered areas and those with till absent. This similarity is not surprising in that the permeability of the till is not a dominating factor. **Table 7-1** presents a comparison of estimated annual recharge values for each land cover classification used in the recharge analysis.

Annual recharge is estimated to be highest for barren conditions, which will occur within the mine footprint during excavation. Recharge estimates are reduced by predicted evapotranspiration, and evapotranspiration is lowest for barren conditions due to the absence of plants. Annual recharge is estimated to be lowest for coniferous trees, which will occur within the mine footprint after reclamation. Evapotranspiration is estimated to be highest for coniferous trees due to the year-round presence and relatively high surface-area of foliage.

Despite the narrow range of predicted *annual* average recharge rates among till-present and till-absent groupings, month-to-month recharge patterns do show a significant difference. **Figure 7-1** shows that the recharge pulse is more "peaked" or "flashy" for the outwash (i.e., till-absent) grouping. The till perching layer reduces the maximum monthly rate of recharge but sustains the duration of recharge two months longer into the dryer late-spring months. Winter rates of recharge generally range from 3 to 4 inches/month in till covered areas, and 5 to 6 inches/month where till is absent. Recharge during summer months is predicted to be zero.

Over the course of mine development, annual recharge at the mine site would first increase due to creation of barren areas and then decline as areas are reclaimed with coniferous trees. Removal of till cover at the mine site would change the timing of recharge introduced at the land surface by removing the dampening effect. Higher recharge inflows would occur during the winter months, and recharge would be significantly reduced during the late spring (April and May). On Maury Island; however, recharge from the land surface must travel vertically downward through thicknesses of unsaturated ***Qva*** sediments ranging from tens of feet to over 300 feet before reaching the water table. The following section presents analysis of how the seasonal recharge pulse is altered as it propagates through the vadose zone on way to the water table. Understanding the process of recharge movement through the vadose zone is crucial for evaluating the impacts of mine excavation.

7.2 Evaluation of Recharge Movement Through the Vadose Zone

7.2.1 Overview of Methods

Time lag and dampening of the recharge pulse within the vadose zone were evaluated so that recharge input could be specified for the groundwater flow model presented in Section 8. Literature review identified previous analysis of time lag between the onset of the rainy season and rising groundwater levels by Carr (1983). Carr's analysis presented a graph and description of the relationship between well completion depth and

observed time lag, but did not present the raw time-series data used to estimate the lag. PGG used Carr's data to perform a regression analysis between depth to water and observed time lag. In addition, PGG compared 1999 groundwater level trends in AESI's seven monitoring wells to antecedent precipitation to derive time-lag responses. These field observations were used as a guide for the numerical analysis of recharge propagation through the vadose zone.

Hydrus-2D, a variable saturation, finite element, computer flow model, was used to evaluate the timing and rate of recharge entering the water table as a function of depth to water (Simunek, 1999). The model was set up to simulate a vertical "column" of the vadose zone, through which monthly recharge applied to the land surface was tracked. Two columns were simulated: a 300-foot thick column representing the current (pre-mined) condition and a 16-foot thick column to representing the worst-case excavated condition. Monthly recharge rates for forest cover with no underlying till as presented in Section 7-1 were applied to the top of the vadose zone columns. Soils texture, and associated hydraulic properties were specified as sand with increasing silt content as a function of depth. Soil property variables were based on physical testing results derived from soil samples collected in this study (**Appendix A**) and from existing testing data (AESI, 1998).

For the 300-foot column, silt content was specified as 2 percent at the land surface grading to 12 percent at the water table. For the 16-foot column, silt content was uniformly set at 12 percent. Observation points were used along the columns to monitor predicted soil moisture content as a function of time. Downward flux at the top and bottom of the column was also extracted from the model results. Model sensitivity to estimates of soil hydraulic conductivity (K) was evaluated by varying (doubling) the K values within the column en masse. Detailed description of the model's design, approach, and hydraulic properties are presented in **Appendix E**.

7.2.2 Results

Figure 7-2 presents a plot of observed time lag versus depth from Carr's published data for Vashon *and* Maury Islands (1983) and AESI's 1999 groundwater level data for the mine site. Carr's original data points, which relate time lag to well completion depth, are plotted alongside our revised relationship of time lag to depth to water. PGG's revised approach is considered more appropriate, since the recharge pulse ceases to travel through the vadose zone after it reaches the water table. Time lags from the onset of the rainy season to an observed rising groundwater level in AESI's on-site wells were taken from **Figure 6-4**. This figure shows considerable scatter in the relationship between depth to water and time lag. The correlation coefficient for Carr's data is not as good (approximately 0.6) as the correlation of lag time and depth in AESI wells (approximately 0.8). Associated time lags from the Carr data suggest that the recharge pulse propagates through the vadose zone at a rate of about 20 feet/month. Lags observed in the AESI wells suggest a faster rate of propagation of about 41 feet/month.

The scatter observed on **Figure 7-2** arises from three dominant factors:

- Soil textures in the vadose zone are heterogeneous (rather than being uniform, they vary both laterally and vertically).
- The relationship between time lag and depth to water is unlikely to be perfectly

linear. For instance, finer sedimentary texture with depth is likely to slow the recharge pulse.

- Water-level fluctuation at a given measuring point is affected not only by arrival of recharge from above, but also by propagation of groundwater level fluctuations from other areas of the island. Seasonal high/low water levels at distant locations represent "water-level pulses" that are transmitted laterally towards groundwater discharge areas. In a manner similar to recharge in the vadose zone, these pulses are dampened as they travel downgradient. Nevertheless, such up gradient pulses can exert more influence on water levels than the arrival of recharge from the vadose zone.

Because of these factors, considerable caution must be used when trying to relate observed lags in water-table responses to recharge pulse propagation rates in the vadose zone. Consequently, the Hydrus-2D model was used to develop a better understanding of recharge propagation above the water table. The Hydrus model was not expected to provide exact values for lagging and dampening of the recharge pulse, but rather to provide reasonable estimates of the *magnitude* of these processes. The model addresses the non-linearity of recharge propagation by explicitly simulating the physics that control the advance of the recharge pulse and by incorporating the observed fining of soil texture with depth. Hydrus-2D was not used to evaluate the effects of heterogeneity due to the prohibitive level of effort (and therefore costs) involved. Thus, the Hydrus results should be viewed as a simplification rather than an actual portrayal of the physical system. The cumulative effect of heterogeneities within the vadose zone, however, may cancel out one another on the large overall scale of the Maury Island study area.

Propagation of the recharge pulse, and associated time lag as a function of depth is shown on **Figure 7-3**. The figure presents modeled water content vs. time at various depths within the idealized 300-foot vadose zone column. The magnitude of monthly precipitation and recharge input to the land surface is shown on a separate scale. Approximately two months of time lag are visible between the onset of the recharge pulse at the land surface and the soil moisture response predicted at a depth of 50 feet (modeled elevation = 250 feet). With each 50-foot increase in depth, the predicted arrival of the recharge pulse arrives at a later time. Propagation of the recharge pulse from the land surface to the water table (300 feet) is predicted to require about 16 months.

The relationship between lag time and depth predicted by the Hydrus model is summarized on **Figure 7-4**. Modeled lag between the land-surface recharge pulse and the soil moisture pulse at depth is presented in two ways: from onset to onset and from peak to peak. Results from the sensitivity analysis, with doubled best estimates of hydraulic conductivity distributions, are also presented. Time lags are presented every 50 feet for the 300-foot simulation, and every 7.5 feet for the 16-foot simulation. Results from the 300-foot simulation show the predicted non-linearity of time lag versus depth, and show that a doubling of hydraulic conductivity generally resulted in a 15 to 30 percent reduction in the time required for propagation of the pulse. Despite the nonlinear (concave-downward) relationship between time lag and depth, the Hydrus predictions show marked similarity to the linear relationship derived from Carr's field data on **Figure 7-1**. Model results from the worst-case excavated (16-foot) thickness simulation predict slower propagation of the recharge pulse. Siltier textures at the bottom

of the vadose zone are predicted to cause time lags of up to 50 days at a depth of 15 feet to the water table.

While **Figures 7-1** and **7-3** demonstrate the relationship between time lag and depth, they tell little about the dampening of recharge rate as a function of depth. Seasonal variation of downward vertical flow in the vadose zone ("dampening") decreases significantly with depth. **Figure 7-5** presents a comparison of recharge rates applied to the land surface to rates of water-table inflow for both the 300-foot and 16-foot simulations. The range of water-table inflow rates predicted for the 16-foot simulation is very similar to the range in monthly recharge rate. Water-table inflow rates for the 300-foot simulation show a much narrower range of seasonal variation. Maximum and minimum rates of water-table inflow for the 300-foot simulation range from 72 to 140 percent of the average annual recharge rate (0.165 cm/day equals 23.7 in/yr). For the 16-foot simulation, rates of water-table inflow range from 15 percent to 182 percent of the average annual recharge rate. Thus, delivery of recharge to the water table is more constant and less variable with increasing thickness of the vadose zone. It should be noted that doubling the hydraulic conductivity distributions caused virtually no change in the dampening of the recharge pulse, despite apparent changes in the modeled time lag.

The degree of time lag and dampening predicted by the Hydrus model provides a basis to design further investigations of recharge dynamics and predictive simulations of impacts associated with mine excavation. The groundwater flow model of Maury Island was used to investigate how lagging the arrival of recharge based on water-table depth affects observed groundwater level responses at selected locations on the island. The results of this investigation, together with consideration of recharge pulse dampening, were used to design simple yet concise predictive simulations for the proposed mine excavation.

