Department of Ecology
Publication No.14-03-025

PACIFIC groundwater GROUP

HYDROGEOLOGIC EVALUATION OF PROPOSED LEQUE ISLAND RESTORATION

December 2012

HYDROGEOLOGIC EVALUATION OF PROPOSED LEQUE ISLAND RESTORATION

Prepared for:

Ducks Unlimited
17800 SE Mill Plain Blvd• Ste. 120
Vancouver, WA 98683
www.ducks.org

Prepared by:

Pacific Groundwater Group
2377 Eastlake Avenue East, Suite 200
Seattle, Washington 98102
206.329.0141
www.pgwg.com

December 10, 2012
JY1006

TABLE OF CONTENTS

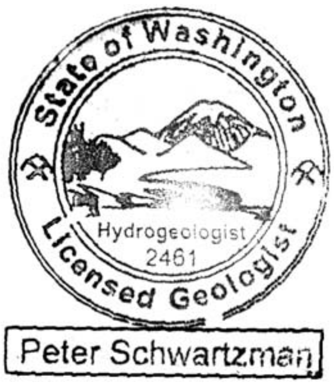
TABLES

FIGURES

APPENDICES

SIGNATURE

This report, and Pacific Groundwater Group's work contributing to this report, were reviewed by the undersigned and approved for release



Peter Schwartzman
Principal Hydrogeologist
Washington State Hydrogeologist #2461

1.0 INTRODUCTION

In 2004, the Washington Salmon Funding Recovery Board funded the design, permitting, and construction of a levee setback project proposed by Ducks Unlimited (DU) for the Leque Island Wildlife Area near Stanwood, Washington. The project would restore approximately 115 acres of estuarine intertidal vegetated wetlands, including 72 acres of freshwater wetland habitat. The site had been converted from salt marsh to agricultural land in the late 19th century by constructing perimeter dikes to keep out seawater, ditches to drain saturated soils, and a tide gate to facilitate ditch discharge during low-tide. Historic conversion of salt marshes to agriculture led to significant loss of biological and ecological services in the Stillaguamish watershed. The Leque Island site represents the one of the best opportunities for restoration of estuarine habitat in the Stillaguamish Watershed (Snohomish County, 2012).

The proposed restoration would include removal of the perimeter dikes, backfilling of the existing drainage ditches, and re-excavation of a relic channel that existed on the site prior to agricultural conversion. With the dikes removed, the site would be inundated by brackish seawater during high-tide an average of 5 hours per day. A more complex drainage network would develop with distributaries emanating from the restored relic channel. Average annual groundwater levels beneath the restored site are expected to rise due to the daily periods of tidal inundation.

In late 2009, the Camano Water Systems Association (CWSA) submitted a letter to the Washington State Department of Fish and Wildlife (WDFW) objecting to the proposed project. CWSA and their consultants raised concerns that the proposed restoration would cause further saltwater contamination of the sea-level aquifer that underlies the northeast lobe of Camano Island. This area of Camano Island already exhibits low groundwater elevations (approximately 2 feet above mean sea level); and elevated chloride concentrations observed in coastal wells led the Juniper Beach Water District (JBWD) to move their pumping activities farther inland and distribute groundwater withdrawals among multiple wells. Available hydrogeologic studies of the area were regional in scale and did not provide detailed understanding of local hydrogeologic conditions. Some stakeholders interpreted the regional characterization to imply the possible occurrence of westerly groundwater flow from the mainland to Camano Island, and expressed concern that the proposed restoration would salinate groundwater beneath Leque Island, which would then flow to the west beneath Camano Island to increase local salinity. DU initially addressed these concerns with a hydrogeologic analysis of existing information performed by ABC Consultants (2009). JBWD's consultant expressed additional concern that increased groundwater levels beneath Leque Island would further increase the likelihood of westerly groundwater flow from Leque Island to Camano Island. Ultimately, these comments, discussions among stakeholders, and multi-agency review led to the conclusion that actual field investigation and detailed local hydrogeologic analysis was needed to assess the potential for increased salinization of groundwater beneath Camano Island.

DU engaged Pacific Groundwater Group (PGG) for hydrogeologic assistance in performing this evaluation, and PGG worked with DU to develop a scope of work for field investigation and hydrogeologic analysis. Along with consideration of comment letters from CWSA's and JBWD's consultants, the scoping process included input/direction from the U.S. Environmental Protection Agency (EPA) and review/comment from WDFW, Washington Department of Ecology (Ecology), and the U.S. Geological Survey (USGS).

This report summarizes the field investigation performed by PGG and presents the results of PGG's analysis of the potential for saltwater intrusion beneath Camano Island resulting from the proposed Leque Island restoration. The project study area is shown on **Figure 1-1**. A summary of key findings and recommendations is presented in the executive summary (Section 2). Detailed description of local hydrogeologic conditions is presented in Section 3, with a summary of field investigations in Appendix A and synoptic water-level maps in Appendix B. Section 4 presents analysis of how the proposed restoration is likely to change hydrogeologic conditions on Leque Island, and Section 5 addresses how the changes on

Leque Island are likely to affect groundwater conditions below Camano Island. PGG's analysis of potential impacts to Camano Island is based on a three-dimensional groundwater flow model of the project area documented in Appendix C. PGG's analysis suggests that the proposed restoration will not cause further groundwater salinization beneath Camano Island.

PGG's work was performed, and this report prepared using generally accepted hydrogeologic practices used at this time and in this vicinity for exclusive application to the study area and for the exclusive use of Ducks Unlimited. This is in lieu of other warranties, express or implied.

2.0 EXECUTIVE SUMMARY

- PGG's scope of work included: compilation/review of existing hydrogeologic data; drilling and installation of 8 monitoring wells in 2 east-west transects across the study-area monitoring site; preparation of 3 hydrogeologic cross sections across the study area; monitoring of water levels and salinity in the referenced wells; estimation of aquifer properties based on hydraulic testing; interpretation of the collected data; and modeling analyses to assess potential impacts to Camano Island groundwater. PGG's scope of work met all requirements set forth by the EPA, and was expanded soon after project initiation to include monitoring of water-levels and salinity in ditches on the monitoring site and on Leque Island.

- The monitoring site was selected with consideration of multi-party input during the scoping process under the premise that increased potential for saltwater intrusion beneath Camano Island due to the proposed restoration is unlikely if hydrogeologic analysis shows groundwater discharge from Camano Island towards the "Leque Lowland". PGG's interpretation of existing and collected data suggests that the monitoring site between Camano and Leque Islands is an area of groundwater discharge. This finding is based on observation of a horizontal groundwater gradient from Camano Island *towards* Leque Island and on upward groundwater gradients beneath the monitoring site. Groundwater flow from Camano Island towards the "Leque Lowland" (the monitoring site and Leque Island) was expected because the lowland is drained by Davis Slough, the Stillaguamish River and agricultural ditches with elevations near to mean sea level. Groundwater flow from the Camano Island upland to the Leque Lowland offsets the concern of westerly flow from the mainland towards Camano Island.

- Salinity monitoring revealed that groundwater and ditch-water on the monitoring site are brackish and similar to the salinities expected for Port Susan and Skagit bays. Ditch water on Leque Island, likely representative of local groundwater, is also brackish. Brackish groundwater results from historic inundation of the Leque Lowland, deposition of sea spray, and salt concentration due to evapotranspiration from shallow groundwater. The observed similarity between groundwater and marine-water salinity suggests that increased inundation frequency on (restored) Leque Island will not significantly change groundwater salinities beneath the Leque Lowland.

- Hydrogeologic characterization revealed that the Camano Island upland is underlain by a series of stratified glacial and interglacial aquifers. Much of the Leque Lowland is covered by a surficial deposit of marsh sediments which overlie alluvium. Whereas the monitoring site exhibits variably silty alluvium to explored depths of 65 feet below land surface, borings on Leque Island show several tens of feet of sandy alluvium beneath the marsh sediments, and deeper borings along SR532 show about 100 feet of silty alluvium overlying another 100 feet of gravelly alluvium. A similar alluvial profile is assumed within the Stillaguamish Delta sediments on the adjacent mainland, whereas mainland upland areas are underlain by a stratified sequence of glacial and non-glacial sediments.

- The proposed Leque Island restoration will result in additional groundwater recharge on the restored site due to frequent inundation, and increased drainage efficiency due to replacing (partially clogged) drainage ditches with newly formed open channels. The net effect of restoration on local groundwater levels will depend on how the balance between increased recharge and increased drainage affects the groundwater budget. PGG developed a 2-dimensional groundwater model to represent the effects of both increased recharge and increased drainage. The model was run over a range of aquifer properties considered representative of Leque Island subsurface conditions. Model results suggest that average-annual groundwater levels beneath Leque Island will rise by roughly 1 foot to a relatively consistent, year-round elevation of about 6.9 feet NAVD88.

- PGG developed a 3-dimensional groundwater flow model to evaluate whether the estimated Leque Island groundwater level rise would cause existing groundwater flow from Camano Island to the Leque Lowland to reverse direction. The groundwater model includes representation of hydrogeologic conditions on the Camano Island upland, Leque Lowland, mainland lowland and mainland upland. Represented surface-water features include drainage ditches, Davis Slough, the Stillaguamish River and Port Susan and Skagit bays (groundwater discharges to the bays via submarine springs). USGS estimates of groundwater recharge were also represented, along with major groundwater withdrawals and evapotranspiration of shallow groundwater in lowland areas. Four versions of the model were generated to represent various interpretations of the groundwater flow system and hydraulic connections between groundwater and surface water. Model calibration included a sensitivity analysis, and the final versions of the model reasonably met calibration goals. Post-restoration conditions were simulated in all model versions by specifying a constant groundwater elevation of 6.9 feet NAVD88 beneath Leque Island. Results of the predictive simulations showed no reversal of groundwater flow from Camano Island to Leque Lowland.

- The 3-D model predicted less than 0.1 feet of increased groundwater levels beneath upland Camano Island adjacent to the Leque Lowland. Although this is a very small increase, it should be noted that increased groundwater heads generally result in reduced potential for saltwater intrusion because higher freshwater hydraulic heads cause the saltwater interface to deepen, thereby thickening the freshwater lens. The effects of Leque Island restoration via this mechanism are likely to be negligible, but should not be viewed as adverse.
- Data gaps identified in this report create some uncertainty in model parameters and calibration targets. Although PGG addressed this by generating multiple versions of the model, our model versions are not the only possible depictions of the groundwater flow system. Other depictions could be generated that would likely also meet the calibration criteria. Nevertheless, the impacts of Leque Island restoration on Camano Island predicted by our models are so small that other reasonable versions of the model are unlikely to show significant differences.

3.0 STUDY AREA CHARACTERISTICS

The area of interest for this investigation extends from the northeastern edge of Camano Island eastward across Leque Island to the western edge of the Puget Sound mainland near Stanwood, WA. A study area map is presented on **Figure 1-1**. As the site of the proposed restoration, Leque Island lies at the center of attention within the study area. However, all adjacent areas are equally important in evaluating the potential impacts of the proposed restoration.

Leque Island is a small marshland located between the City of Stanwood and Camano Island in Snohomish County near the mouth of the Stillaguamish River Estuary. It is bounded by the West Pass and South Pass of the Stillaguamish River on the east, Davis Slough on the west, Skagit Bay on the north and Port Susan Bay on the south. The island is low lying, with an average land surface elevation of around 7 feet NAVD88 (about 2.6 feet above mean sea level, and *below* average high tide). The island has dikes around its perimeter to exclude tidal inundation and a system of internal drainage ditches which discharge to tide gates – all of which were constructed in support of historic agricultural practices. The island is now used for recreation and hunting.