8.0 Estimation of Hydrogeologic Impacts

8.1 Description of Groundwater Flow Model

A groundwater flow model of Maury Island was developed based on the hydrogeologic characterization presented in preceding sections. Information regarding the spatial occurrence and hydraulic properties of aquifers and aquitards, groundwater elevations, spring flows, and groundwater recharge was used to design and calibrate the model. The model was written and run using "MODFLOW," a finite-difference numerical modeling code developed by the USGS (McDonald and Harbaugh, 1988), and the proprietary graphical user's interface "Groundwater Vistas" by Environmental Simulations Limited. In map view, the model domain covers approximately 95 percent of the island and is divided into a grid of 36 rows and 79 columns. Rows are oriented parallel to the coastline adjacent to the mine site, and grid cell dimensions range from 200 feet near the site to as much as 600 feet in distant locations. The model's grid layout is shown on **Figure 8-1**. The model is divided into three layers with the Principal Aquifer depicted in the top layer, the ***Qpvu*** aquitard depicted in the middle, and the deep aquifer depicted in the bottom. The top layer also included portions of the ***Qpvu*** where the ***Qva*** was absent.

The top of the model domain is the land surface, and was defined based on digital elevation model (DEM) data obtained from the USGS. The bottom of Layer 1 represents the base of the ***Qva*** deposits, and was defined within the study area based on interpretation of driller's logs from eleven wells that penetrate the unit and seven wells that define a minimum depth below sea level. Surficial geologic mapping and regional interpretation (Booth, 1991) were also used to define this surface, both within and beyond the study area. Geologic contact elevations estimated from the well logs, as well as elevation contours for the bottom of Layer 1, are presented on **Figure 8-2**.

Although the contact elevations used to define the base of Layer 1 show clear spatial trends, they also show considerable variability in areas of clustered data. It should be noted that definition of the layer bottom is a best approximation, with no data available over significant areas. Geologic descriptions provided in well logs vary in quality and level of detail and often use nonstandard nomenclature, making contact definition difficult. Uncertainties inherent in this bottom surface are unavoidable, and are accepted as part of translating the conceptual model to the numerical model.

The base of Layer 1 ranges from several tens of feet below sea level to over 150 feet above sea level. Higher elevations occur towards the southwest and northeast "ends" of the island, and bottom elevations fall below sea level along the northwest-southeast trending "***Qva*** trough" that runs through the "neck" of the island. Along the coast, the location of the trough is defined by beach exposures of fine-grained ***Qva*** that suggest a bottom elevation below sea level. Surficial geologic mapping by the USGS (Booth, 1991) was used to define the base of ***Qva*** on the island coastline. In inland areas, definition of the "***Qva*** trough" is less certain. The seven wells showing ***Qva*** occurrence below sea level do not penetrate the bottom of the trough. Initially, bottom elevations of the trough were approximated by the observed range in minimum depths, but were adjusted slightly at the onset of calibration to improve prediction of observed heads. Final

bottom elevations range from –10 to –50 feet mean sea level. While the true geometry of the trough remains unknown, the geometry used in the flow model is generally consistent with the relief defined in other areas of the island and with previous regional interpretations (Booth, 1991).

Layer 2 represents the ***Qpvu*** aquitard, and the bottom of this layer represents the uppermost occurrence of the deep aquifer. As noted in Section 6, well data are insufficient to fully characterize the spatial distribution of the deep aquifer. **Figure 8-2** presents interpreted contact elevations for the bottom of the ***Qpvu*** aquitard (i.e., the top of the deep aquifer) from 12 available well logs (11 of which occur in the model domain) and model elevation contours of the bottom of Layer 2. Wells showing similar completion depths and lithologies were used to describe an approximate top elevation for the deep aquifer. Wells used in this approach have aquifer top elevations ranging from about –70 to –355 feet. The model contours show the layer bottom dipping to the northwest.

Layer 3 represents the deep aquifer beneath the ***Qpvu*** aquitard. Locally variable contact elevations suggest that the deep aquifer may not be laterally continuous beneath all of Maury Island. Instead, several water-bearing zones with variable hydraulic connections may exist. For the purpose of this model; however, the deep aquifer and the ***Qpvu*** aquitard were both modeled as laterally continuous layers. This approach to describing the deep aquifer system is consistent with previous characterization efforts for Maury Island by Carr (1983) and VMGAC (1998). Simulation of downward leakage from Layer 1 (the intended purpose of including Layers 2 and 3) is accomplished with this approach. Layer 3 was assigned a constant thickness of 10 feet as shown in **Figure 8-2**. Based on the model's design, predicted water levels and downward vertical flow from the Principal Aquifer are not sensitive to the thickness of Layer 3.

The model domain is larger than Maury Island, and extends beyond its coastline in most places. Beyond the coastline, model cells are generally designated as "inactive" and are therefore not included in groundwater flow calculations. Immediately beyond the coastline (seaward), some model cells are held "active" and used to simulate the hydraulic connection between groundwater and ocean water using a variety of mathematical "boundary conditions". In addition, some inland cells along the coastline of Layer 1 are simulated as inactive. These cells are shown on **Figure 8-3**, and occur where the ***Qva*** deposits are absent and the ***Qpvu*** aquitard occurs at (or near) the land surface. Shallow ***Qpvu*** deposits along the coast exert little influence on the Principal Aquifer flow system in the island's interior. The model therefore does not simulate flow in these cells and allows recharge from the land surface to pass downward to the ***Qpvu*** sediments in model Layer 2. The bottom elevations of the Layer-1 ***Qpvu*** cells are all set above sea level so that simulation of a hydraulic connection with the sea is unnecessary.

Boundary conditions used in the model include constant head, drain, and general head cells. The locations of boundary conditions for all three layers are presented in **Figure 8-3**. In Layer 1, constant head values of sea level (zero) were assigned to model cells along stretches of coastline where the bottom of the Principal Aquifer occurs below sea level. This allows a hydraulic connection between the aquifer and the sea where submarine contact exists between the two bodies. No reduction of permeability was as-

signed to the constant head cells, and the hydraulic connection was assumed to occur at the permeability of the Principal Aquifer. Drain cells were placed at spring locations to simulate groundwater discharge to the land surface. Elevation data from Spring E, East Dockton, West Dockton, and Ferguson springs were used to set the drain parameters. Spring A was not included in the model because it likely occurs in a localized perched zone about 10 to 20 feet above the Principal Aquifer.

In Layer 2, general head boundaries were placed around the entire coastline to simulate hydraulic connection with marine waters over the distance between the cell and where Layer 2 intersects marine water. The locations of general head cells are shown on **Figure 8-3**, and formulation of the general head parameters is described in **Appendix F**.

All of the cells in Layer 3 were assigned a constant head condition based on head measurements in November 1999. The model assumes that hydrogeologic impacts to the Principal Aquifer will have negligible effects on water levels in Layer 3. Constant head values represent static water levels measured in 10 wells completed below an elevation of about -80 feet and showing similar aquifer lithologies (generally medium sand to gravel). Head values in these wells range from about 5 to 27 feet. The Sandy Shores well (Well Number 31) had an anomalously high water-level elevation of about 73 feet and was not used to define constant head conditions in Layer 3. The well is shallower than the other deep aquifer wells selected for Layer 3 heads. The Sandy Shores well may show a higher water level due to completion depth or local variation of ***Qpvu*** aquitard properties. **Figure 8-3** shows the modeled distribution of constant head values as well as the measured heads used to develop the Layer 3 coverage

Model Layer 1 was specified as unconfined, whereas Layers 2 and 3 were specified as confined (fully saturated). The model was calibrated to steady-state (average) conditions, and then used to evaluate the dynamics of groundwater recharge on a seasonal basis. After successful steady-state calibration and enhanced understanding of the role of various factors affecting recharge were achieved, predictive simulations were performed to evaluate the hydrogeologic impacts of the proposed mine.

8.2 Steady-State Calibration

Steady-state calibration was performed to achieve reasonable agreement between model predictions and observed groundwater elevations and spring discharges. Steady-state simulation holds all hydrologic inflows and outflows constant, and thus provides non-varying predictions of groundwater levels and springflows. In most cases, steady-state simulations are used to represent average annual hydrologic conditions. Steady-state calibrations can, however, yield non-unique representations of the groundwater flow system. Unless all components of the island's water budget are known, it is possible that more than one combination of aquifer properties and boundary conditions can yield the same, or similar, predictions of groundwater elevations. The steady-state calibration for the Maury Island model included a systematic evaluation of many combinations of these variables to define value ranges that produce acceptable model calibration results. The full extent of these ranges was taken into account when using the model to predict the hydrogeologic impacts of mine excavation (Section 8.4).

8.2.1 Calibration Approach

The goal of steady-state calibration was to generate a range of "model scenarios" that provide reasonable matches to available hydrogeologic observations and can be used to predict the likely range of impacts associated with the proposed mine excavation. There are many variables that could be adjusted, both regionally and locally, to optimize agreement between observations and predictions during model calibration. From the onset, our approach to calibration has been geared to minimize added model complexity without compromising the usefulness of the model as a predictive tool. Highly localized adjustments to model parameters, intended to improve matches at singular observation points but without documented bases, were generally avoided. Calibration scenarios were considered acceptable when the geometry and hydrologic boundaries of the model domain agreed with the known hydrogeologic framework and model predictions provided reasonable matches with observed groundwater levels and springflows.

Observed measurements of groundwater elevations and spring discharges are typically referred to as "targets" for calibration. Differences between observed and modeled values are referred to as "residuals". In this report, positive residuals indicate that predictions are too low and negative residuals indicate that predictions are too high. For calibration to groundwater levels, residuals were generally considered to be acceptable if less than 10 percent of the measured head value. In most cases, model residuals were significantly lower than 10 percent. In some cases, however, residuals larger than 10 percent of the measured head were permitted. This was the case in distant regions of the model domain or in a known area of anomalous water levels. Given the existing uncertainty in bottom elevation for model Layer 1, such departures were expected and believed not to compromise the predictive ability of the model.

Hydrogeologic scenarios were kept as simple as possible during calibration. After initial definition of recharge distributions and layer-bottom elevations, no additional changes were made to these parameters. Recharge is believed to be adequately predicted by the spreadsheet model (Section 7). Calibration cannot be performed to both hydraulic conductivity *and* recharge ranges without additional calibration targets to define flow components of the island's water budget. When a model is calibrated primarily to water-level targets, as is the case for this study, multiple combinations of hydraulic conductivity and recharge values can yield the same predicted head distributions. Proportional changes to both parameters (e.g., doubling of both) would yield the same head distributions (except perhaps in the immediate vicinity of springs).

In a similar fashion, layer-bottom elevations were not adjusted after initial definition. When calibrating the flow model, it is the combination of saturated thickness and hydraulic conductivity that controls the aquifer's ability to conduct water. The product of these two terms is referred to as "transmissivity", and lower transmissivity values require steeper gradients to conduct the same amounts of water. For the ***Qva*** trough, where water levels are held constant at sea level along the coast, raising the bottom elevation decreases the saturated thickness and therefore reduces the transmissivity. With lower transmissivity, higher heads are predicted at inland locations due to steeper gradients away from constant heads at the coast. Simultaneous adjustment of both bottom elevation and hydraulic conductivity in the trough provide redundant adjustment on

trough transmissivity. Although subtle variations in predicted head distributions can be achieved by adjusting both parameters, such adjustment was not needed and was therefore avoided.

A minimum number of geographic hydraulic conductivity "zones" were used to achieve reasonable matches with water-level targets. Initially, calibration was attempted using only one hydraulic conductivity zone for model Layer 1. However, acceptable head matches could not be achieved with this simplification. By increasing the number of permeability zones to two, more reasonable head matches were obtained throughout most of the model domain. Residuals were further improved by adding a third zone in an anomalous area near OBW-5. Uniform values of hydraulic conductivity (both horizontal and vertical) were used for model layers 2 and 3.

In order to define the likely range of aquifer properties, both high-end and low-end hydraulic conductivity values were sought for the Principal Aquifer. Calibrated values of hydraulic conductivity (permeability) for the Principal Aquifer are directly linked to the values used in the ***Qpvu*** aquitard. When aquitard permeability is low, little groundwater is lost to downward leakage and aquifer permeability must be relatively high to allow water to move towards coastal discharge points without excessive head buildup. Conversely, when aquitard permeability is high, much groundwater is lost to downward leakage and aquifer permeability must be relatively low to build up heads to observed values. This relationship was used to define the high-end permeability value for the Principal Aquifer. Aquitard permeability was reduced to the point that the assumed minimum downward leakage to the deep aquifer was achieved. Aquifer permeability was then iteratively increased and spring parameters adjusted until a reasonable head match was achieved. To define the low-end of the range, minimum acceptable Principal Aquifer permeability values were specified and aquitard permeability was increased until modeled heads fell to the observed values. The smallest acceptable Principal Aquifer permeability was too low to allow sufficient discharge at spring target points. Permeability was gradually increased until modeled springs could produce the observed or reported discharges.

Acceptable ranges of hydraulic conductivity, and an assumed minimum rate of downward leakage from the principal aquifer to the underlying deep aquifer, are discussed in the following section.

8.2.2 Calibration Targets and Parameter Ranges

Groundwater elevations measured in November of 1999 were used as targets to calibrate the steady-state model. Nineteen of the 42 wells visited during PGG's water-level survey were considered representative of conditions in the Principal Aquifer. The locations of these water-level targets are shown on **Figure 8-1**. Groundwater hydrographs for on-site wells, discussed in Section 6.3, showed relatively little seasonal variation in groundwater elevations. Groundwater levels measured in March of 2000 generally showed little seasonal change in Principal Aquifer elevations compared to November 1999 measurements. For these reasons, the water-level "snapshot" obtained in November of 1999 is considered adequate for definition of an average annual condition used for steady-state model calibration. Given the observed magnitude of seasonal variation and potential for year-to-year variation, the effective accuracy of these targets for model calibration is likely on the order of ± 2 feet.

Reported and/or measured discharges from West Dockton Springs, East Dockton Springs, Ferguson Springs, and on-site Spring E were also used as calibration targets. Given the low seasonal springflow variation discussed in Section 6.4, these values can also be considered representative of average annual conditions. The effective accuracy of springflow target values for model calibration is likely no better than ± 20 percent. **Table 8-1** presents steady-state target values for groundwater levels and springflows.

During calibration, aquifer properties and drain parameters for the simulated springs were varied to obtain reasonable matches with calibration targets. Acceptable property ranges were defined to prevent inappropriate values from being used. Based on published values and best professional judgment, hydraulic conductivity was allowed to vary within the following ranges:

	Horizontal Hydraulic Conductivity (K_h)	Vertical Hydraulic Conductivity (K_v)
Principal Aquifer	2.8 – 60 ft/d	10percent of K_h
Qpvu Aquitard	100 times K_v	0.0003 – 0.03 ft/d

Vertical hydraulic conductivity of the ***Qpvu*** aquitard was further constrained with the condition that a minimum value of approximately 1 to 1.5 cfs (450 to 670 gpm, or 86,400 to 129,600 cfd) of leakage is simulated from the Principal Aquifer to the underlying deep aquifer through the ***Qpvu*** aquitard. While little is known about actual leakage in the island's water budget, this relatively small flow rate is proposed as a rough minimum required to sustain existing levels of deep groundwater development without unacceptable impacts. Ultimately, a minimum leakage of 1.3 to 1.4 cfs was used for the model simulations.

Modeled groundwater discharge to springs is controlled by both the elevation difference between the spring and predicted nearby groundwater levels and by a user-defined flow conductance term. Springflow is equal to the product of these two values. Surveyed spring elevations are likely accurate to ± 2 feet at Dockton Springs and Ferguson Springs because of uncertainties in the water collection systems constructed at these springs. The estimated elevation of Spring E is likely accurate to only ± 4 feet based on spring characterization by Herrara (2000). These potential measurement errors, as well as numerical effects of model geometry, were considered when defining acceptable ranges of modeled spring elevations. MODFLOW simulates drain locations at the center of associated model cells. This approximation and other approximations regarding the "step-wise" shape of the coastline and distances to the aquifer-seawater exposure effect model predictions of heads near the coast. During calibration, spring elevations were typically varied by no more than ±2 feet from the measured value, although Spring E was allowed to vary within the full extent of its reported range.

Spring conductances were allowed to vary based on assumptions about the geometry and hydraulic properties of aquifer materials in the immediate vicinity of the springs. Assuming hydraulic conductivity values near the springs ranging from 5 to 100 feet/day, various possible spring geometries, and various possible spatial extents of potentially higher permeability aquifer zones comprising the spring, a range of conductance values between 500 and 6,000 ft^2/day was considered reasonable.

Steady-state recharge values were defined for each model cell based on the annual average values for each recharge class and the geographic distribution of recharge classes

as presented in Section 7.1. Using a GIS analysis, the model grid was projected over the recharge classes and the percent of each class determined for each model cell. Recharge values were calculated as the spatially weighted average of the annual average values for each class.

8.2.3 Steady-State Scenarios and Model Results

Three steady-state calibration scenarios are presented in this section. Scenarios A and C define the endpoints of the acceptable permeability range for the Principal Aquifer, and Scenario B incorporates a local heterogeneity to achieve improved head match at Wells MW-1 and OBW-5 where observed water levels are anomalously high. **Table 8-2** summarizes the aquifer properties, boundary condition parameters, and statistical measures of calibration success for the three scenarios.

8.2.3.1 Scenario A

Scenario A is the high-end hydraulic conductivity simulation for the Principal Aquifer. During this calibration, the vertical hydraulic conductivity (Kv) of Layer 2 was lowered until downward flow to Layer 3 was reduced to approximately 1.3 cfs. The process was iterative in that lowering the Kv in Layer 2 required adjustment of horizontal hydraulic conductivity (Kh) values in Layer 1, and then further adjustment of Layer 2 Kv until adequate results were obtained. Where Principal Aquifer is absent in Layer 1 and cells are inactive, recharge rates directly to the underlying ***Qpvu*** aquitard were set equal to Layer 2 Kv. Layer 2 Kh values were maintained at 100-times Kv, and the hydraulic conductivity values used to generate parameters for general head boundaries in Layer 2 were similarly adjusted.

During calibration, it became apparent that a better head match was achieved when Layer 1 Kh values in the trough were lower than values in other areas of the island. This may be caused by lower Kh of saturated transitional bed materials occurring within the trough compared to coarser-grained (and higher Kh) ***Qva*** deposits on the trough flanks. Thus, two hydraulic conductivity zones were specified. Zone 1, in the immediate vicinity of the trough, was given a Kh value of 11 ft/d versus 21 ft/d in outlying areas. Spring outlet elevations were generally maintained at their target values except for Spring E, which required reduction to the bottom of its range to obtain a reasonable calibration to springflow in all scenarios (**Table 8-1**). Spring conductance values were adjusted within the acceptable range to achieve the target springflows. The resulting springflow predictions, listed on **Table 8-2**, are all within 10 percent of their target values.

Figure 8-4 presents modeled groundwater elevation contours and head residuals at model targets. Most of the residuals in and around the ***Qva*** trough are within 5 feet of the target elevations. Near the shoreline, where modeled coastal geometries are approximate, residuals are sensitive to errors in modeled distance between the well and the aquifer-marine interface. In addition, water levels in places along the shoreline are shown to be sensitive to completion elevations (see **Table 8-2**). Higher residuals were permitted in these areas and in locations farther from the ***Qva*** trough. Within the trough, one anomalous residual stands out at Well OBW-5 where predicted water levels were 17 feet lower than observed. This anomalous feature is believed to result from local heterogeneity (variability) in aquifer

properties. Scenario B, discussed in the next section, includes a local heterogeneity that improves the head match at this location.