The northeastern lobe of Camano Island is predominantly an upland area relative to Leque Island, with typical elevations ranging from 70 to 150 feet NAVD88. The island supports residential and agricultural land use. Water for these activities is supplied by local wells, and locally elevated chloride concentrations indicate areas with vulnerability to seawater intrusion. Camano Island also has low-lying coastal areas which support beach communities and agricultural activities. Of particular interest near Leque Island are the Juniper Beach community and a swath of grazing land where PGG performed intensive hydrogeologic monitoring and analysis ("monitoring site") to evaluate groundwater flow patterns between Camano and Leque islands (**Figure 1-1**). Similar to Leque Island, the grazing land includes a system of dikes, internal drainage ditches and a tide gate to support agricultural activities. The grazing land is separated from Leque Island by Davis Slough, which is dry during low tide but wet during mean-to-high tides.

East of Leque Island, the West and South Passes of the Stillaguamish River play a key hydrologic role by cutting into the shallow groundwater flow system. Groundwater beneath the mainland is expected to flow towards and discharge to the river. The river is tidally influenced and thus exhibits water-level elevations influenced by both tides and freshwater discharge.

3.1 CLIMATE

The USGS characterized climate and recharge in Island County, which includes and abuts the Leque study area:

> Island County has a temperate, marine climate with dry summers and wet winters. Average annual maximum temperature for 1984-2000 was 57.9 °F at Coupeville on Whidbey Island; average annual minimum temperature for the same period was 41.7 °F. July typically is the warmest month, with an average maximum temperature of 71.3 °F and January is the coldest month, with a long-term average minimum temperature of 50.3 °F (Western Region Climate Center, 2001).
>
> Data from PRISM (Precipitation-Elevation Regression on Independent Slopes Model; Daly and others, 1994) indicate that average annual precipitation from 1961 to 1990 ranged from 35 inches on southern Whidbey Island to 29 inches on northern Whidbey Island, and from 25 inches on western Camano Island to about 31 inches on the northern part of Camano Island nearest the mainland.

Figure 3-1 shows the USGS isohyetal map for Island County. Precipitation in the Leque study area is about 31 to 33 in/yr. PGG reviewed precipitation data for two nearby climate stations (Coupeville and Arlington, 1948-2005) and found that 65 percent of the precipitation generally falls between the months of November and April.

3.2 SURFACE-WATER FEATURES

Surface-water features have a significant influence on groundwater flow in the study area, and therefore the issues addressed in this report. Most of the time, groundwater discharges to the various marine and inland surface-water features. However, several inland surface-water features (Stillaguamish River and Davis Slough) are directly connected to marine waters and therefore experience tidal flushing with saline water. It is also worth noting that many low-lying "terrestrial" areas, such as Leque Island, were once included in the intertidal zone. Breaching of the dikes that now surround these lowlands (e.g during storm surges) results in marine inundation that recharges shallow groundwater with saline water.

PGG monitored surface-water elevations and electrical conductance (an indicator of salinity) at 4 locations within the study area. Monitoring locations are shown on **Figure 1-1,** and **Appendix A** describes our monitoring methods and protocols. The following sub-sections describe the key marine and inland surface-water features in the study area.

3.2.1 Marine Features

The study area is bordered by Skagit Bay on the north and Port Susan Bay on the south. Relative to mean sea level (MSL = 4.4 feet NAVD88), mean low low water (MLLW) is about -1.6 feet NAVD88, and high tides are known to exceed 10 feet NAVD88. Tides are highest during winter months, as is the likelihood of storm surges. Near the shoreline, both Skagit and Port Susan bays contain extensive mud flats. The mud flats occur at similar elevations to mean sea level such that marine water recedes up to several miles offshore during low tide. The mudflats are dissected by the South Pass and West Pass channels. Limited data review by PGG suggests that the West Pass channel has a base elevation as low as -5 feet NAVD88 (WSDOT, 2012) and the South Pass channel has a base elevation at least as low as 0 feet NAVD88.

The salinity of seawater in Skagit and Port Susan bays is moderated by freshwater discharge from the Stillaguamish River. **Figure 3-2** shows the salinity of marine water at high tide under current conditions predicted by hydrodynamic modeling performed by Battelle (Yang et al, 2008). Relative to salinities under open-water conditions (approximately 28 parts per thousand or "ppt"), the predicted salinity distribution suggests significantly lower salinities near the coastline, with values less than 8 ppt on the north side of Leque Island in Skagit Bay and values ranging from 6 to 18 ppt immediately south of Leque Island.

3.2.2 Inland Surface-Water Features

Key inland surface-water features within the study area include the Stillaguamish River (South and West Pass), Davis Slough, and the various ditches constructed to drain lowland areas surrounded by dikes (**Figure 1-1**). Both passes of the Stillaguamish River and Davis Slough are directly connected to marine water, and therefore exhibit direct tidal influence. Whereas the Stillaguamish passes form a connection between Skagit and Port Susan bays, Davis Slough is only open to Skagit Bay (its former connection with Port Susan Bay is obstructed). **Figure 3-3** presents a hydrograph of water-level elevations in Davis Slough which shows tidal variation between the base elevation of the slough (approximately 4.2 feet NAVD88) and values exceeding 10 feet NAVD88. Because streambed elevations of the Stillaguamish River passes fall below approximately 0 feet NAVD88, even larger tidal variations are expected in these channels.

Tidal influences on water levels in the ditches are limited by tide gates at their discharge points designed to exclude tidal inflow. Leaky gates, however, do allow limited tidal inflow to inland ditch systems. Monitoring stations on the "South", "Middle" and "North" ditches on PGG's monitoring site (mapped on **Figure 1-1**) show varying amounts of tidal variation relative to Davis Slough (**Figure 3-3**). Tidal influence is consistently noted at the "Middle" ditch station, immediately upstream of the Davis Slough tide gate. Although all of these ditches are connected, obstructions or constrictions apparently cause higher water-level stages with distance from the tide gate. Water levels at the “South” ditch location are about 0.9 feet higher than those at the “Middle” ditch location, and show no significant tidal variation. Water levels at the “North” ditch location are yet another 0.8 feet higher and show minor tidal influence during consecutive days of relatively high tides. The reason for different sensitivity to high-tide events between the “South” and “North” ditch locations is unknown, but may be related to differences in groundwater interactions or Davis Slough conditions between the north and south ends of the monitoring site. Water-level monitoring of an inland ditch on Leque Island (location shown on **Figure 1-1**) shows no tidal variation; however, ditches on Leque Island are not maintained and may exhibit significant constrictions or restrictions to flow (Rotton, 2012).

Figure 3-4 shows average daily water-level elevations in the monitored ditches. Ditch monitoring began in early March 2012, and showed significant responses to rainfall events through early May. Davis Slough monitoring began in early May and illustrates variation of the tidal cycle. Spring and summer ditch levels are predominantly stable on the monitoring site, with slight declining trends noted in August. A more significant summer decline is noted in the “Leque” ditch, where a single measurement in early October showed the ditch to be dry, with a ditch bottom elevation of about 4.8 feet NAVD88.

Fluxes were not measured in the monitoring-site ditches; however, visual observations were made of discharge at the tide-gate connecting the middle ditch to Davis Slough. Flow rates observed at low tide were relatively low – presumably less than one cubic foot per second (cfs). It should also be noted that discharge occurs only about half the time, when the water level in Davis Slough falls below the water level in the middle ditch (typically about 4.5 to 4.8 feet NAVD88).

PGG monitored electrical conductance (EC) at the above-mentioned monitoring stations to evaluate surface-water salinity. **Figure 3-5** presents EC time series for the four ditch locations and Davis Slough. EC is a measure of dissolved salts concentration, and is roughly correlated to salinity by a factor of 0.6[1]. Based on this relationship, the observed range of EC values (about 5,000 to 23,000 umhos/cm) suggests a salinity range of about 3 to 14 ppt. Davis Slough exhibits the greatest range of EC/salinity, and is most representative of concentrations in Skagit Bay as predicted by Battelle (discussed above). EC values in the “South”, “Middle” and “Leque” ditch locations are higher than Davis Slough, indicating that Davis Slough is not the source of these higher salinities. The reason for these higher values may be associated with groundwater recharged by periodic inundation and discharged to the ditches (see Section 3.3.5 for discussion of groundwater quality). Salinities at the “North” ditch monitoring location appear to be similar to Davis Slough salinities.

3.3 HYDROGEOLOGY

PGG evaluated the hydrogeologic framework of the study area based on maps of surficial geology and soils, reports summarizing hydrogeologic conditions, and interpretation of geologic logs from wells and borings. Along with logs obtained from Department of Ecology records, Washington State Department of Transportation (WSDOT deep borings along SR532) and GeoDesign Inc. (soils investigations on Leque Island), PGG logged and oversaw installation of 8 monitoring wells on the project monitoring site. Geologic logs compiled for the project (mapped on **Figure 3-6**) were used to construct 3 hydrogeologic cross sections through the study area (**Figures 3-7, 3-8** and **3-10**). PGG monitored groundwater elevations in the 8 monitoring wells and 3 nearby private wells to develop synoptic groundwater elevation maps and groundwater level hydrographs. These water-level data were used to evaluate groundwater flow directions and groundwater-level responses to tidal variations. PGG sampled four monitoring wells to evaluate

[1] i.e. Salinity (in ppm) = 0.6 x EC (in umhos/cm). Note that seawater is reported to have an salinity/EC factor of about 0.5; however, our groundwater samples showed factors ranging from 0.57 to 0.73. The ditches are likely largely supplied by groundwater discharge.

groundwater quality, and obtained time-series measurements of EC to evaluate variations in salinity. During our sampling event, we collected drawdown and recovery data for one monitoring well as an aquifer test to estimate aquifer properties. Comparison of water-level elevations and EC values between wells and surface-water features supported evaluation of groundwater/surface-water interactions within the study area.

Monitoring locations are shown on **Figure 1-1** and summary information for the monitored wells is presented in **Table 3-1**. **Appendix A** describes logging and construction of the monitoring wells and PGG's monitoring methods and protocols.

3.3.1 Hydrogeologic Framework

Hydrogeologic conditions differ significantly between upland and lowland areas. Upland areas are underlain by stratified sequences of glacial and interglacial sedimentary deposits, whereas lowland areas are underlain by thick deposits of alluvium. The upland areas cover most of Camano Island and the mainland (i.e. east of Stanwood), whereas lowland areas include the eastern margin of Camano Island, Leque Island and the Stillaguamish River valley floodplain.

Figure 3-6 shows surficial geology and soils mapped across the study area, with detailed descriptions of units provided on **Tables 3-2** and **3-3** (respectively). The lowland area is mapped as containing Holocene (recent) deposits, including: beach deposits (Qb), marsh deposits (Qm), alluvium (Qa) and artificial fill (af) used to construct dikes. Both Leque Island and the monitoring site are covered with Qm which overlies Qa, whereas the Stillaguamish floodplain has Qa exposed at the land surface. The marsh deposits are generally fine grained silt and clay with some organic material, and mapped Qm correlates to mapped Puget silty clay loam soil. This soil is described as 85 to 95 percent silt- and clay-sized particles (Geodesign Inc., 1997). The alluvium includes sediments ranging from sand, silty sand, silt, silty clay, and clay; although gravels were encountered in wells penetrating the alluvium on the monitoring site and along SR532.

Within the study area, the Camano Island upland is predominantly covered with Everson glaciomarine drift ($Qgdm_e$) with exposed windows of underling Vashon till (Qgt_v). Sandy Vashon advance outwash ($Qgas_v$) deposits are exposed along slopes down to the lowland. The glaciomarine drift is a clayey to silty diamicton (poorly sorted mixture) with variable content of gravel clasts that also includes silt, clay, and sand and contains sparse shells. The till is also a diamicton, but is generally more compact, less stratified, and less likely to contain fossils. Both units are fine-grained relative to the underlying advance outwash sands. The sandy advance outwash may include silt layers and gravel near the top of the deposit.

Cross-sections A-A' and B-B' (**Figures 3-7** and **3-8**) extend from the Camano Island upland eastward through the Leque Island lowland. In preparing these sections, PGG differentiated between:

- Relatively permeable medium- to coarse-grained sediments (sand and sand/gravel),
- Mixtures of medium to coarse grained sediments and silt (likely to reduce permeability),
- Predominantly fine-grained low-permeability sediments (silt/clay and silt/gravel), and
- Glacial till.