The model predicted two small areas of "dry cells" in Layer 1. **Figure 8-4** shows these cells as isolated purple patches to the southwest and northeast of the mine site. In MODFLOW, dry cells are intended to represent areas without aquifer saturation. Clusters of dry cells generally occur in areas where the predicted ***Qva*** bottom elevation is relatively high (see **Figure 8-2**), and thus locally dewatered conditions could exist. In actuality, however, such areas are more likely to exhibit thin aquifer saturation. These areas are generally consistent with areas where domestic wells are completed in the deep aquifer, suggesting that the Principal Aquifer may be relatively thin to non-existent at higher elevations. In trying to calculate saturation in such marginal areas, MODFLOW sometimes becomes unstable and fails to converge on a numerical prediction. To achieve stability, MODFLOW was set up so that once the head value of a cell was iterated to be dry, it remained dry. In addition, a very gradual, de-accelerated iteration scheme was used to prevent over-prediction of dry cell occurrence. Mass balance evaluations confirmed that the model predictions were numerically reliable despite the gradual iteration. The nine dry cells shown on **Figure 8-4** do not have a significant impact on the flow patterns predicted for model layer 1.

Groundwater flow directions defined in Scenario A, as in all model scenarios, agree with the flow field interpretation presented in Section 6.2. Groundwater flows from the upland regions of the island towards the central ***Qva*** trough, where a southwest-northeast trending groundwater divide separates flow to the northwest and southeast coastlines. The model predicts that the majority of groundwater flow, which occurs perpendicular to the water-level contours, discharges to the island's southeast coast between Summerhurst and Gold Beach. This conclusion is expected since there is much more hydraulic continuity between the Principal Aquifer and marine water on the southeast shore of the study area compared to less extensive marine-aquifer exposure in Quartermaster Harbor. The broad coastal exposure of the ***Qva*** trough on the southeast shore of the study area suggests increased trough depth on this side of the island. By contrast, groundwater flow is restricted to the relatively narrow section of ***Qva*** trough exposure on the northwest shore in Quartermaster Harbor. Groundwater flow in this area discharges to the marine beach face near Dockton Park with local surface discharges at East Dockton and Ferguson Springs.

8.2.3.2 Scenario B

Scenario B is a modification of Scenario A. It was created to achieve a better head match in the area of anomalous water levels surrounding wells OBW-5 and MW-1. Similar to Scenario A, Scenario B represents a high-end ***Qva*** permeability assumption. No change was made to the relatively low Kv values used for the ***Qpvu*** aquitard in Layer 2. In order to raise predicted heads in the vicinity of the two wells, a low permeability zone was inserted along the northern boundary of the mine site immediately down- and cross-gradient of the anomalous wells. The low permeability zone is oriented parallel to the northern edge of the ***Qva*** trough. This orientation was chosen, in part, so that predicted worst-case impacts associated with mine excavation would be focused on Dockton and Ferguson Springs (areas of concern for impacts). It should be noted that this local heterogeneity was applied for cali-

bration purposes only and is not based on a lower permeability zone observed in field data, although such a zone may exist. Layer 1 hydraulic conductivity was adjusted to optimize the head match with resulting values of 11 ft/d in the ***Qva*** trough, 2.8 ft/d in the local heterogeneity, and 25 ft/d in outlying areas. A minor (1 foot) adjustment was also made to the elevation of East Dockton Spring (see **Table 8-2**).

Figure 8-4 presents modeled groundwater-elevation contours and head residuals at model targets for Scenario B. The modifications resulted in a significant improvement in the modeled water-level residual at Well OBW-5 (from a 17-foot under-prediction in Scenario A to 8 feet in Scenario B), and minor improvements in outlying areas. **Table 8-2** shows that the sum of squared water-level residuals, a common statistical measure of the degree of error between modeled and observed conditions, is greatly reduced for Scenario B. The predicted pattern of groundwater flow directions is generally unchanged, except along the northern side of the mine site where the heterogeneity causes groundwater contours to "bow" slightly towards the southeastern coast. Several additional dry cells are added to the model prediction, but these few dry cells cause little distortion of the regional flow field.

8.2.3.3 Scenario C

Scenario C is the low-end hydraulic conductivity simulation for the Principal Aquifer. During this calibration the Kh of layer 1 was gradually increased from a minimum value of 2.8 ft/d, and the Kv of Layer 2 gradually reduced, to achieve acceptable matches in both groundwater levels and predicted springflows. While observed groundwater levels could be matched at the minimum value of Kh, the permeability of the Principal Aquifer was too low to supply target discharges to the springs. Thus, both Kh values and spring conductances were increased within allowable ranges until matches in both heads and discharges were achieved. Scenario C employed the same distribution of layer-1 hydraulic conductivity zones used for Scenario A, however Kh values were reduced to minimum values of 8.5 ft/d in the ***Qva*** trough and 11 ft/d in outlying areas. No attempt was made to adjust for anomalous water levels around wells OBW-5 and MW-1.

Figure 8-4 presents modeled groundwater elevation contours and head residuals at model targets for Scenario C. Water-level residuals are similar to Scenario A, except for an increased over-prediction of heads (negative residuals) in outlying areas at Wells 18. The number of dry cells is marginally increased, but without significant effect on the regional groundwater flow field. Groundwater flow patterns predicted for Scenario C are very similar to those predicted for Scenarios A and B.

8.2.3.4 Discussion of Steady-state Calibration Results

The purpose of model calibration was to optimize agreement between known and predicted hydrologic conditions, thereby narrowing the range of possible model configurations. Calibration consisted of adjusting hydraulic parameters within a range of reasonable values to best match water levels and spring flows in the Principal Aquifer. Calibration parameters were consistent with the conceptual site model. Model configurations defined by the calibration process maximize simplicity in representing the groundwater flow system.

The steady-state calibration process resulted in three model scenarios. Scenarios A and C bracket the range of hydraulic conductivity expected for the Principal Aquifer and match available hydrologic observations. Scenario B includes a fairly large heterogeneity and provides a better head match than the two endpoint scenarios. Taken together, these scenarios represent a reasonable range of hydrogeologic interpretations to be used for prediction of mine excavation impacts on the groundwater flow system. The range of hydraulic conductivity values used in the model for the Principal Aquifer is relatively narrow, however this is dictated by the model's ability to match observed targets. Thus, the calibration process has both narrowed and defined the degree of "non-uniqueness" of the hydraulic conductivity distribution used for steady-state simulation.

Although the three scenarios show similar groundwater flow patterns and predicted heads, notable differences exist in the associated water budgets. **Table 8-2** shows that differences in modeled vertical hydraulic conductivity in Layer 2 result in significant variation in predicted groundwater flow from the Principal Aquifer to the deep aquifer. Scenarios A and B, which employ a lower value of Kv, allow about 25 percent of the downward vertical flow predicted in Scenario C. Consequently, significantly more water is retained by the Principal Aquifer in Scenarios A and B.

No single scenario among the three is considered to be better suited for prediction of hydrogeologic impacts associated with mine excavation. Therefore, all three scenarios were used for predictive simulations over the course of mine excavation and subsequent reclamation. Predictive simulations are presented in Section 8.4 of this report.

8.3 Transient Investigation of Recharge Processes

The processes affecting the movement of recharge, from its infiltration at the land surface to its movement through the vadose zone, have been evaluated and discussed in Sections 7.1 and 7.2. PGG's proprietary spreadsheet model was used to estimate the portion of rainfall that infiltrates below the root zone (or below the till layer) to recharge the underlying unsaturated ***Qva*** sediments. Field observations and Hydrus-2D predictions were used to characterize the time lag between infiltration at the land surface and arrival at the water table. Hydrus-2D alone was used to estimate the "dampening" of the recharge pulse as it moves downward though the vadose zone. It was recognized that both time lag and dampening affect the delivery schedule for recharge to reach the water table from the land surface. The range of depth to groundwater on Maury Island causes variability in time lag and degree of dampening that effects seasonal water-level trends observed in wells on different parts of the island.

Based on characterization of time lags, PGG performed several transient simulations to try to calibrate the groundwater flow model to observed (current condition) seasonal water-level variations. While seasonal water-level calibration was never achieved, a good deal was learned about how various schedules of recharge inflow to the water table affect the timing and magnitude of seasonal water-level fluctuations. In addition, consideration of the recharge processes and modeled water-level fluctuations led to development of a "worst-case" approach for evaluating the hydrogeologic impacts associated with mine excavation.

Attempts at transient model calibration to seasonal water-level fluctuations involved

generating a series of monthly recharge "snapshots" for import to the model. These snapshots specified average monthly recharge rates for each model cell based on its estimated recharge schedule at the land surface and an estimated time lag based on depth to water. Depth to water was determined by subtracting interpolated values of the Principal Aquifer water-table surface from the DEM land-surface elevation for each model cell. Time lag, rounded off to the nearest month, was specified by dividing depth to water by an assumed linear rate of propagation for the recharge pulse. Section 7.2 describes a linear propagation rate of 20.3 feet/month, but notes that considerable variability may surround that value. No attempt was made to account for dampening of the recharge pulse in the transient calibration. The level of effort required to generate recharge import files which incorporate variation of lag *and* dampening as a function of depth to water was prohibitive and beyond the scoped budget of this project.

The MODFLOW model used for transient calibration was an earlier version of Scenario A. All parameters used in this prior version were the same as the current version, except for minor variations in bottom elevations of Layer 1 and general head boundary conductances in Layer 2. Specific yield for the Principal Aquifer was set to 28 percent, and storativity for the ***Qpvu*** aquitard was set to 0.0001. Conclusions derived from this calibration investigation are believed to be transferable to the current version of Scenario A, as well as Scenarios B and C. Transient calibration was considered potentially unreliable because of uncertainties associated with use of observed 1999 water-level fluctuations as representative, long-term calibration targets (see Section 6.3). More importantly, transient calibration could not be achieved by varying the propagation rate of the recharge pulse alone. Using pulse propagation rates ranging from 14 to 30 feet/month, predicted magnitudes of water-level variation generally exceeded those observed in on-site wells and the timing of seasonal lows/highs did not correspond to those observed.

Figures 8-5 and 8-6 present comparisons of model predicted seasonal fluctuations with observed fluctuations for on-site wells OBW-1, OBW-2, OBW-6 and OBW-7. The MODFLOW model was run for a 24-year period until predicted seasonal variations were repeated from year to year. Accepting the uncertainty inherent in comparing observation well data to model predictions, the following observations can be noted:

- The degree of match between predicted and observed trends, for both magnitude *and* timing of water-level fluctuation varies significantly among wells.
- Varying the propagation rate of the recharge pulse effects predictions of both the magnitude and timing of modeled water-level variations. A slower propagation rate reduces the magnitude of variation, and delays the occurrence of water-level highs and lows.
- Additional dampening of the recharge inflow to the water table is likely needed to reduce predicted water-level fluctuations down to observed values.

The variation in degree of calibration match among observation wells results from known and unknown complexities in the vadose zone and groundwater flow systems. Under the MODFLOW model simulations, these complexities are based entirely on variation in lag time required for recharge to reach the water table from the land surface due to variation in depth to water. This variation affects localized schedules of water-table inflow for individual model cells,

but model cells can also be affected by recharge schedules occurring in distant areas of the model domain. Seasonal water-level mounding in distant locations, which may occur at offset schedules to local recharge inflows, causes water-level pulses to be transmitted to local observation points. The cumulative effect of local recharge inflow to the water table and the arrival of water-level pulses from distant locations controls the predicted water-level variation at a given model location. Complexities in the *actual* groundwater flow system additionally include dampening of the recharge pulse within the vadose zone and various heterogeneities not taken into account in the MODFLOW and Hydrus-2D models.

MODFLOW model results show that reducing the propagation rate of the recharge pulse in the vadose zone reduces the magnitudes of predicted water-level fluctuations. This is because the amount of variation in lag time among cells with varying depths to water is reduced with faster propagation rates. For instance, if depths to water vary from 20 to 300 feet and the propagation rate is 100 feet/month, recharge pulses will arrive at all model cells within 3 months of infiltration at the land surface. In contrast, a propagation rate of 20 feet/month would allow a variation in recharge-pulse arrival ranging from 1 to 15 months. Thus, over the entire model domain, recharge inflow would be less "flashy" and much more evenly distributed over time. Model predictions of water-level trends presented in **Figures 8-5 and 8-6** show smaller magnitudes of variation for the slower recharge propagation rates (e.g. 14 feet/month) relative to the faster recharge propagation rates (e.g. 30 feet/month). Modeled water-level peaks and troughs also occur incrementally later for each reduction of the recharge propagation rate is reduced.

Dampening of the recharge pulse would be needed to further reduce the predicted magnitude of water-level fluctuations. Seasonal water-level variations observed in 1999 were relatively small, and generally did not exceed ± 1 foot (Section 6.3). While simultaneous adjustment of both time lag and dampening could be used to calibrate the model to observed water-level variations, the level of effort required to adjust both these parameters and generate multiple sets of recharge input files is prohibitive and beyond the scope of this project. Nor is it considered justified to perform such a calibration to just one year of observation data, which may be influenced by an antecedent high rainfall year. For these reasons, transient calibration with lag effects *and* dampening was not conducted for this modeling study. The observation that actual water-level fluctuations are quite small can be used to formulate an approach to predictive simulations, as presented in the following section.

8.4 Predictive Simulations

8.4.1 Impact Prediction Approach

An approach was developed to evaluate the hydrologic impacts of mine excavation based on the understanding of recharge dynamics refined over the course of this project. This approach provides a relatively conservative, worst-case impact estimate because it considers the maximum potential change in groundwater recharge associated with the mine. Current understanding of recharge processes on Maury Island suggests that a high degree of time-lag variation and recharge pulse dampening serve to minimize the seasonality of recharge inflow to the water table. Because the timing of recharge inflow varies between different areas of the island, and due to dampening of the recharge

pulse originating at the land surface, groundwater level variations on Maury Island are relatively small. These processes occur over the entire island, including the site of proposed mine excavation.

Figure 8-7 shows that current depth to groundwater beneath the proposed mine footprint is relatively uniformly distributed up to a depth of 320 feet. While definite spatial trends are expected in this distribution (e.g., shallower depths to water along the coast), the existing degree of variation still causes considerable variation of recharge inflow to the water table beneath the mine footprint. Similar to the rest of the island, variable recharge schedules beneath the mine site are expected to minimize the magnitude of seasonal water-level fluctuation. Over the depths to water shown on **Figure 8-7**, dampening of the recharge pulse is also expected to stabilize seasonal water-level fluctuation.

The maximum change to recharge dynamics would occur if all of the time-lag variability and recharge-pulse dampening were removed due to mine excavation. There would be no reduction in the seasonality of recharge generated at the land surface, and the bulk of recharge would reach the water table during only a limited portion of the year. Discussion presented in Section 7.2 and data presented **Figure 7-1** suggest that without time lag, dampening, or till cover, the bulk of recharge would reach the water table over a 5-month period between November and March. Recharge occurring during this limited time period would remain in the groundwater flow system only so long as it takes to flush out to sea, and no additional recharge would be available to maintain groundwater levels until the next rainy season. Thus, a worst-case impact scenario dictates that all of the reduced seasonality ("temporal spreading") of recharge inflows to the water table be removed within the mine footprint.

Depths to water beneath the mine footprint after proposed excavation are also shown in **Figure 8-7**. The percent of model cells in the mine footprint with depths to water less than 60 feet is increased from 21 to 47 percent due to excavation. However, the change in depth-to-water distribution is not so extreme as to fully eliminate temporal spreading of the recharge pulse beneath the footprint. For this reason, modeling the change in recharge inflow as a complete conversion to zero time lag and zero dampening is considered to be a conservative, worst-case approach to impact estimation. This approach was used for predictive simulations of mine development impacts.

To isolate the hydrologic impacts associated with recharge changes at the mine, all other components of the groundwater flow system were held constant. Recharge inflow was set to the average annual values used in the steady-state simulations for all model cells outside the mine footprint. Recharge values within the mine footprint were set to monthly rates estimated for the land cover and till occurrence expected to be present during various stages of mine development. Predicted monthly recharge schedules are discussed in Section 7.2, and anticipated stages of mine development are discussed in Section 8.4.2. With no simulated variation outside the mine, the impacts of mine excavation on surrounding water levels and coastal springflows could be isolated.

8.4.2 Model Representation of Mine Development

Mine development, as presented in the preferred alternative of the DEIS (King County, 1999), is expected to occur in four phases. In

three, separate sub-areas of the mine site are to be excavated, followed by an extended period of reclamation and natural vegetative recovery. Each excavation phase is anticipated to occur over a 12-year period, with reclamation starting in each "excavation cell" after mining switches over to the next cell. **Figure 8-8** shows the geographic distribution of the model excavation cells. The first cell to be excavated occurs in the center of the proposed mine site. The second cell is comprised of two separated areas along the west side of excavation cell 1, and the third cell is located to the north of excavation cell 1. As excavation proceeds, shallow soils will be scraped from the land surface and placed in a consolidated cell along the northern boundary of the mine site. When complete, the consolidated cell will form a 30-foot high berm with 3:1 horizontal to vertical side slopes. The finished dimension of the berm will be 2,100 feet long by 250 feet wide. The berm will be covered with an impervious geomembrane and capped with approximately one foot of soil and grass. For the purpose of this analysis, the berm is assumed to build out from west to east along the northern mine site boundary.

In order to represent this progression of mine development, the model was set up to simulate the physical conditions and time periods anticipated for each of the four phases. During the first phase, recharge applied to excavation cell 1 was modified from average annual values to monthly values estimated for barren soils without underlying till (see Section 7.1). In addition, recharge was set to zero for the westernmost three model cells of the soil berm and anticipated perched flow atop the impervious geomembrane was routed to adjacent cells as additional recharge. Total available additional recharge was estimated as the shallow recharge expected beneath a grass-covered soil plus a runoff term of ten percent of monthly precipitation. One third of the additional recharge available from the soil berm was routed to adjacent model cells to the south, whereas two thirds was routed to adjacent model cells to the north. The model simulated the first excavation phase over a period of 12 years with these monthly recharge values repeated on an annual cycle. This modeling approach results in additional conservative (high-end) estimates of hydrologic impact, since the entire Phase 1 excavation is modeled as complete at the onset of the 12-year model simulation.

During the second phase of mine development, monthly recharge values for excavation cell 1 were altered from values estimated for barren soils to values estimated for grass-covered soils. Monthly recharge values for excavation cell 2 were altered from original average annual values to monthly values estimated for barren soils with no underlying till. The length of the berm was extended another one third of its full build-out dimension to the east by designating three additional model cells as zero recharge. Similar to the first phase of mine development, available additional recharge generated atop the geomembrane was routed one third to the south and two thirds to the north. During the third phase of mine development, monthly recharge values for excavation cells 1 and 2 were set to values estimated for grass-covered soils. In addition, monthly recharge values for excavation cell 3 were set to values for barren soils and the berm was expanded to its full build-out dimension of nine model cells. Model simulations for the second and third phases of mine development were also run for twelve years to approximate the excavation schedule proposed under the DEIS preferred alternative.

Long-term hydrologic impacts expected from the reclaimed mine condition were evaluated by setting recharge values for all

cells in the mine footprint equal to those estimated for coniferous forest without underlying till. Replanting with conifers was specified in the DEIS. Routing of available additional recharge generated atop the berm geomembrane to adjacent model cells was maintained during this long-term simulation. The model was run for 30 consecutive years using this monthly recharge distribution until recurrent seasonal water-level trends were established at several scrutinized model cells within and surrounding the mine site footprint. Recurring water-level trends indicate that the full hydrologic impact of the reclaimed mine condition is in effect.

8.4.3 Predicted Impacts

Hydrologic impacts associated with the four phases of mine development were evaluated based on model predictions of changes in Principal Aquifer groundwater level elevations, spring discharges, and downward fluxes between the Principal Aquifer and the deep aquifer. Model runs required to simulate the four phases of mine development were performed for all three interpretations of the groundwater flow system defined during steady-state calibration (Scenarios A, B, and C). Groundwater level hydrographs were extracted from model results at four locations within the Principal Aquifer. **Figure 8-1** shows that three of these "prediction points" surround the mine site, and the fourth is located directly beneath the mine site. Prediction point locations were selected to assess water-level impacts near the margins of the mine site in the direction of water supplies of concern. These locations are considered to represent worst-case impacts to the aquifer given their proximity to the mine boundary. Spring discharge hydrographs were extracted for the four modeled springs, and rates of transfer to the deep aquifer were derived from the model mass balance for selected timesteps.