It should be noted that the private wells located on Camano Island were logged by drillers, and associated geologic descriptions may not be as accurate as those generated by geologists for the lowland wells. Both cross sections show a thick deposit of till-like sediments (most often represented as till but sometimes represented as silt/gravel of sand/silt) immediately below the Camano Island upland. This corresponds to the Qgt_v and is underlain by gravelly deposits of the $Qgas_v$ which contains the sea-level aquifer. **Figure 3-9** reproduces a USGS hydrogeologic cross section across northern Camano Island which shows the glacial/interglacial stratigraphy interpreted by Jones et al (1985). All wells on the northeast lobe of Camano

Island are completed in the sea level aquifer ("Aquifer D" of Jones), which is shown as underlain by deeper aquifers and aquitards defined based on well logs from adjacent portions of Camano and Whidbey Islands. The hydrogeologic units defined by Jones et al can be missing in places, and their presence beneath the northeast lobe of Camano Island or the immediately adjacent lowland has not been confirmed by local hydrogeologic characterization.

Cross-sections A-A', B-B' and C-C' all extend across the Leque Island lowland. The wells included in sections A-A' and B-B' are relatively shallow (< 70-foot depth), whereas section C-C' (**Figure 3-10**) is based on deep wells (~200 feet) logged by WSDOT along SR532. Most lowland logs on Sections A-A' and B-B' show silty sediments (Qm) in upper 3 to 9 feet below the land surface; however, Qm is absent in places. Where present, the Qm deposits form a thin confining unit over the saturated Qa; however, the Qa is unconfined where Qm is absent. Sections A-A' and B-B' show considerable textural variability within the Qa sediments, with textures ranging from sand/gravel to sand to sand/silt to silt/clay. The GeoDesign boring logs on Leque Island (e.g. B-1, B-2, etc.) all show a similar sedimentary profile, with silty Qm underlain by Qa sand. The lack of variation among these logs likely represents locally more homogeneous textures in the shallow subsurface rather than any artifact of the logging style of GeoDesign's geologists.

Section C-C' shows deeper boring logs across the lowland, generally portraying a thick silt/sand sequence from the land surface to an elevation of about -60 feet NAVD88. Lower permeability sediments (silt/clay and silt/gravel) are noted in several wells within a -60 to -90 feet NAVD elevation interval. The lateral continuity of these finer-grained sediments is unknown, as is the possibility that they may represent an extension of "Aquitard D" shown on **Figure 3-9**. A greater proportion of clean coarser-grained sediments (sand/gravel and sand) is noted below -90 feet NAVD88, with no deep confining unit encountered within the maximum logged depth of -220 feet NAVD88. The presence of this coarser-grained unit is consistent with geologic interpretation of WSDOT logs by Shannon & Wilson Inc. (2009) along the SR 532 corridor, which shows silt/sand sediments to an elevation of -85 feet overlying gravel and sand/gravel to an elevation of at least -200 feet, in this case *without* suggesting the presence of an intervening silt/clay aquitard. It is worth noting that Sections A-A' and C-C' both show the Stillaguamish River cutting into the saturated upper portion of the Qa sediments.

3.3.2 Aquifer Properties

Key aquifer properties used in hydrogeologic analysis include hydraulic conductivity (K), transmissivity (T) and storage coefficient (S). Both K and T are measures of an aquifer's ability to transmit groundwater. S can be divided into specific yield (an aquifer's ability to store water under unconfined conditions) and specific storage (storage under confined conditions).

Aquifer property estimates are limited within the study area, although likely ranges of property values can be generally inferred from sedimentary textures. PGG performed a short-duration (15 minute), low-rate (1.8 gpm) pumping test on Well N3S. Time-drawdown and time-recovery data are presented on **Figure 3-11**, and lead to interpreted T values ranging from 1,360 to 1,580 gpd/ft (averaging 1,470 gpd/ft or 197 ft^2/d) based on the Jacob-Cooper method (Driscoll, 1986). K is estimated from T by dividing by the effective saturated thickness of the aquifer. Well N3S has a 10-foot well screen completed in at least 11 feet of slightly silty sand underlying 2 feet or silty clay (see well log in **Appendix A**). Assuming an effective thickness of 11 feet provides an associated K estimate of 18 ft/d. S could not be estimated due to lack of an observation well during the test; however unconfined S values for unconsolidated sandy materials are expected to range from about 0.1 to 0.3.

While this K estimate may be representative of sandy materials in the shallow Qa aquifer beneath the lowlands, deeper aquifer materials beneath the lowlands contain more gravel and sand/gravel combinations. K values for the gravelly sediments may be over an order of magnitude higher than the sandy sediments in which Well N3S is completed.

The USGS estimated aquifer properties beneath Camano Island during development of groundwater flow models for Island County (Sapik et al, 1988). The models were run in steady state, so S values were not developed or estimated during the modeling effort. The USGS first estimated K based on well tests reported on driller's logs using the modified Theis nonequilibrium formula (ibid). K values were then adjusted during modeling within an order of magnitude of aquifer-test estimates. Modeled K estimates for Aquifer D on the northeast lobe of Camano Island were relatively high (540 ft/d), with similarly high values locally for Aquifer C. USGS modeling also employed vertical hydraulic conductivity (Kv) values of $8.6x10^{-4}$ ft/d for Aquitard D and $8.6x10^{-5}$ ft/d for Aquitard C (ibid).

3.3.3 Groundwater Levels and Flow Directions

PGG installed automated water-level monitoring probes in the eight constructed monitoring wells, along with a private well on the upland immediately adjacent to the monitoring site ("Oksendahl"). Every 2-to-3 months, PGG downloaded the continuous time-series data, manually measured depth to water to confirm the accuracy of the continuous data, and manually measured water levels in two other private wells ("Hambre" and "McIntyre"). All measuring points were surveyed and all water-level measurements were resolved to the NAVD88 elevation datum. Monitored locations are shown on **Figure 1-1**, well information is summarized in **Table 3-3** and monitoring protocol is summarized in **Appendix A**. Continuous time-series water-level data were also obtained from WSDOT for shallow monitoring wells completed in their deep borings along SR532; however, PGG was unable to determine if the elevation values had been confirmed based on manual measurements and surveyed elevations – therefore the WSDOT data may be off by several feet. As discussed in Section 3.2.2, PGG also collected continuous time-series water-level elevation data for 3 ditch locations on the monitoring site, Davis Slough, and a ditch on Leque Island.

Groundwater levels are very close to land surface in all the monitored wells, with depth to water ranging from 1.2 to 4.2 feet. Similarly, on Leque Island during excavation of 6 temporary borings in early November 2007 (wet season condition), GeoDesign (2007) noted that groundwater was present within 1 foot of ground surface in all borings.

Based on the manual and time-series data, PGG constructed a series of bi-monthly synoptic water level maps. All water-levels were corrected for the density of the brackish water within the well casings (water quality is discussed in Section 3.3.5), so that the maps portray equivalent freshwater heads calculated at the well screens. The synoptic map for May 2012 is shown on **Figure 3-12**, and all synoptic maps are presented in **Appendix B**. All maps show the following similar water-level relationships:

- The lowest groundwater elevations occur in Well N3s, which is nearest to the ditch labeled "Middle". The middle ditch has the lowest ditch-stage elevation recorded on the monitoring site and discharges at low tide to Davis Slough via a tide gate. Groundwater appears to discharge to the ditches based on the fact that the ditches penetrate below the water table and generally have water-level elevations below groundwater[2]. Groundwater elevations in the WSDOT wells north of the monitoring site (shallow wells predominantly completed within 20 feet of land surface) are generally higher than in onsite wells, thereby suggesting groundwater flow toward the ditch-drained monitoring site.

- Comparison of water-level elevations at the "South" ditch monitoring site and nearby wells S1s/S1d suggests that the ditch must have considerable skin resistance in this vicinity. If the

[2] Water-level elevations in ditches vary, likely due to constrictions and restrictions to flow. Monitoring at the "North" ditch station shows the highest surface-water elevation, and may be influenced by interception of discharge from the spring emitting from the adjacent upland slope.

ditch were highly coupled to the local groundwater system in this location, water-level elevations would be more similar. The hydraulic coupling between groundwater and ditches may vary across the monitoring site.

- Groundwater-level elevations within the lowland monitoring site are consistently lower than the Oksendahl Well (located on the eastern edge of the Camano Island upland), thus suggesting that groundwater flows from this eastern edge towards the lowland. Groundwater elevation data have been collected by Island County west of the Oksendahl Well, but are not contemporaneous with PGG's data and therefore cannot be incorporated into this assessment of groundwater flow patterns. While it is possible that summer agricultural and residential withdrawals form a cone of depression west of the Oksendahl Well, PGG's summer-2012 monitoring showed consistently higher heads in the Oksendahl Well than the lowland monitoring wells.
- Groundwater-level elevations in the Hambre Well are significantly higher than lowland groundwater elevations to the southeast. Because a log is not available for this well, PGG cannot evaluate hydrogeologic conditions in this immediate vicinity to explain the high water-level elevation. The wellhead elevation was surveyed twice and the calculations confirmed by the surveyor.
- The monitoring site includes two locations where adjacent shallow and deep monitoring wells allow assessment of vertical gradients (N2s/N2d and S1s/S1d). Both locations show upward gradients, with average head differences of 0.18 and 0.14 feet and gradients of 0.005 and 0.007 ft/ft (respectively).

These observations are all consistent with the lowland monitoring site functioning as a groundwater discharge area where groundwater discharges to local ditches. This is consistent with the fact that the ditches represent the lowest elevation water features in the lowland – lower than water bodies that experience tidal variation due to direct connection to Port Susan or Skagit bays (e.g. Davis Slough or the Stillaguamish River). Water-level elevations in the monitored ditch on Leque Island are relatively high, likely due to flow constrictions in the Leque Island drainage system.

Figure 3-13 presents a hydrograph of average daily groundwater elevations at the monitoring site. Variations on the scale of days to weeks are dominated by responses to individual precipitation events and broad-scale tidal trends (i.e. variation of average daily sea level over a 28-day lunar cycle). Seasonal high groundwater levels occur between January and March. Based on precipitation patterns, seasonal low groundwater levels likely occur sometime in late October. Groundwater declines between seasonal highs and seasonal lows likely range from about 1.5 to 2.5 feet. The ditch on Leque Island ("Leque") is also included on this plot because its seasonal variation appears to be more similar to monitoring-site groundwater trends than to the monitoring-site ditches (**Figure 3-4**). This observation suggests that the Leque Ditch is largely obstructed such that the ditch water is fairly static during winter months rather than draining towards the tide gates down to the base level of the ditch (4.8 feet NAVD88). Levels at the "Leque" ditch may largely reflect nearby groundwater levels, only mildly influenced by slow surface-water drainage.

Figure 3-14 presents a high-resolution time-series record of groundwater elevations and Davis Slough stage over a 10-day period within the 2.5-month Davis Slough data record. Tidal responses are evident in groundwater levels on both a diurnal basis and in response to general tidal trends on the multi-day scale. **Figure 3-15** presents a map of median daily water-level range (maximum minus minimum) in the monitored wells, considered roughly representative of the magnitude of tidal variation. WSDOT wells are included in this distribution and tend to exhibit higher daily variations than the monitoring site wells. The reason for this difference is unknown; while the WSDOT wells are a bit closer to the Stillaguamish River, their boring logs do not show particularly high permeability materials in the upper 90 feet below land surface. Overall, the distribution of median daily water-level variation shows considerable variability. This variability, combined with the fact that several tidally-influenced surface-water features at a variety of distances may be influencing tidal groundwater response, precluded meaningful analysis of aquifer properties based on tidal efficiency or time lag.

3.3.4 Recharge and Discharge

Groundwater on Camano Island and Leque Island is recharged predominantly from precipitation and predominantly discharges to surface-water features such as ditches, Davis Slough, the Stillaguamish River, Port Susan Bay and Skagit Bay. A small portion of recharge is also supplied by septic systems and agricultural irrigation; however, these recharge mechanisms are sourced by wells and therefore do not provide "new" water to the groundwater flow system. Discharge also occurs to evapotranspiration where groundwater levels are within several feet of the land surface and to coastal springs above sea level (e.g. the spring on the upland escarpment shown on **Figure 1-1**).

The USGS estimated recharge on Whidbey and Camano Islands (Sumioka & Bauer, 2003) based on consideration of factors such as precipitation, temperature, solar insolation, soil properties, land cover. Their study area included the northeast "lobe" of Camano Island, which is included in our study area. For areas where fine-grained unconsolidated deposits occur at the land surface (typical within the study area), precipitation recharge was predominantly estimated to occur within two categories: 0 to 4 in/yr and 4 to 8 in/yr. These rates applied to soils developed upon upland Everson glaciomarine drift ($Qgdm_e$), upland Vashon till (Qgt_v), and lowland marsh deposits (Qm, coincident with Puget Silty Clay Loam). A small area on the southeast corner of the northeast lobe had an estimated recharge rate of 18.3 in/yr (ibid).

PGG evaluated the influence of precipitation recharge by plotting precipitation events along with groundwater level elevations. **Figure 3-16** shows that all significant precipitation events result in a visual groundwater level increase in the monitoring site wells. Although significant portions of the monitoring site are overlain by fine-grained Qm soils, these soils appear sufficiently permeable to allow precipitation recharge to reach the underlying Qa aquifer. The Qm Puget silty clay loam soils have saturated hydraulic conductivity values ranging from 1.4 to 4.8 in/day (**Table 3-2**), which are sufficient to accommodate most rain events assuming that groundwater levels are below land surface.

3.3.5 Groundwater Quality

PGG monitored electrical conductivity (EC) of groundwater in monitoring-site wells between late November 2011 and early May 2012. The automated monitoring probes were installed close to the screened interval of the wells, and were therefore assumed to represent EC of the aquifer. Probe failures as early as January 2012 led PGG to swap out all monitoring probes for instruments incapable of measuring EC in May 1012. Although the EC monitoring record is shorter than the groundwater level record, a time-series plot of EC trends shows very stable values over the 5-month period (**Figure 3-17)**. The plot also shows that groundwater sampling from wells S1d, S1s, S2s and S3s in early March 2012 resulted in reductions in measured EC which did not recover over time. The reason for these responses is unknown. While pumping the wells may have drawn water to the well from adjacent portions of the aquifer, one would expect groundwater flow patterns (and EC) to return to the (assumed stable) conditions in effect prior to the sampling event. Hydraulic isolation of the wells appears unlikely since water-level monitoring shows daily and seasonal variations. In any case, the observed responses to sampling indicate that some variation may exist between the measured values and nearby aquifer conditions.

Figure 3-18 shows a map of EC ranges observed among the monitored wells and ditch monitoring sites. Based on correlation between laboratory analyses of salinity in wells S1d, S1s, S2s and S3s and associated probe measurements, PGG estimates salinity in the project area by multiplying EC by a factor of 0.6. EC values on the monitoring site therefore range from near zero to as much as 15.4 ppt. Where shallow/deep well pairs occur (S1s/S1d and N2s/N2d), the deeper completions show notably lower EC than the shallower completions; thus, the EC reductions observed during sampling may be related to upwelling of deeper, less saline groundwater during pumping. EC ranges for wells adjacent to Davis Slough are higher than EC in Davis Slough, thus suggesting that infiltration of brackish water from tidal flushing in Davis Slough is not the source of nearby brackish groundwater. Higher observed groundwater EC values are similar to values observed at the South, Middle and Leque ditch sites, thus suggesting that groundwater discharges to these ditches. Lower EC values at the North ditch site may be due to the fact that spring discharge from the upland escarpment is captured by the North ditch system. The escarpment spring discharges significantly above sea level, likely from groundwater perched above upland glacial till. EC measurements from wells in the sea-level aquifer beneath the upland ("Aquifer D") also suggest relatively low EC/salinity. For example, the Oksendahl Well shows no significant EC/salinity, and JBWD production wells (located further inland) generally exhibit chloride concentrations between 30 and 50 mg/l (although values exceeding 100 mg/l have been occurred with high pumping rates). None of these values are brackish. Monitoring wells located close to the upland escarpment (S3s, S2s) are less brackish than other monitoring wells, thus suggesting that upland groundwater may be discharging in these locations and locally reducing monitoring-site groundwater salinity.

Figure 3-19 presents a trilinear diagram showing relative percentages of common ions for groundwater samples taken from wells S1d, S1s, S2s and S3s. All 4 water samples fall into the sodium-chloride water type and indicate a seawater source for saline conditions.

Similar to water in the monitored ditches, brackish groundwater salinities are similar to salinities expected for Port Susan and Skagit bays (as presented in Yang et al, 2008). Brackish groundwater is likely caused by a combination seawater recharge during inundation events, concentration of salts due to evapotranspiration of shallow groundwater, and deposition of salt spray. Discussions with the owner of the monitoring site indicate that marine flooding generally occurs every 8 to 10 years during high seawater events. For example, sometime between 2005 and 2007, a large log jam accumulated at the Davis Slough Bridge causing Davis Slough to overflow so that several feet of water covered the lowlands. Flooding generally emanates from dike breaches on the south side of the monitoring site. Flood water either infiltrates, evaporates, or discharges into the drainage ditches (McIntyre, 2012). The higher salinities noted in shallower groundwater (relative to deeper groundwater) on the monitoring-site are consistent with the combined effects of: 1) infiltration of seawater from the land surface during inundation events and 2) upward vertical discharge of fresher groundwater from deeper portions of the groundwater system.

4.0 CHANGES ON LEQUE ISLAND DUE TO RESTORATION

Restoration of Leque Island will include dike removal, backfilling of existing ditches, and development of a new drainage network. The proposed restoration will create a new hydrologic balance between shallow aquifer recharge (via frequent periodic tidal inundation) and active drainage (the new tidal channels will likely support more efficient drainage than the currently clogged ditches). This section describes how the proposed restored condition will change from current conditions, with specific attention to changes in groundwater levels and salinity. These two areas of change are key to estimating the impacts of Leque Island restoration on groundwater conditions below northeastern Camano Island (Section 5).

4.1 PROPOSED RESTORATION DESIGN

Under current conditions, Leque Island is surrounded by dikes constructed along its perimeter and is drained by a system of ditches that discharges to 2 tide gates[3] (**Figure 4-1**). The dikes and ditches were constructed in the late 1800's to accommodate agriculture on the island. Since their construction, breaches have occurred allowing periodic inundation during storms and tidal surges, and leaks have developed (not all of which have been repaired). WDFW staff recall dike breaches in the early 1990's and in 2008 (Berg, 2012). Available data suggest that groundwater levels range from close to the land surface during the wet season to possibly several feet lower during the dry season (see discussion of monitoring the "Leque" ditch site in Section 3.4.3). Direct measurements of groundwater salinity are unavailable; however, salinity at the "Leque" ditch site is likely representative of shallow groundwater and is interpreted as showing values of approximately 11 ppt.

Changes associated with the proposed restoration are summarized below:

Dike Removal

Ducks Unlimited and WDFW are currently proposing to move forward with an estuarine restoration alternatives analysis. The specific alternatives have not yet been determined; however, proponents speculate they will range from full tidal restoration of WDFW owned lands to a partial restoration of 115 acres on the south end of Leque Island south of SR 532 as previously proposed in 2008. In the full tidal scenario, all perimeter dikes would be removed to field grade, which averages 7 feet NAVD88. In the conservative partial restoration scenario, the section of perimeter dike would be removed that surrounds the restored area, and that fill material would be used to construct a setback levee. All current dikes shown on **Figure 4-1** will be removed by DU in the full tidal scenario.

Tidal Inundation

Relative to mean sea level (MSL = 4.4 feet NAVD88), high tides commonly exceed 8.2 feet NAVD88 and mean low low water level (MLLW) is about -1.6 feet NAVD88. Removal of existing dikes will allow flooding tides to inundate most of Leque Island (which has an average land surface elevation of approximately 7 feet NAVD88). Modeling analysis by Battelle suggests that the land surface will be inundated an average of 5 hours per day during high tide conditions (Yang et al, 2008).

Development of a drainage network under restored conditions is described below. After restoration, the existing "remnant channel" on Leque Island will be reactivated and will remain inundated longer than the land surface because its bottom elevation is expected to range from about 3 feet NAVD88 (about 1.4 feet below MSL) to 4.5 feet NAVD88 (about 0.1 feet above MSL).

[3] Prior to October 2011 there was only one active tide gate at the south end of the island. In October 2011 they replaced the Davis Slought tide gates. In the summertime standing water and ponds dry up. From Belinda.

Drainage Network Development

A new drainage network is expected to evolve as an outgrowth of periodic tidal flooding and ebbing within the pre-existing natural channel (present prior to agricultural activities) shown on **Figure 4-1**. Although the final distribution of the drainage network is unknown, PGG requested that DU estimate the expected layout for purposes of evaluating the hydrologic impacts of restoration. Unfortunately, historic data from the site (e.g. channel width from a T-sheet) is unavailable for Leque, because the site was already diked and ditched by 1886. Channel geometry design on previous projects in Puget Sound and PSNERP conceptual designs have applied geomorphology guidelines that use empirical models calibrated with data collected from field sites (PWA, 2011). DU generated a conceptual drainage network based on anecdotal information from previous blind channels associated with tidal restoration projects in the Pacific Northwest, the current footprint of the remnant relict channel, and will refine channel design using the empirical regression models during the alternative analysis design phase in which distributories are developed from the existing remnant channel ("main channel").

The main channel is expected to range in bottom elevation from 3 feet NAVD88 near Port Susan Bay to 4.5 feet NAVD88 near its head, and to be approximately 50 feet wide. Tributary channels are assumed to have similar bottom elevations, but will be significantly narrower (e.g. 5 to 8 feet). Distances between channels are generally expected to exceed 500 feet, as are distances from channels to surrounding key surface-water features (e.g. Davis Slough and the South Pass of the Stillaguamish River).

Expected Salinities

Estimates of typical salinities in Port Susan Bay are shown on **Figure 3-2**. Hydrodynamic modeling by Battelle indicated that post-restoration salinities in the Leque Island vicinity are expected to remain similar to existing salinities (Yang et al, 2008). Battelle used their model to predict salinities at 6 locations in the Leque Island vicinity under restored conditions: 2 locations immediately south of the existing southern dike (outside of the restored area), 1 location in the restored "main" Leque Island channel, 2 locations east of the channel where land surface elevations are relatively low and 1 location west of the channel where land surface elevations are relatively high. Model predictions are shown on **Figure 4-2**, and suggest that salinities will remain below 10 ppt most of the time. South of the existing dike, both locations are expected to show short duration salinities in excess of 15 ppt, but average salinities still remain below 10 ppt over the time period analyzed by Battelle.

Land Cover

Leque Island has been fallow farmland for quite some time. Existing vegetation is expected to consist of a mix of perennial and annual grasses and forbs such as bentgrass. Perhaps some remnants of farming for cereal grains (e.g. barley, buckwheat, etc.) still remain. Post restoration plant communities are expected to be a mix of low and high salt marsh species including; gumweed, seaside arrowgrass, saltweed, salt grass, pickleweed, fleshy jaumea, and seaside plantain.

4.2 EFFECTS OF PROPOSED RESTORATION ON GROUNDWATER SYSTEM

PGG evaluated how the proposed restoration would affect groundwater levels and groundwater salinity in order to assess how changes in conditions on Leque Island might propagate to northeastern Camano Island (Section 5).

4.2.1 Estimated Effects on Salinity

The predicted salinities associated with inundation during restored conditions (discussed above) are very similar to the salinity measured in the central ditch on Leque Island and assumed representative of existing groundwater salinity. As discussed in Section 3.2.2, monitoring at the "Leque" ditch site showed EC values on the order of 18 mS/cm, which is correlated to a salinity of approximately 11 ppt. This value is very similar to predicted salinities during inundation. Thus, post-restoration groundwater salinities on Leque Island are expected to show little change from current salinities.