Graphs were constructed to present hydrographs of water levels and spring discharges over the final two years of each phase in mine development. These final two-year periods represent the maximum predicted impact associated with each excavation step. Model results show little difference between impacts predicted under model Scenarios A, B, and C. Although the hydrographs presented in this report show predicted impacts for all three model scenarios, discussion of these impacts is often presented as general statements which pertain to all three scenarios.

Predictive simulations were performed using a model value of specific yield in the Principal Aquifer of 0.28. Typical values of specific yield for sand are reported to range from 0.23 to 0.28 (Todd, 1980), with lower values for siltier materials. Modeling the Principal Aquifer with lower values of specific yield would result in greater seasonal variation in predicted impacts. In order to evaluate variability of seasonal impacts associated with lower values of specific yield, sensitivity analysis was performed using a specific yield value of 0.20. Model Scenario B was run under the reclaimed condition for both values of specific yield to allow comparison of predicted impacts. Discussion of the sensitivity of predicted impacts to groundwater levels, springflows, and downward flow to the deep aquifer is also included in the following sections.

8.4.3.1 Impacts to Groundwater Elevations and Flow Directions in the Principal Aquifer

Groundwater level hydrographs for model Prediction Points 1 through 4 are presented

on **Figures 8-9 and 8-10**. The figures present the modeled steady-state water level in the pre-mining condition (shown as "current condition") followed by predicted water-level trends for each prediction point. They show the water level impacts of mine development predicted for the final two years of each excavation phase and the reclamation period. To interpret these graphs, it must be understood that impact is expressed as the change from the steady-state condition to the conditions shown for each excavation phase. In actuality, these impacts would be superimposed over any seasonal water-level fluctuation naturally present at the prediction point. Because the impacts shown on **Figures 8-9 and 8-10** are based on a recharge assumption of zero time lag for the entire excavated mine area, they are likely to overpredict actual impacts. In addition, since time lags are expected to occur beneath the mine footprint, the absolute timing of predicted impacts cannot be defined based on the model results. The water-level impacts shown on **Figures 8-9 and 8-10** should be interpreted as high-end values that may occur with uncertain timing relative to the seasonal water-level cycle.

Modeled impacts to groundwater levels at Prediction Point 1, located southwest of the mine site, show very little change in water-level elevation. Overall reduction in water-level between the current and reclaimed condition is on the order of 0.1 foot. Increased seasonal variation of the water-level impact occurs as the mine is expanded through the three excavation phases. A slight increase in average water-level occurs between the current condition and excavation phases 1 and 2. Water levels decline slightly in excavation phase 3, and show a further decline into the reclaimed condition. The initial increase in groundwater levels is likely influenced by a higher annual recharge rate predicted for the "barren without till" land cover, and the final decrease is likely influenced by a lower annual recharge rate predicted for the "conifers without till" land cover. Annual recharge values for all land covers are presented in **Appendix D**, and monthly values are graphically presented in **Figure 7-1**.

Modeled impacts to groundwater levels at Prediction Point 2, located northwest of the mine site in the direction of domestic supply wells, are slightly larger than at Prediction Point 1. A total water-level decline of 0.3 to 0.4 foot is predicted from the current to the reclaimed condition. Superimposed on this decline is a seasonal water-level impact on the order of ± 0.1 feet. The same pattern of minor water-level rise in excavation steps 1 and 2 followed by decline in excavation step 3 and reclamation is observed.

Modeled impacts to groundwater levels at Prediction Point 3, located northeast of the mine site in the direction of the Gold Beach wells, are the smallest recorded. A total decline of 0.1 to 0.2 foot is predicted, with little seasonal fluctuation in impact. This contrasts to modeled impacts at Prediction Point 4, located directly beneath the mine footprint. In this case, the maximum predicted decline in average annual water levels is 0.6 feet for Scenario C. Scenarios A and B show slightly lower predicted declines. Predicted seasonal water-level fluctuations resulting from changing the recharge schedule from annually uniform to monthly without time lag are on the order of ± 1.7 feet.

Sensitivity analysis to the value of specific yield assumed for the Principal Aquifer revealed that reducing the value from 0.28 to 0.20 resulted in the predicted seasonal variation of water-level impact increasing by a factor of 1.4 beneath the mine site to as much as 2.1 in the three prediction points surrounding the site. Changes in predicted

annual average water levels were insignificant. Thus, had a specific yield value of 0.20 been used for the predictive simulations, predicted seasonal water-level impacts predicted beneath the mine site would likely have been on the order of ± 2.4 feet, whereas impacts to the surrounding prediction points would be no more than ± 0.2 feet.

Groundwater flow directions on Maury Island are expected to show little change given the water-level declines and seasonal fluctuation predicted by the model. Water-level elevations beneath the mine site range from about 10 feet mean sea level (msl) at the coast to over 60 feet msl in the center of the island. Relative to this 50+ foot range and the horizontal gradients it creates, predicted long-term average annual declines of 0.1 to 0.6 feet are unlikely to significantly alter the pattern of groundwater flow observed in the Principal Aquifer. Seasonal water-level impacts may cause slight changes to groundwater flow directions in the immediate vicinity of the mine where fluctuations of approximately ± 2 feet may occur. However, model runs indicate that fluctuations diminish quickly between the mine site and surrounding prediction points, and changes in flow directions in these areas are expected to be insignificant.

8.4.3.2 Impacts to Spring Discharge

Discharge hydrographs for the four springs simulated by the model are presented on **Figures 8-11 and 8-12**. The figures presents the modeled steady-state discharge in the pre-mining condition (shown as "current condition") for each spring followed by discharge trends predicted for the final two years of each excavation phase. The figures show the estimated impacts of mine development on spring flow. Interpretation of these graphs is performed in the same fashion of interpreting the water-level hydrographs: impacts are expressed as the change from the steady-state condition to the conditions shown for each excavation phase. Predicted impacts are likely on the high side due to the assumption of zero time lag for recharge within the entire mine footprint. Because of this assumption, the timing of predicted recharge on actual springflows cannot be determined from this analysis.

Modeled impacts to discharges at all springs follow the same pattern as groundwater level impacts: a slight initial increase in flow during excavation steps 1 and 2 followed by a progressive decline during excavation step 3 and the reclaimed condition. The magnitude of predicted seasonal impact variation increases from excavation step 1 to excavation step 2, but shows little additional increase thereafter. The predicted reduction of discharge from West Dockton Springs is on the order of 0.5 gpm (1 percent of total flow) with a maximum seasonal impact variation of ± 0.2 gpm. East Dockton and Ferguson Springs are predicted to experience similar impacts. At East Dockton Springs, average annual discharge is predicted to decrease by about 0.5 gpm (2 percent of total flow), with a maximum seasonal impact variation of ± 0.1 gpm. At Ferguson Springs, average annual discharge is predicted to decrease by 0.5 gpm (2 percent of total flow), with a maximum seasonal impact variation of ± 0.1 gpm.

The predicted impacts to Spring E are much higher due to its location immediately downgradient from the mine site. These impacts are mostly expressed in the form of seasonal discharge variation as opposed to significant reductions in annual springflow. Overall reduction in average annual discharge is predicted on the order of 0.7 gpm (2 percent of total flow), with a maximum

seasonal impact of ± 3.3 gpm (about 10 percent of annual average flow).

The analysis of the sensitivity of the specific yield assumed for the Principal Aquifer revealed that reducing the value from 0.28 to 0.20 increased the predicted seasonal variation of springflow by a factor of 1.3 near the mine site at Spring E. It also increased by factors as high as 2.4 in the three springs on the northwest side of the island. Changes in predicted annual average spring discharges were insignificant. Thus, had a specific yield value of 0.20 been used for the predictive simulations, predicted seasonal variation in spring discharge would have increased to ± 20 percent of total flow in Spring E. Seasonal variation in discharge at Dockton and Ferguson Springs would remain relatively small at less than 1 percent.

8.4.3.3 Impacts to Flux Rate to Deep Aquifer

Modeled rates of groundwater flow from the Principal Aquifer to the underlying deep aquifer have been calculated for all three steady-state scenarios, and are presented in **Table 8-2**. Given the relatively small changes in groundwater levels predicted by the model over the course of mine excavation and reclamation, little change to these flow rates are expected. In order to quantify modeled changes in downward flow, steady-state rates were compared to rates when predicted water levels beneath the mine footprint were at their lowest. Water levels predicted by the model were recorded only on the first day of each month. The hydrograph from Prediction Point 4 shows a minimum water-level elevation on the first day of November during the reclaimed condition. Therefore, steady-state flow rates were compared to rates predicted for the first day of November for all three model scenarios.

Model flow rates to Layer 3 for the predictive simulations during the seasonal low water-levels beneath the mine were reduced by no more than 0.5 percent of steady-state (current condition) fluxes. This translates to a reduction of about 600 to 900 cfd, or 3 to 5 gpm for the entire model area. Sensitivity analysis for Scenario B using a specific yield value of 0.20 for the Principal Aquifer (rather than 0.28) increased the predicted flux reduction to approximately 0.6 percent of the steady-state flux, a reduction of about 6 gpm for the entire model area. Changes in groundwater flux to Layer 3 during seasonal high water levels will be less, and may even be greater than the steady-state fluxes. Given the small order of magnitude of predicted changes, no further checking of model results was performed to evaluate changes in flow to the deep aquifer. Predicted changes in deep aquifer flux rates are not expected to impact water availability or well yields in the deep aquifer.