4.2.2 Summary of Hydrologic Changes

The hydrologic regime of the restored portion of Leque Island is expected to change in two significant ways: 1) recharge to the groundwater system will increase due to frequent inundation, and 2) drainage of the groundwater system will likely become more efficient due to evolution of a natural drainage network. These changes will affect the groundwater budget for the affected area, and the altered balance between recharge and discharge will likely affect groundwater levels.

Based on USGS analysis of natural (precipitation) recharge on Camano Island, existing recharge to Leque Island is unlikely to exceed 8 in/yr (Sumioka & Bauer, 2004). Under restored conditions, recharge will increase due to periodic inundation. The rate of inundation recharge will be a function of the daily duration of flooding, the permeability of surficial soils, and groundwater levels that develop beneath the inundated area. The maximum rate of recharge will occur when the soils are not saturated up to the land surface. Once the soils are fully saturated, additional recharge is impossible and further consideration of recharge under this condition is unnecessary.

The restored area is expected to be inundated an average of 5 hours/day. Leque Island is underlain by Puget Silty Clay Loam soils, which have an estimated saturated hydraulic conductivity (Ksat) range of 0.06 to 0.20 in/hr (**Table 3-2**). During inundation, the hydraulic gradient beneath the inundated area is likely to exceed 1 when soils are not fully saturated. Assuming a hydraulic gradient of 1 and 5 hours of inundation per day, the capacity for recharge is estimated to range from 0.3 to 1.0 in/day (100 to 365 in/yr) based on the following equation:

R = D*i*Ksat *(where R = daily recharge rate, D = flooding duration, i = hydraulic gradient)*

Where soils become saturated to land surface, recharge will be rejected and the above recharge rate will not be achieved. Where soils are not saturated to land surface, recharge rates may exceed the above estimate due to higher hydraulic gradients. In any case, the capacity for recharge to the restored portions of Leque Island is significantly enhanced from existing estimates (<8 in/yr) due to frequent inundation.

The capacity for drainage will likely be enhanced due to evolution of a drainage network with multiple tributary channels feeding into the existing main channel. Drainage efficiency is a function of the density of channels, the depth to which the channels penetrate the shallow groundwater system, and the hydraulic conductivity of the sediments which collect in the channel. Leque Island is currently drained by ditches which flow to the tide gates, as shown on **Figure 4-1**. Flow through the ditches is reportedly affected by clogging in various places, and current drainage efficiency is unknown. For example, it is unclear whether dry conditions observed at the "Leque" ditch location in October 2012 were due to slow drainage of the ditch network or drawdown of groundwater levels due to evapotranspiration. However, the density of drains under current conditions will likely be increased when ditches are replaced by natural tributary channels (**Figure 4-1**). In addition, whereas the current ditches have typical bottom elevations ranging from 4 to 4.5 feet NAVD88, the restored drainage system will likely have channel bottom elevations ranging from 3 to 4.5 feet NAVD88. Deepening of drainage features is likely to enhance the capacity of the drainage system (Peters, 2012).

The combined effects of increases in recharge capacity and drainage capacity will affect groundwater levels beneath Leque Island. The following analysis attempts to distinguish whether restoration is likely to cause groundwater levels to rise, stay the same, or fall.

4.2.3 Estimated Effects on Groundwater Levels

PGG developed a simple 2D groundwater flow model to estimate how groundwater levels beneath Leque Island are likely to respond to changes in recharge and drainage capacity. The model was developed using the USGS modeling code "MODFLOW2005" (Harbaugh, 2005) and the graphical user's interface "Groundwater Vistas" (ESI, 2012). The model slice is oriented vertically through Leque Island, and represents conditions between any two tidally influenced drainage features present under the restored condition (i.e. main channel, tributary channels, Davis Slough, Stillaguamish River). The model represents:

- Aquifer materials to a depth of -200 feet NAVD88;
- Tidally influenced drainage features;
- Recharge from inundation (rejected where saturation reaches the land surface); and,
- Deep aquifer discharge to marine water bodies.

The model design is illustrated on **Figure 4-3**. In plan view, the model is composed of a single row of 50 cells (10-foot square) cells. In cross-section view, the model includes 16 layers starting at the land surface (7 feet NAVD88) with 10-foot thickness down to an elevation of -103 feet NAVD88 and 20-foot thickness down to an elevation of -203 feet NAVD88. The model was run in transient (time varying) mode for a period of 100 days using 6-hour stress periods to represent the semi-diurnal tidal cycle[4]. Boundary conditions include MODFLOW's constant head (CHD), drain (DRN), general head (GHB) and recharge (RCH) boundaries.

CHD cells are used to represent tidal conditions in the drainage features, oscillating between the bottom drainage depth (assuming an average channel bottom elevation of 3.75 feet NAVD88) and high tide (assuming 8.5 feet NAVD88). The CHD cells are located in model layer 1 at the outside edges of the model domain (blue cells shown on **Figure 4-3**). **Figure 4-4** shows the water-level cycle specified for the CHD cells (shown in green), which is linearly interpolated by MODFLOW between high and low values in 6-hour, semi-diurnal pattern. Given MODFLOW's method of representing CHD cells, PGG selected high and low values that reasonably approximated the expected actual water-level or drain elevations in the channels. Although the modeled CHD values don't exactly match the expected drain stage elevations (shown in dashed magenta), the overall affect on the groundwater flow system is expected to be similar.

DRN cells are also specified in layer 1 for all cells between the CHD representation of channels. The DRN cells (yellow cells on **Figure 4-3**) are assigned a drainage elevation just above land surface and a very high drain conductance such that anytime modeled groundwater elevations reach 7.1 feet NAVD88 all additional recharge is drained off (rejected).

GHB cells provide a path for groundwater discharge to distant areas where deeper portions of the aquifer are exposed to submarine water in Port Susan and Skagit bays. GHB cells define a distant marine head (sea level = 4.4 feet NAVD88), a distance to the marine aquifer exposure (ranging from 15,000 to 23,000 feet based on bathymetric data), a cross-sectional area for the flow tube (equal to the layer thickness times the cell width), and a hydraulic conductivity for the groundwater system between the model cell and the marine aquifer exposure (set equal to the aquifer hydraulic conductivity, discussed below).

Recharge was applied to all cells in model layer 1 during the first 6-hour model stress period of each day of the transient simulation. Recharge was specified at the midpoint of the rates estimated above (Section 3.3.4), resulting in a daily recharge application of 0.65 in/day (0.13 in/hr x 5 hrs/day). While actual recharge due to inundation may occur at different times of any given day and during one or two periods

[4] 100 days was sufficient for the model to achieve a "cyclic steady state", such that predicted daily groundwater head variations were the same from one day to the next.

per day, simulation within one of the four daily 6-hour stress periods was most expedient and considered to be a reasonable representation of "loading" the aquifer with inundation recharge.

Aquifer properties assigned to model cells included hydraulic conductivity (K) and storage coefficient (S). K was divided into horizontal (K_h) and vertical (K_v) components, with the ratio between the two K_h/ K_v defining aquifer anisotropy. S was divided into specific yield (Sy) for the top model layer and specific storage (Ss) for the underlying layers. A number of aquifer property combinations were simulated with the model:

Model Simulation	K_h (ft/d)	K_v (ft/d)	Sy	Ss
"Slice-1"	20	2	0.15	0.00001
"Slice-2"	20	0.2	0.15	0.00001
"Slice-3"	60	6	0.15	0.00001
"Slice-4"	60	0.6	0.15	0.00001

The selected aquifer K values were considered conservatively high, in that they are likely higher than the predominantly silty sand sediments which dominate the flow system and reasonable for the sandy materials encountered immediately below the Puget Silty Clay Loam in Geodesign's borings B1 through B6. The S values were considered typical for unconfined (0.15) and confined (0.00001) conditions.

A profile of the predicted daily average water-table elevation along the 2D slice is shown on **Figure 4-5** for all four simulations. Predicted average daily water levels are depressed by up to 1.8 feet within the immediate vicinity of the channels (i.e. within 50 feet), whereas water-level drawdown is relatively small within a 50-100 foot buffer and insignificant beyond 100 feet of the channels. Transient model results were extracted for the "observation points" shown on **Figure 4-4** with the following findings:

- Daily water-level variations at a distance of 20 feet from the channels was predicted to range from about 1.3 to 2.2 feet depending on the aquifer properties simulated.
- Daily water-level variations at a distance of 50 feet from the channels was predicted to range from about 0.2 to 0.8 feet depending on the aquifer properties simulated.
- Daily water-level variations at a distance of 120 feet from the channels was predicted to be insignificant.

PGG compared the model predictions to inferred information regarding current groundwater level variations beneath Leque Island to estimate the long-term average change in hydraulic head beneath the island. There are two major differences between current and future groundwater level conditions:

1) Groundwater levels will be depressed in the immediate vicinity of channels in the future condition. In the current condition, available data suggest that existing ditches may not be efficiently draining the shallow aquifer, such that only minor water-level depression is expected near existing ditches.

2) Groundwater levels are currently interpreted to exhibit a seasonal fluctuation. Wet-season groundwater levels have been observed between 0 and 1 feet below land surface. Wet season water-levels at the "Leque" monitoring site were approximately 6.2 feet NAVD88 with a dry-season decline to below 4.8 feet NAVD88 (**Figure 3-4**). Once restoration creates daily tidal inundation, groundwater levels are expected to remain near the land surface without seasonal variation.

These differences are summarized on the following table, which was used to estimate weighted average groundwater elevations below Leque Island.

Condition	Location	Duration	Assumed Groundwater Elevation (Ft NAVD88)	Portion of Annual Condition (%)	Estimated Annual Weighted Average Groundwater Elevation (Ft NAVD88)
Current	Entire Site	Wet Season (8 mos)	6.2	67%	5.73
	Entire Site	Dry Season (4 mos)	4.8	33%	
Future	<50' from Ditches	Year Round	6.3	12%	6.92
	>50' from Ditches	Year Round	7	88%	

Averaging for the current condition is based on temporal variation, where most of the island is assumed to have similar groundwater elevations due to poor drainage efficiency of ditches. Although the actual timing distribution is unknown, PGG assumed a representative seasonal high:low ratio of 8:4 months. Averaging for the future condition assumes no significant temporal variation, but assumes that groundwater levels within 50 feet of channels are depressed by an average of 0.7 feet (**Figure 4-5**). PGG used GIS to estimate that ±50-foot ditch buffers represent about 12 percent of the site. The time- and spatially-weighted averages of water-level elevations suggest that average annual groundwater elevations under restored conditions will likely be about 1.2 feet higher than under the current condition, with an average annual groundwater elevation of about 6.9 feet NAVD88.

5.0 EFFECTS ON CAMANO ISLAND GROUNDWATER

PGG developed and calibrated a 3D groundwater flow model to predict how increased groundwater levels beneath Leque Island will affect groundwater flow and saltwater intrusion potential along the eastern edge of Camano Island. The model domain includes the northeast lobe of Camano Island, the Leque Lowland and the adjacent coastal portion of the mainland (the Stillaguamish Delta and glacial uplands). PGG created 4 versions of the model to address hydrogeologic uncertainty. Because deeper hydrostratigraphy is not well defined beneath the Leque Lowland, PGG created one version ("GS") in which deeper glacial/interglacial stratification defined beneath Camano Island is extended throughout the model domain and another version ("LA") in which lowland sediments are represented based on textural observations from borehole logs and stratification (or interbedding) is handled through assigned anisotropies (the ratio of horizontal to vertical hydraulic conductivity). Because the impacts of Leque Island restoration may be sensitive to the degree of hydraulic connection between shallow groundwater and surface-water features, two versions of each model were created to represent a range of hydraulic connection (the "C" versions have more hydraulic connection than the "D" versions). All four versions of the model (GS-C, GS-D, LA-C, LA-D) were run to evaluate hydraulic impacts on Camano Island groundwater due to Leque Island restoration.

This section provides an overview of the model design, calibration and predictive results. A more detailed account of the model development and application is presented in **Appendix C**.

5.1 MODEL DESIGN

The groundwater flow model was developed using the U. S. Geological Survey's finite difference modeling code "MODFLOW-2005" (Harbaugh, 2005). This code was selected it is widely accepted, well validated and technically defensible. PGG used Groundwater Vistas 6.0, a Graphical User Interface (GUI), for processing and viewing input and output MODFLOW files (ESI, 2012). The model was run in steady-state mode to simulate average annual conditions.

The total model domain covers approximately 69 square miles, with a north-south dimension of 10 miles and an east-west dimension of 6.8 miles. The model grid consists of 98 rows, 85 columns and 16 layers which extend from the land surface down to -200 feet NAVD88. Horizontal cell dimensions range from 125 feet in the Leque Lowland to 1500 feet on the edges of the model domain, and layer thickness range from 10 to 20 feet. **Figure 5-1** shows the model grid and boundary conditions.

The model uses a variety of MODFLOW packages to represent recharge, evapotranspiration (ET) from plants with roots tapping the shallow water table, groundwater withdrawals, drainage ditches, other inland surface-water features (Davis Slough and the Stillaguamish River), and marine bodies such as Port Susan Bay and Skagit Bay. Recharge, ET and pumping were represented with MODFLOW's "Recharge", "ET" and "Well" boundary condition packages. The Stillaguamish River was represented with MODFLOW's "River" boundary condition package. Drainage ditches, Davis Slough and submarine springs discharging to Port Susan and Skagit bays were all represented with MODFLOW's "Drain" package.

Aquifer properties reflected published estimates and observed sedimentary textures. Key hydraulic properties included horizontal and vertical hydraulic conductivities of aquifers (K_h and K_v), the hydraulic conductivity of the riverbed (K_r), and hydraulic conductivities associated with both freshwater and marine drain cells (K_{dr}). The effect of all of these parameters on the model was evaluated using sensitivity analysis, and the more sensitive parameters were varied during model calibration.

5.2 MODEL CALIBRATION

The model was calibrated to available groundwater level observations, measured upward vertical gradients beneath the monitoring site, field observation of relatively low discharge from the monitoring-site drains and standard calibration statistics. Observations used for calibration are called “targets” and departures from these observations are called “residuals”. Although available groundwater level data are limited in their ability to represent long-term average annual conditions, calculated residuals were considered reasonably good and the calibration was considered to be acceptable. **Figure 5-2** presents model-predicted shallow groundwater levels and calculated residuals for model version GS-C. Results for other versions of the model were similarly good and are presented in **Appendix C**.

Groundwater contours from the calibrated models show higher groundwater levels on Camano Island relative to the adjacent lowland, thus representing groundwater flow from the upland to the lowland. Upward gradients were also predicted beneath the monitoring site, and discharge to monitoring-site ditches did not exceed general field observations. Note that the model predicts a small groundwater mound off the southeast corner of the Camano Island upland due to locally elevated values of recharge predicted by the USGS. PGG did not attempt to assess the accuracy of this local perturbation in USGS recharge estimates.

5.3 PREDICTIVE RESULTS

PGG used all four versions of the model to predict the impacts of Leque Island restoration on groundwater conditions beneath Camano Island. Restoration was simulated by replacing the modeled drains in layer 1 within Leque Island with a large area of constant head cells covering most of the island. The constant head cells had a specified head of 6.9 feet NAVD88, consistent with PGG’s estimation of post-restoration average groundwater levels on Leque Island (Section 4.2.3). **Figure 5-3** presents the predicted model results for selected versions of the model (see **Appendix C** for all results). The figure shows predicted drawdowns associated with increased heads on Leque Island (negative drawdowns indicate a groundwater rise) and arrows showing the directions of groundwater flow. All results are shown for the shallowest portion of the groundwater flow system (Layer 1), but are very similar in underlying layers. The model simulations predict that:

- Increased groundwater levels beneath Leque Island do not cause a reversal of groundwater flow directions on the eastern edge of Camano Island. The model predicts that post-restoration groundwater flow remains from Camano Island towards the Leque Lowland,
- Groundwater changes on Camano Island due to Leque Island restoration are less than 0.1 feet.

Both of those predictions suggest no significantly increased potential for saltwater intrusion beneath eastern Camano Island. Continued groundwater flow from Camano Island to the Leque Lowland means that brackish groundwater beneath the lowland would not migrate to aquifers beneath Camano Island. Although the predicted rise in groundwater elevation beneath Camano Island is very small, increased groundwater heads generally result in reduced potential for saltwater intrusion based on the Ghyben-Herzberg relationship (Davis & De Wiest, 1966), whereby higher freshwater hydraulic heads cause the saltwater interface to deepen, thereby thickening the freshwater lens. The effects of this mechanism are likely to be negligible, but should not be viewed as adverse.

5.4 MODEL LIMITATIONS

Design and calibration of the 3D groundwater flow model are based on currently available information that has some limitations. As previously mentioned, the deeper portions of the groundwater flow system are not well characterized, water-level data available for steady-state calibration are limited to shorter-term data records, variable–stage drainage ditches crossing the monitoring site have only been surveyed at 3 locations, and discharge from the drainage ditches has not been rigorously measured. PGG attempted to address these uncertainties by generating different versions of the model and by accepting slightly larger residuals during model calibration. All 4 versions of the model provided reasonable agreement with observed calibration targets; however, it should be recognized that other depictions of the groundwater flow system are possible and PGG's model representations are non-unique. Nevertheless, all 4 model predictions suggested no significant impact of Leque Island restoration on Camano Island groundwater conditions. Predicted impacts on the groundwater system near Camano Island were so small that other reasonable model configurations are also unlikely to show significant impact.

The 3D model was run in steady-state mode, and therefore does not simulate seasonal variations. The largest relative rise in Leque Island groundwater levels will occur in the summer months, as current conditions exhibit seasonally depressed groundwater levels whereas future conditions will maintain high groundwater levels due to daily inundation. While PGG did not attempt to simulate summer conditions, model predicted impacts for average annual conditions were so small that significant summer impacts are unlikely. Additionally, greater groundwater level rises on Leque Island during summer months will be counteracted by increased evapotranspiration rates in the lowland area between Leque and Camano island during the same season.

REFERENCES

Berg, Raymond. 2012. WDFW Capital and Asset Mgt Program. Email communication with Peter Schwartzman of Pacific Groundwater Group on October 31, 2012.

Davis, Stan and Roger DeWiest, 1966. Hydrogeology. John Wiley & Sons, Inc.

Daly, Christopher, Neilson, R.P., and Phillips, D.L., 1994, A statistical-topographic model for mapping climatological investigation over mountainous terrain: Journal of Applied Meteorology, v. 33, p. 140-158.

Driscoll, Fletcher G. 1986. Groundwater and wells - 2nd edition. Johnson Screens Wheelabrator.

ESI (Environmental Simulations Inc.). 2012. Groundwater Vistas Version 6.27, www.groundwatermodels.com.

Geodesign, Inc. 2007. Report of geotechnical engineering services, Leque Island restoration (DU project WA-62-2), Snohomish County, Washington. Report prepared for Ducks Unlimited, October 15 2007, Geodesign Project DU 7 01.

Geodesign, Inc. 2008. Report of geotechnical engineering services, Leque Island restoration (DU project WA-62-2), north tidal restoration, Snohomish County, Washington. Report prepared for Ducks Unlimited, March 28 2008, Geodesign Project DU 7 02.

Harbaugh, A.W., 2005, MODFLOW-2005, the U.S. Geological Survey modular ground-water model -- the Ground-Water Flow Process: U.S. Geological Survey Techniques and Methods 6-A16.

Island County, 2001. Island County water resource management plan, 2514 watershed planning, adopted June 20, 2005, appendix C: early action plan (2001). http://www.islandcountyeh.org/Uploads/FKCEditor/file/Watershed%20Plan%20-%20APPENDIX%20C.pdf

McIntyre, Brian. 2012 . Owner of the monitoring site property. Personal communication with Peter Schwartzman of Pacific Groundwater Group on October 10, 2012.

Peters, Graham. 2012. Ducks Unlimited. Personal communication with Peter Schwartzman of Pacific Groundwater Group, multiple occasions.

PWA (Phillip Williams & Associates), 2011. Puget Sound nearshore ecosystem restoration project, strategic restoration conceptual engineering – design report, appendix c: applied geomorphology guidelines and hierarchy of openings.

Sapik, D.B.; Bortleson, G.C.; Drost, B.W.; Jones, M.A.; Prych, E.A., 1988. Groundwater resources and simulation of flow in aquifers containing freshwater and seawater, Island County, Washington. U.S. Geological Survey Water-Resources Investigations Report 87-4182.

Schasse, Henry W.; Kalk, Michael L.;Polenz, Michael, 2009, Geologic map of the Juniper Beach 7.5-minute quadrangle, Island County, Washington: Washington Division of Geology and Earth Resources Geologic Map GM-70,1 sheet, scale 1:24,000.

Shannon & Wilson, Inc. 2009. Geotechnical design memorandum GD-6, SR532 corridor improvements project, Camano Island to I-5, Island and Snohomish Counties, Washington, General Mark W. Clark Memorial Bridge Foundations. Technical Memorandum prepared by Shannon & Wilson, Inc., Geotechnical Consultant for Parsons/Kuney Joint Venture. Final Submittal dated September 24, 2009.

Sumioka, S. S. and Bauer, H. H., 2004. Estimating ground-water recharge from precipitation on Whidbey and Camano Islands, Island County, Washington, water years 1998 and 1999. U.S. Geological Survey Water-Resources Investigations Report 03-4101. Prepared in cooperation with the Island County Health Department.

Thomas, B.E.; Wilkinson, J.M. and Embrey, S.S., 1997. The ground-water system and ground-water quality in western Snohomish County, Washington. U.S. Geological Survey Water-Resources Investigations Report 96-4312 Prepared in cooperation with Snohomish County Public Utilities District No. 1 of Snohomish County and Washington State Department of Ecology.

Rotton, Belinda. 2012. Personal communication with Peter Schwartzman of Pacific Groundwater Group (multiple phone conversations).

USDA (U.S. Department of Agriculture, 1985. State of Washington Irrigation Guide: Appendix A, Climatic Stations for Consumptive Use.

WSDOT (Washington Department of Transportation), 2012. SR 532 corridor improvements design build project website, link to “preliminary bridge data - Gen. Mark. W. Clark” http://www.wsdot.wa.gov/biz/contaa/DESIGNBUILDCONTRACTS/SR532/

Yang, Zhaoqing; Khangaonkar, Tarang and Lee, Cheegwan. 2008. Hydrodynamic modeling analysis for Leque Island restoration feasibility study. Technical report prepared by Battelle Memorial Institute in January 2008.