8.4.3.4 Impact of Infiltration Pond at Bottom of Pit

During the course of mine excavation and final reclamation, preliminary site designs call for installation of a pair of small ponds on the bottom of the mine floor to allow infiltration of runoff from the sides of the pit. Questions have been raised as to the potential impacts of pond infiltration to water levels on adjoining properties, and as to whether mounding directly beneath the pond could cause standing water at the land surface during periods of high infiltration. PGG used the groundwater flow model to predict groundwater level responses to estimated high rates of infiltration to the ponds.

Preliminary mine development plans indicate the total infiltration pond area to be on

the order of 20,000 square feet (King County, 1999). During a typical high precipitation event, estimated as two consecutive days of 0.75-inch rainfall, the runoff inflow to the pond is estimated to be about 39 gpm. This inflow rate assumes that 50 percent of the mine catchment area drains to road surfaces and ditches that lead directly to the infiltration pond. The other 50 percent of the mine catchment area is assumed to drain and infiltrate to either to cut-back benches on sides of the pit or to the mine floor and not to the infiltration pond. Based on a StormShed model analysis performed by Herrara Environmental Consultants using a range of surface soil conditions, three percent of storm precipitation will runoff to the infiltration pond. All other storm precipitation will infiltrate directly to the land surface at the point of contact. Scenario B was used to simulate infiltration of 39 gpm to a 20,000 square foot pond over a 2-day storm period. Row 24 of the model grid was divided in half, and specified flux boundary (well) was positioned in this model cell at approximately the same location of the proposed ponds. **Figure 8-1** shows the model grid with numbered rows, and the position of the simulated pond cell. The area of the cell was 20,000 square feet.

The model was run using specific yield values of both 0.28 and 0.20 for the Principal Aquifer. **Figure 8-13** shows modeled water-level responses directly beneath the pond for two days of pond infiltration simulated at 39 gpm. Water level hydrographs were extracted from model results for Prediction Points 1 through 3 and a fourth prediction immediately below the pond cell. Predicted water-level responses at Prediction Points 1 through 3 were less than 0.01 feet, and were therefore not presented graphically. Directly beneath the pond, observable water-level mounding was predicted to occur over the two days of infiltration. Water-level rise in the Principal Aquifer was predicted to be 1.7 feet for a specific yield value of 0.28 and 2.1 feet for a specific yield value of 0.20. The majority of this mounding was predicted to dissipate within 2 weeks of cessation of the storm event.

8.5 Discussion of Model Predictions

The impact predictions presented above represent the culmination of the various field investigations, hydrogeologic interpretations, and quantitative analyses performed over the course of this study. Information from all of these sources was integrated to refine the conceptual model and develop the computer model of Maury Island's groundwater flow system. Hydrogeologic issues identified during model development supported further refinement and enhancement of the conceptual model. Thus, both conceptual and computer models are formed on the most current, best available understanding of the groundwater flow system. The computer model simulates all the major, known structural and functional components of the groundwater flow system. Where uncertainties remain, such as the issue of perched subflow above shallow till, additional calculations and model simulations were performed to evaluate the likely significance of alternative interpretations. The model maximizes simplicity in representing the flow system, but retains the level of detail needed to perform predictive simulations of mine expansion impacts. The three "model scenarios" and the sensitivity analysis to specific yield reasonably define the likely range of hydrogeologic conditions and associated range of predicted impacts.

A large component of this hydrogeologic investigation focused on the recharge processes that supply water to the Principal Aq-

uifer. Recharge was analyzed from a variety of perspectives to better understand: quantities of water passing through the root zone; effects of shallow perching over surficial till; propagation of the seasonal recharge pulse through various thicknesses of unsaturated sediments; and the mechanisms by which schedules of recharge delivery to the water table effect observed water-level variations. This emphasis on recharge processes is appropriate since the primary hydrogeologic impacts associated with mine excavation will result from a change in recharge regime within the mine footprint. Conclusions derived from these analyses and investigations led to development of a conservative (worst case) approach to estimating the impacts of altered recharge within the mine footprint. In the predictive simulations, the factors responsible for limiting seasonal variation of recharge inflow to the water table were removed at the mine site due to excavation of a significant portion of the unsaturated zone. Resulting recharge schedules at the mine site changed from mild seasonal variations in the premined condition to sharp, pronounced seasonal variations in the mined and reclaimed conditions. This approach, applied to each of the three model scenarios over a representative range of aquifer specific yields, defined the range of predicted hydrogeologic impacts.

The model was used to simulate impacts to water levels, springflows, and inter-aquifer fluxes incurred over three phases of mine excavation and subsequent reclamation. Predicted impacts to the overall function of the groundwater flow system were relatively small. Impacts were largest within and immediately adjacent to the mine footprint, but rapidly declined with distance from the footprint. Impacts to groundwater levels were documented at only four "prediction points" in the flow system: three surrounding the mine and the fourth within the mine footprint. However, the relatively small impacts at the three surrounding prediction points establish the magnitude of impacts predicted for outlying portions of the study area. Long-term water-level declines ranging from 0.1 to 0.4 feet are predicted for the three points outside the mine footprint, compared to 0.6 foot declines within the footprint. Modeled seasonal variations to recharge at the mine lead to additional seasonal water-level variations superimposed over existing fluctuations outside the footprint. Modeled seasonal water-level variations of up to ± 2.4 feet beneath the mine lead to predicted seasonal impacts of ± 0.2 feet or less at the surrounding three prediction points. Seasonal water-level impacts at water supply wells near the site will be smaller than those estimated at prediction points.

These predicted impacts to groundwater levels will cause negligible changes in the overall groundwater flow pattern of the island. Increased seasonal variations are expected in the immediate vicinity of the mine, but will be largely dampened out over representative distances between the site and surrounding domestic wells. It should also be remembered that predicted impacts are considered to be worst-case, conservative estimates. Likely impacts to groundwater levels and resulting impacts to groundwater flow patterns will be smaller.

Predicted impacts to spring discharge are similarly small. Long-term reductions in average annual spring discharge on the order of 2 percent or less of current flows are predicted for Dockton Springs, Ferguson Springs, and Spring E. While predicted impacts to average discharge are similar for all three springs, impacts to seasonal springflow variation differ as a function of distance to the mine site. Existing measurements, taken

over a period of two months, show discharge from Spring E to vary by ± 6 percent (Herrera, 2000). While current full-range seasonal variations may be higher, model predicted worst-case springflow variations are on the order of ± 20 percent. Predicted seasonal impacts to discharges at Dockton and Ferguson springs are less than ± 1 percent.

Groundwater flow from the Principal Aquifer is believed to be the dominant source of recharge to the deep aquifer system. Impacts to this transfer between aquifers are also predicted to be small. After reclamation is completed, a reduction in groundwater flow to the deep aquifer of up to 0.5 percent is predicted when water levels at the mine site are at their seasonal low. This translates to a reduction of approximately 5 gpm for the model area. This impact is unlikely to affect water availability or well yields in the deep aquifer.

While the groundwater flow model is appropriately designed for prediction of impacts at the scale of the mine excavation, it should be noted that the degree of simplification inherent in the model structure may limit its application to some uses. Simulation of localized flow phenomena and aquifer responses is limited by the fact that the model did not attempt to simulate local-scale heterogeneities. Uncertainty in bottom elevations for the Principal Aquifer may also limit the reliability of localized predictions. The model did not attempt to simulate localized perched conditions within the unsaturated zone overlying the Principal Aquifer. Such perched conditions were assumed to be localized, and have little influence on the overall flow system.

The model also did not attempt to simulate spatial redistribution of shallow recharge caused by perched subflow above surficial till. Little is known about the perched groundwater system above the till, however calculations presented in **Appendix D** suggest limited capacity for such a perched system to conduct water. Assuming that the perched system conducts water across the top of the till at estimated capacity, and that lateral flowpaths are extensive and continuous over the till surface, a portion of recharge to till-covered areas at the mine site could be redirected away from the site via perched subflow. During excavation, removal of till within the mine footprint would remove that portion of recharge from the perched flow system and redirect it downward towards the water table. Preliminary model simulations, performed to evaluate such a redistribution of recharge, are discussed in **Appendix D**. Modeled impacts associated with this redistribution of recharge show increased groundwater levels and springflows, except along the northwest (downslope) edge of the till covering the island center, where groundwater levels are predicted to decline. In general, the modeled average annual impacts associated with recharge redistribution would offset the impacts predicted under the worst-case simulations discussed above. Given the desire to retain conservative (worst case) prediction and the fact that little is actually known about the perched flow system, these additional predictions were not incorporated into the impact analysis.

It should be remembered that three model scenarios, each run under two values of aquifer specific yield, were used to define a representative range of depictions of the groundwater flow system. No single depiction of the system is the only possible interpretation. Any further predictive work should be performed, at minimum, over the range of depictions presented in this report.

9.0 Definitions, Acronyms, and Abbreviations

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

Aquifer - A hydrostratigraphic unit that yields significant (economically feasible) amounts of water to wells; also called a "water-bearing" unit.

Aquitard - A hydrostratigraphic unit that does not yield significant amounts of water to wells. An aquitard can store large quantities of water, but it only allows *slow* vertical (upward or downward) movement of groundwater into other units. Because some aquitards are large in aerial extent, relatively large volumes of water may flow through them.

Vertical Datum - The elevation reference used in this study. Equivalent to North American Vertical Datum (NAVD) of 1988.

cfd – cubic feet per day

cfs – cubic feet per second

cm/sec – Centimeters per second, a unit of measurement used to describe aquifer hydraulic conductivity.

Confined aquifer - An aquifer that is overlain by an aquitard (a confining unit) and contains groundwater under sufficient pressure to rise above the top of the aquifer. Also known as an artesian aquifer. In some cases, groundwater levels may be above land surface, and wells completed in the confined aquifer may flow.

Ecology - Washington State Department of Ecology

Fluvial - Produced by the action of a stream or river.

ft/day - Feet per day, a unit of measurement used to describe aquifer hydraulic conductivity.

gpm - Gallons per minute; a unit of measurement used to describe pumping rate from wells or gravity flow rate from springs.

GIS - Geographic Information System; a computer-based system that provides an interface between many types of graphical and non-graphical data over geographic areas.