Table 3-1
Summary of Monitored Wells

WELL ID	Well Depth (ft)	Well Diameter (in)	Screen Interval (ft bls)	Drilling Method	Measuring Point	Measuring Point Elevation (ft)	Typical Static Depth to Water (ft)	Northing	Easting
N1S	25	2	12-17	geoprobe	top of pvc casing	7.18	1.2	455136	1260701
N2D	61	2	50-60	hollow stem	top of pvc casing	9.85	4.0	455225	1260263
N2S	25	2	20-25	geoprobe	top of pvc casing	9.85	4.2	455225	1260263
N3S	25	2	15-25	geoprobe	top of pvc casing	6.61	1.4	455210	1259745
S1D	45	2	35-45	hollow stem	top of pvc casing	8.44	1.5	453574	1259972
S1S	25	2	15-25	geoprobe	top of pvc casing	8.37	1.5	453574	1259972
S2S	30	2	24-29	geoprobe	top of pvc casing	8.83	2.2	453528	1259192
S3S	30	2	8-13	geoprobe	top of pvc casing	9.93	3.0	453450	1258900
HAMBRE	NL	6	NL	NL	well cap	76.67	56	456576	1258391
MCINTYRE	33	6	23-33	cable tool	well cap	11.86	5	453235	1258677
OKSENDAHL	90	6	85-90	NR	well cap	74.13	67.1	455663	1258651

NL = no log, NR = not reported, bls = below land surface
Horizontal Datum = WA State Plane NAD83/07
Vertical Datum = NAVD88
Geoid Model = GEOID03

Table 3-2
Summary of Study Area Soils

Map Unit Symbol	Map Unit Name	Component	Landform	Parent Material	Slope (%)	Depth to Water Table (in)	Frequency of Flooding	Drainage Class	Depth to Restrictive Feature (in)	Capacity of the most limiting layer to transmit water (Ksat)	Typical Profile
1018	Coupeville-Mitchellbay, cool, complex, 0 to 5 percent slopes	Coupeville	valleys	glacial drift over dense glaciomarine deposits	0 to 5	0 to 8	none	poorly drained	40 to 60	Very low to moderately low (0.00 to 0.06 in/hr)	loam over clay loam over silty clay loam
		Mitchelbay, cool	valley sides	Glacial drift over dense glaciomarine deposits	0 to 5	4 to 12	none	Somewhat poorly drained	20 to 40	Very low to moderately low (0.00 to 0.06 in/hr)	gravelly sandy loam over sandy loam over loam
1023	Coupeville loam, 0 to 3 percent slopes		valleys	Glacial drift over dense glaciomarine deposits	0 to 3	0 to 8	none	poorly drained	40 to 60	Very low to moderately low (0.00 to 0.06 in/hr)	loam over clay loam over silty clay loam
1054/55	Puget silty clay loam, 0 to 2 percent slopes		tidal flats	alluvium	0 to 2	0 to 8	none	poorly drained	> 80	Moderately low to moderately high (0.06 to 0.20 in/hr)	silty clay loam
2019	Mitchellbay gravelly sandy loam, cool, 2 to 10 percent slopes		hillslopes	Glacial drift over dense glaciomarine deposits	2 to 10	4 to 12	none	Somewhat poorly drained	20 to 40	Very low to moderately low (0.00 to 0.06 in/hr)	gravelly sandy loam over sandy loam over loam
3017	Everett-Alderwood complex, 3 to 15 percent slopes	Everett	hillslopes	glacial outwash	3 to 15	> 80	none	somewhat excessively drained	> 80	High (1.98 to 5.95 in/hr)	sandy loam over gravelly sandy loam over very gravelly coarse sand over extremely gravelly coarse sand
		Alderwood	hillslopes	Glacial drift over dense glaciomarine deposits	3 to 15	12 to 20	none	moderately well drained	20 to 40	Very low to moderately low (0.00 to 0.06 in/hr)	extremely gravelly sandy loam over extremely gravelly coarse sandy loam over gravelly silty clay loam
3022	Aquic Dystroxerepts-Oxyaquic Xerorthents complex, 15 to 70 percent slopes	Aquic Dystroxerepts	Hillslopes, sea cliffs	Beach sand and colluvium from glacial drift	15 to 70	16 to 28	none	moderately well drained	40 to 60	Very low to moderately low (0.00 to 0.06 in/hr)	sligthly decomposed plant material over sand over very fine sandy loam
		Oxyaquic Xerorthents	Sea cliffs, sea cliffs	Beach sand and colluvium from glacial drift	15 to 70	16 to 28	none	Somewhat poorly drained	> 80	Moderately high to high (0.28 to 10.91 in/hr)	decomposed plant material over loamy sand over silt loam over fine sandy loam
20	Fluvaquents, tidal		tide flats	alluvium	0 to 2	0	frequent	poorly drained	> 80	Moderately low to moderately high (0.06 to 0.20 in/hr)	silt loam over stratified sand to silty clay
1025/3008	Beaches-Endoaquents, tidal-Xerorthents association, 0 to 5 percent slopes	Xerothents	beaches	Beach sand and colluvium from glacial outwash	0 to 5	> 80	none	excessively drained	> 80	Very high (19.98 to 99.90 in/hr)	very gravelly sand
		Endoaquents, Tidal	beaches	beach sand	0 to 2	0	very frequent	very poorly drained	> 80	Very high (19.98 to 99.90 in/hr)	gravelly sand over gravelly coarse sand over extremely graveey coarse sand
		Beaches	beaches	beach sand	0 to 5	0	very frequent	NR	NR	NR	Stratified sand to gravel

NR = not reported

Table 3-3
Summary of Surficial Geologic Units

Map Symbol	Name	Era	Detailed Description
af	Fill	Holocene	Clay, silt, sand, gravel, organic matter, rip-rap, and debris placed to elevate and reshape the land; includes engineered and nonengineered fills; shown where fill is readily verifiable, relatively extensive, and appears sufficiently thick to be geotechnically significant.
Qb	Beach Deposits	Holocene	Sand and cobbles; may include boulders, silt, pebbles, and clay; pebbles and larger clasts typically well rounded and oblate; mostly well sorted; loose; derived from shore bluffs and underlying deposits and (or) carried in by longshore drift.
Qa	Alluvium and estuarine deposits	Holocene	Sand, silty sand, silt, silty clay, and clay; loose and soft; sand is fine to very fine grained; sand and silt are gray to olive gray; clay is bluish gray with various admixtures of organic materials; levees have converted parts of the map area underlain by these deposits to agricultural use; unit consists of deltaic deposits near the mouth of the Stillaguamish River in the northeast corner of the map area.
Qm	Marsh deposits	Holocene	Mostly soft to stiff, olive gray to gray silt and silty clay and bluish gray clay, commonly with lenses and layers of peat, muck, and other organic material; deposited in a saltwater or brackish marsh (estuarine or lagoonal) environment; deposits occur near highest tide levels and are covered with salt-tolerant vegetation or floated logs (particularly at Elger Bay). Many of these deposits (at the north end of Port Susan) have been converted to agricultural use by construction of levees. Contacts between marsh and Stillaguamish River deltaic deposits (unit Qa) are commonly gradational or masked by agricultural modifications.
$Qgdm_e$	Everson Glaciomarine Drift, undivided	Pleistocene - Everson Interstade	Clayey to silty diamicton with variable content of gravel clasts; also includes silt, clay, and sand; contains sparse shells, generally marine; dark gray where unweathered; mostly weathers to buff, but ranges to olive gray, ash gray, or white; commonly forms dry, vertical face with failure-prone, vertical desiccation cracks with dark brown staining; best exposures along east shores of Triangle Cove and Livingston Bay; massive to rhythmically bedded, commonly with sharp upper and lower, unit-bounding unconformities (Domack, 1984); mostly loose and soft, but locally hard and compact. May resemble till (Domack, 1982, 1984; Domack and Lawson, 1985), but in general, till lacks fossils and glaciomarine drift has a finer-grained, smoother-feeling matrix, is less compact, and more likely to be stratified. Unit is sea-floor sediment and consists mostly of glacial flour. Its textural diversity reflects proximity of the ice front (Domack, 1983; Dethier and others, 1995).
Qgt_v	Till	Pleistocene - Vashon State	Typically unweathered, unsorted mixture of clay through boulder-size material (diamicton) deposited directly by ice; includes extensive areas of compact (advance outwash?) sand; compact, well-developed facies resemble concrete; locally ranges to loose in ablation till (also separately mapped as unit Qgtaf) and well-sorted in some sand-dominated areas; erratic boulders common on surface; gray where fresh; oxidizes yellowish brown; permeability very low in compact diamicton but locally high in sandy or loose facies; most commonly matrix supported; cobbles and boulders commonly faceted and (or) striated; may include flow banding; typically forms vertical faces in coastal bluffs; locally resembles unit Qgdme (see that unit). Most till deposits have had their surface fluted by overriding ice and form a patchy and seemingly randomly distributed cover that varies from 0 to at least 100 ft thick (as reflected in some water well records), with 2 to 30 ft most common. Cliff exposures along the west shore of Whidbey Island about 7 mi southwest of the map area reveal that even where well developed and
$Qgas_v$	Advance outwash sand	Pleistocene - Vashon State	Mostly lacustrine sand with layers of silt; well-stratified; gray; thick exposures display well-developed crossbedding and cut-and-fill structures that are typical of this unit; locally coarsens upward into gravel; thickness is typically 80 ft; thick and extensive in subsurface, with maximum estimated thickness of approximately 200 ft; commonly forms angle-of-repose slopes along drainages and coastal bluffs. Unit is the most widespread lithology of advance outwash in the map area and includes the Esperance Sand and possibly the Lawton Clay, but the latter was not recognized by us in our mapping.

Unit descriptions reproduced from Shasse et al, 2009.