Glacial drift - All sediments transported and deposited by glaciers or by meltwater derived from the ice; includes tills, outwash, glacio-lacustrian deposits, kames and more.

Groundwater divide - An imaginary no-flow line on a water table (or potentiometric surface) contour map. Groundwater on one side of the line flows in one direction; groundwater on the other side flows in the opposite direction.

Hydraulic conductivity - A coefficient of proportionality describing the rate at which water can move though a porous medium, commonly expressed in units of feet per day (ft/day) or centimeters per second (cm/sec). It is equal to the

transmissivity of an aquifer divided by its saturated thickness. Abbreviated as "K".

Hydraulic gradient - The change in total head (or water level) with a change in distance in a given direction; the coefficient of proportionality that expresses the "driving force" of groundwater flow.

Interglacial - Refers to those geologic processes that occurred during periods when glaciers were not present.

K_h – Horizontal hydraulic conductivity

K_v – Vertical hydraulic conductivity

Lacustrine - Produced by lakes.

mgd - Million gallons per day

Outwash - Sand and gravel deposited by melt water streams from a glacier.

Perched - Groundwater occurring in a saturated zone (all the pore spaces filled with water) that overlies another zone that is not saturated. It is typically a saturated sand or gravel overlying a silt or clay, which in turn overlies an unsaturated sand or gravel.

Permeability – see *Hydraulic Conductivity*

Pleistocene - The period in geologic history between about 2 million to 10,000 years ago. Also known as the time of glaciers, or the "ice age."

Proglacial lake - A lake that forms just beyond the frontal margin of an advancing or retreating glacier; it is generally in direct contact with the ice.

Qpvu - Undifferentiated pre-Vashon deposits

Qva - Vashon advance outwash deposits

Qvr - Vashon recessional outwash deposits

Qvt - Vashon till

Recessional - Refers to processes and sediments deposited by a retreating glacier.

Static water level - A water level measurement obtained under non-pumping conditions, when water levels are not changing in response to recent pumping.

Specific Yield – The ratio of the volume of water that soil or rock will yield by gravity drainage to the volume of the soil or rock. It is expressed in dimensionless units.

Surface Water - Bodies of water on the earth's surface, such as rivers, streams, creeks, lakes, and ponds.

Till - Unstratified, poorly sorted glacial drift deposited directly by a glacier; these sediments are "smeared" along the bottom of a glacier; as such, they are typically very dense and compact. Till often looks like concrete and is often called "hardpan" by well drillers.

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

Unconfined aquifer - An aquifer that is not overlain by a confining unit and in which pore water pressure is atmospheric; water levels in such an aquifer lie below the top of the aquifer.

USGS - United Stated Geological Survey

Vadose Zone – The zone between the land surface and the water table. The pore spaces contain water at less than atmospheric pressure. Saturated bodies, such as perched groundwater, may exist in the vadose zone. Also called the unsaturated zone or zone of aeration.

10.0 References

Associated Earth Sciences Inc, 1998. *Soils, Geology, Geologic Hazards and Groundwater Report, Existing Conditions, Impacts and Mitigation, Maury Island Pit, King County, Washington.* Unpublished consulting report, revised date of April 27, 1998.

Associated Earth Sciences Inc, 1999a. *Addendum Geology and Ground Water Report, Maury Island Pit, King County, Washington.* Unpublished consulting report, revised date of March 3, 1999.

Associated Earth Sciences Inc, 1999b. *Letter to Ron Summers of Lone Star Northwest, Inc. from Jill Wheeler of AESI, regarding monthly groundwater monitoring summary.* Consultant's letter correspondence dated of May 3, 1999.

Bauer, H., and M. Mastin. 1997. *Recharge from Precipitation in Three Small Glacial-Till-Mantled Catchments in the Puget Sound Lowland, Washington.* U.S. Geological Survey Water-Resources Investigations Report 96-4219.

Booth, D. B., 1991. *Geologic Map of Vashon and Maury Island, King County, Washington.* U. S. Geological Survey Miscellaneous Field Studies Map MF-2161 with accompanying text.

Booth, D. K. and Goldstein, B. 1994. "Patterns and Processes of Landscape Development by the Puget Lobe Ice Sheet." *Washington Division of Geology and Earth Resources Bulletin* 80: 207-218.

Buchanan-Banks, J.M. and Donley, S.C. 1995. *Map Showing Depth to bedrock of the Tacoma and Part of the Centralia 30' X 30' Quadrangles, Washington.* U. S. Geological Survey Miscellaneous Field Studies Map MF-2265.

Carr, J.R. & Associates, 1983. *Vashon / Maury Island Water Resource Study.* Consultant's report submitted to King County Department of Planning and Community Development, dated December 1, 1983.

Colombo, Robert, 1999. System Manager for Dockton Water Association. Personal communication on October 20, 1999 with Crispin Prahl of Pacific Groundwater Group.

Easterbrook, D. J. 1994. "Chronology of Pre-Late Wisconsin Pleistocene Sediments in the Puget Lowland, Washington." *Washington Division of Geology and Earth Resources Bulletin* 80:191-206.

EVS Environmental Consultants, Inc. *Maury Island Gravel Mining Impact Study, Nearshore Impact Assessment.* Consultant's report prepared for Pacific Groundwater Group, dated May 2000.

Freeze, R. A., and Cherry, J. A. 1979. *Groundwater.* Englewood Cliffs: Prentice-Hall.

Herrera Environmental Consultants, *2000. Maury Island Lone Star Gravel Mine Evaluation of Spring Water Quality, Proposed Stormwater Management Measures, and Potential Sediment Runoff Impacts.* Unpublished technical memorandum prepared for Washington State Department of Ecology and Pacific Groundwater Group, dated February 3, 2000.

Johnson, Larry, 1999. Owner and head driller for Statewide Drilling Company. Personal communication on October 14, 1999 with Crispin Prahl of Pacific Groundwater Group.

King County Department of Development and Environmental Services, 1999. *Draft Environmental Impact Statement for Maury Island Lone Star Gravel Mine*. Report prepared in association with Jones & Stokes Assoc., Inc., and others, dated July 21, 1999, 481 pp.

McDonald, M.G., and Harbaugh, A.W., 1988. A Modular Three-Dimensional Finite-Differences Groundwater Flow Model. U.S. Geological Survey Water-Resources Investigation, Book 6, Chapter A1.

Pacific Groundwater Group, 1999a. *Proposal and Statement of Qualifications for Maury Island Gravel Mining Impact Studies*. Unpublished consulting proposal prepared for Washington State Department of Ecology, dated August 6, 1999.

Pacific Groundwater Group, 1999b. *Document Summaries and Areas for Further Investigation, Maury Island Gravel Mining Impact Studies*. Unpublished consulting report prepared for Washington State Department of Ecology, dated October 1999.

Pacific Groundwater Group, 1999c. *Summary of Soil Chemistry, Maury Island Gravel Mining Impact Studies*. Unpublished technical memorandum from Janet Knox to Dave Garland, Washington State Department of Ecology, dated October 21, 1999.

Ritzi, R., 1983. *The Hydrologic Setting and Water Resources of Vashon and Maury Islands, King County Washington*. Thesis prepared for fulfillment of Master of Science degree, Wright State University, Dayton, Ohio, dated June 1983.

Rongey & Associates, 1998. *Hydrogeological Review of Maury Island Pit*. Unpublished consulting prepared for Gold Beach Water Company, dated May 1998.

Seabold, Bob, 1999. Owner of Island Pump and Water System. Personal communication on February 6, 1999 with Crispin Prahl of Pacific Groundwater Group.

Simunek, J., Senjna, M., van Genuchten, M. Th., 1999. Hydrus-2D/Meshgen-2D – Simulating Water Flow and Solute Transport in Two-Dimensional Variably Saturated Media, Version 2.0 dated April 1999, U.S. Salinity Laboratory, USDA/ARS. Distributed by International Groundwater Modeling Center, Golden, CO.

Soil Conservation Service. 1973. *Soil Survey, King County Area, Washington*. United States Department of Agriculture Soil Conservation Service in cooperation with Washington Agricultural Experiment Station, issued November 1973.

Terra Associates, 1999. *Groundwater Discipline Report, Geology and Groundwater Sections, Lone Star Pit/Maury Island, King County, Washington*. Presented as Appendix A of Draft Environmental Impact Statement (King County, 1999), dated July, 1999.

U.S. Department of the Interior, 1990. 7.5-minute Orthophotos Quadrangles of Vashon SW, Vashon SE, Tacoma North

NE and Tacoma North NE, U.S. Geological Survey web site at URL:http://edcwww.cr.usgs.gov/Webglis/glisbin/glismain.pl,

Vaccaro, J.J., Hansen, A.J., and M.A. Jones, 1998. *Hydrogeologic Framework of the Puget Sound Aquifer System, Washington and British Columbia*. U.S. Geological Survey Professional Paper 1424-D. Prepared as part of the Regional Aquifer System Analysis – Puget-Willamette Lowland.

Vashon-Maury Island Groundwater Advisory Committee, 1998. *Vashon-Maury Island Groundwater Management Plan and Supplement, Areas Characterization*. Report submitted to King County Department of Natural Resources, dated December 1998.

Washington State Department of Ecology, 1999a. *Request for Proposal Number ECY RFP 9913, Maury Island Gravel Mining Impact Studies and Seatac Airport Proposed Fill Embankment and Runway Construction*. Unpublished document prepared for public response released July 1, 1999.

Washington State Department of Ecology, 1999b. *Maury Island Gravel Mining Impact Studies, Project Startup Fact Sheet*. Public newsletter distributed to project mailing list in October 1999.

Woodward, D. G., Packard, F. A., Dion, N. P., and Sumioka, S. S., 1995. *Occurrence and Quality of Ground Water in Southwestern King County, Washington*. U. S. Geological Survey Water-Resources Investigations Report 92-4098. Prepared in cooperation Washington State Department of Ecology, Regional Water Association of South King County, and Seattle-King County Department of Public Health.