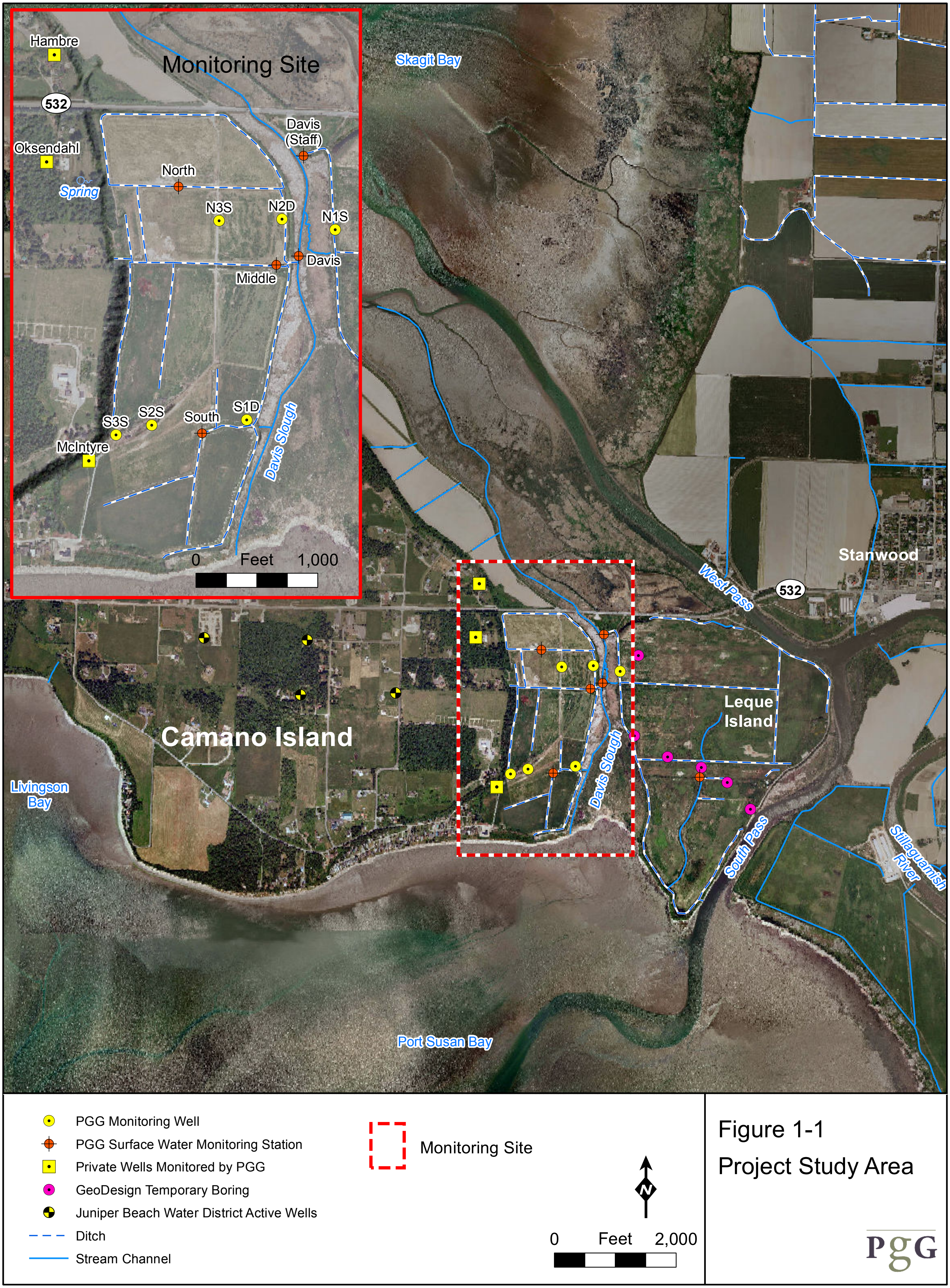
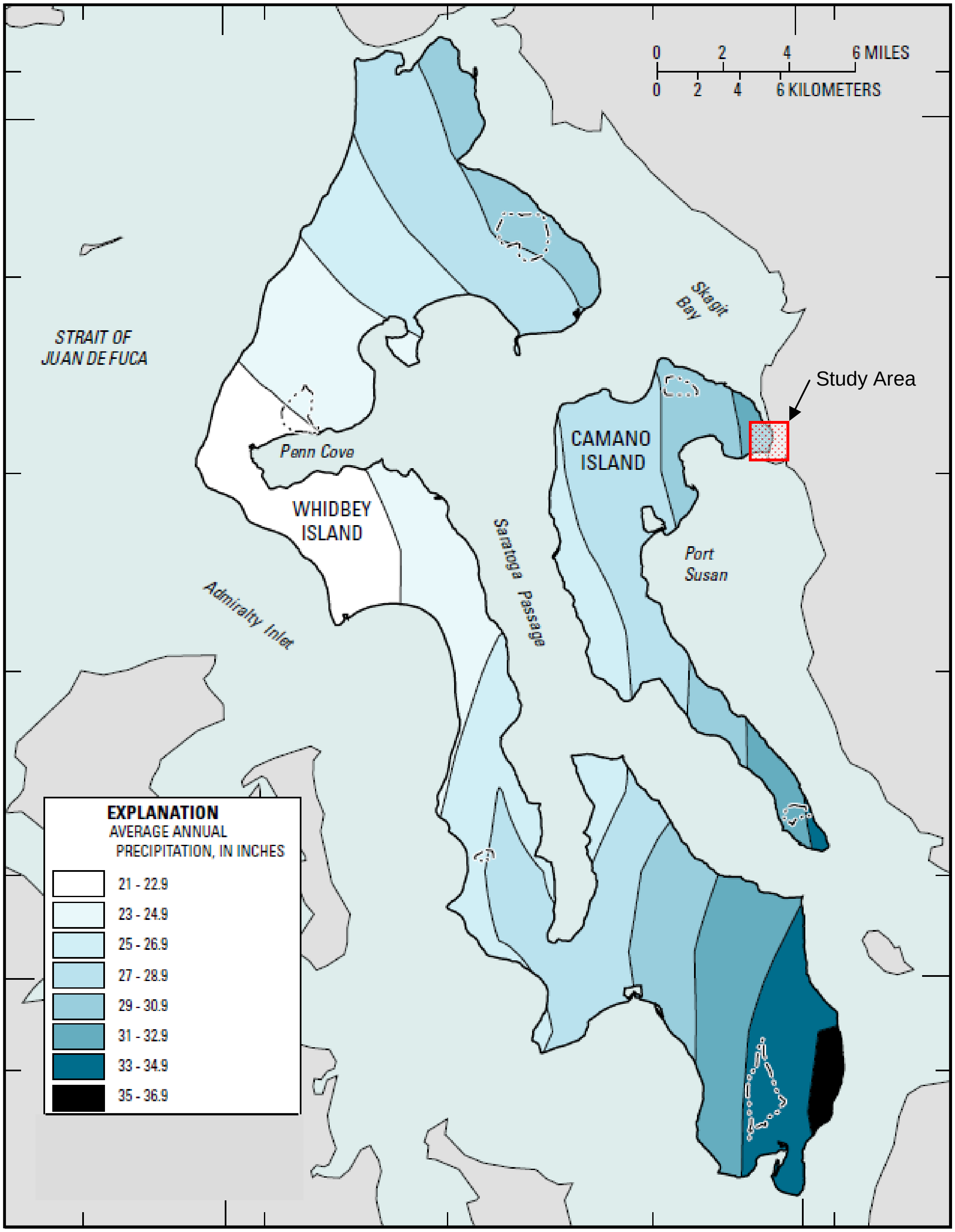


Figure 1-1

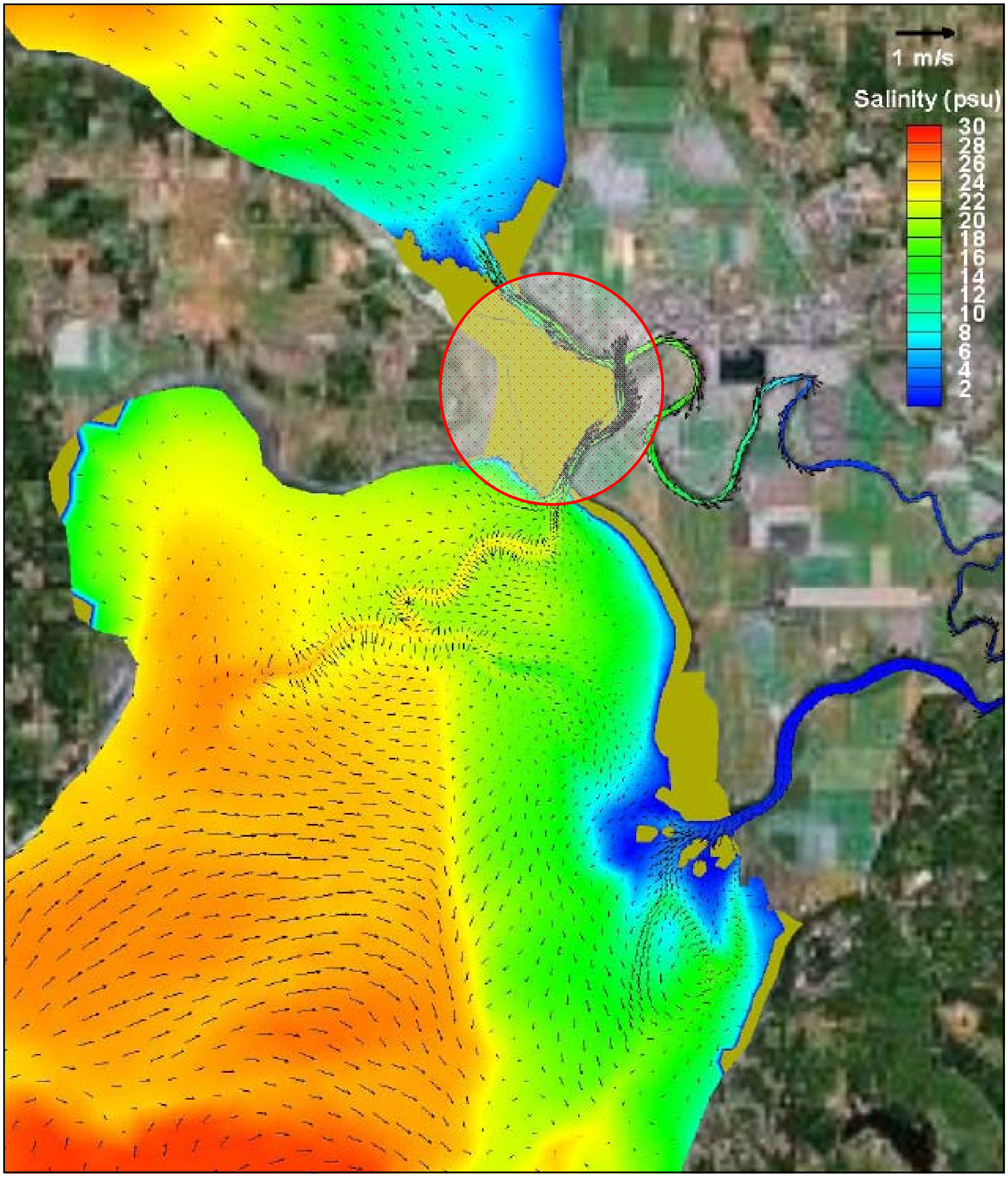
Project Study Area



NOTES:
Isohyetal map modified from Sumioka & Bauer, 2003.
Study area precipitation = 31—32.9 in/yr

Figure 3-1
Isohyetal Map

Ducks Unlimited
Leque Island Restoration



NOTES:
Modified from Yang et al, 2008.

- Leque Island Lowland

Figure 3-2
Predicted Salinity at High Tide for Existing Condition

Ducks Unlimited
Leque Island Restoration

PGG

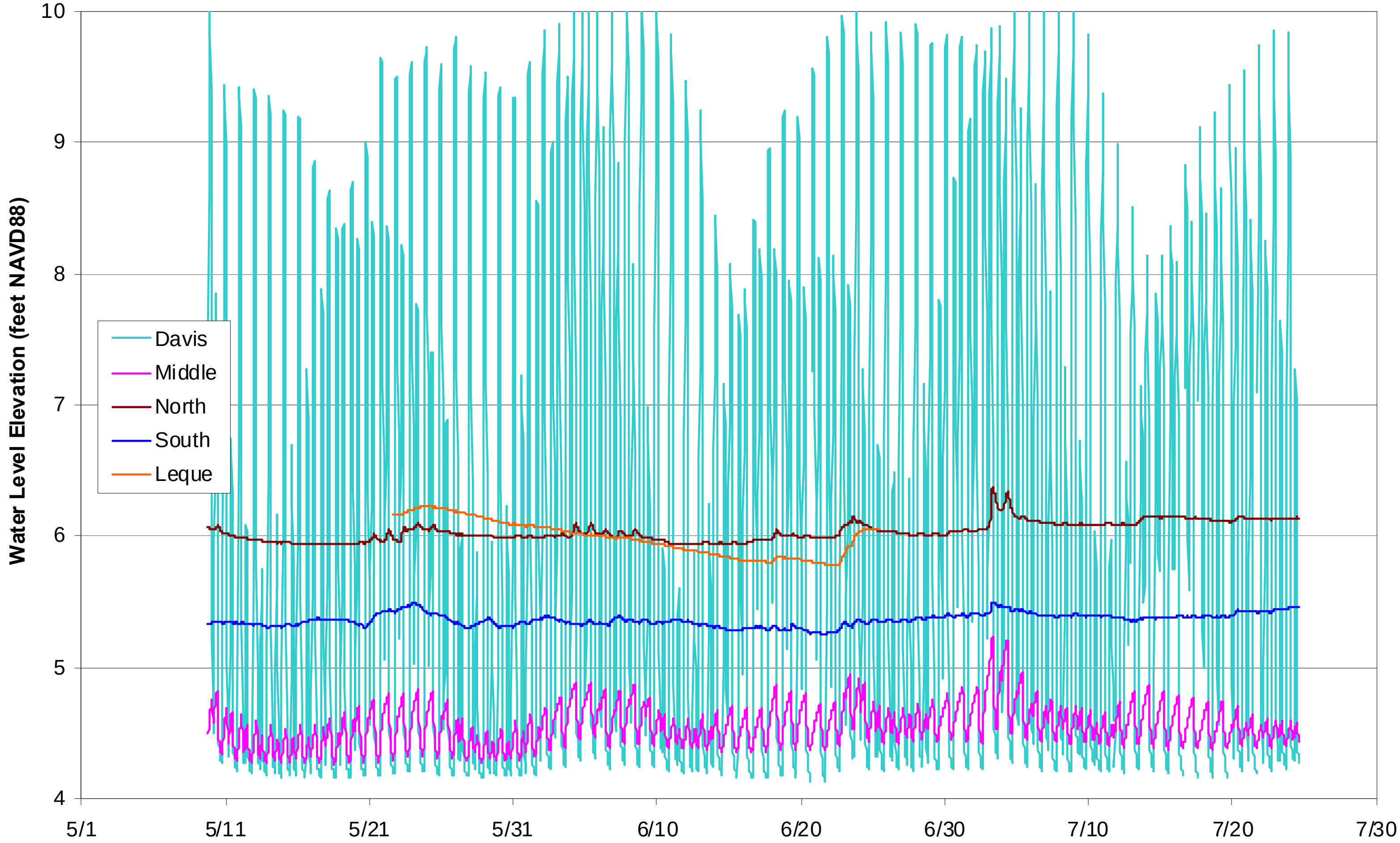
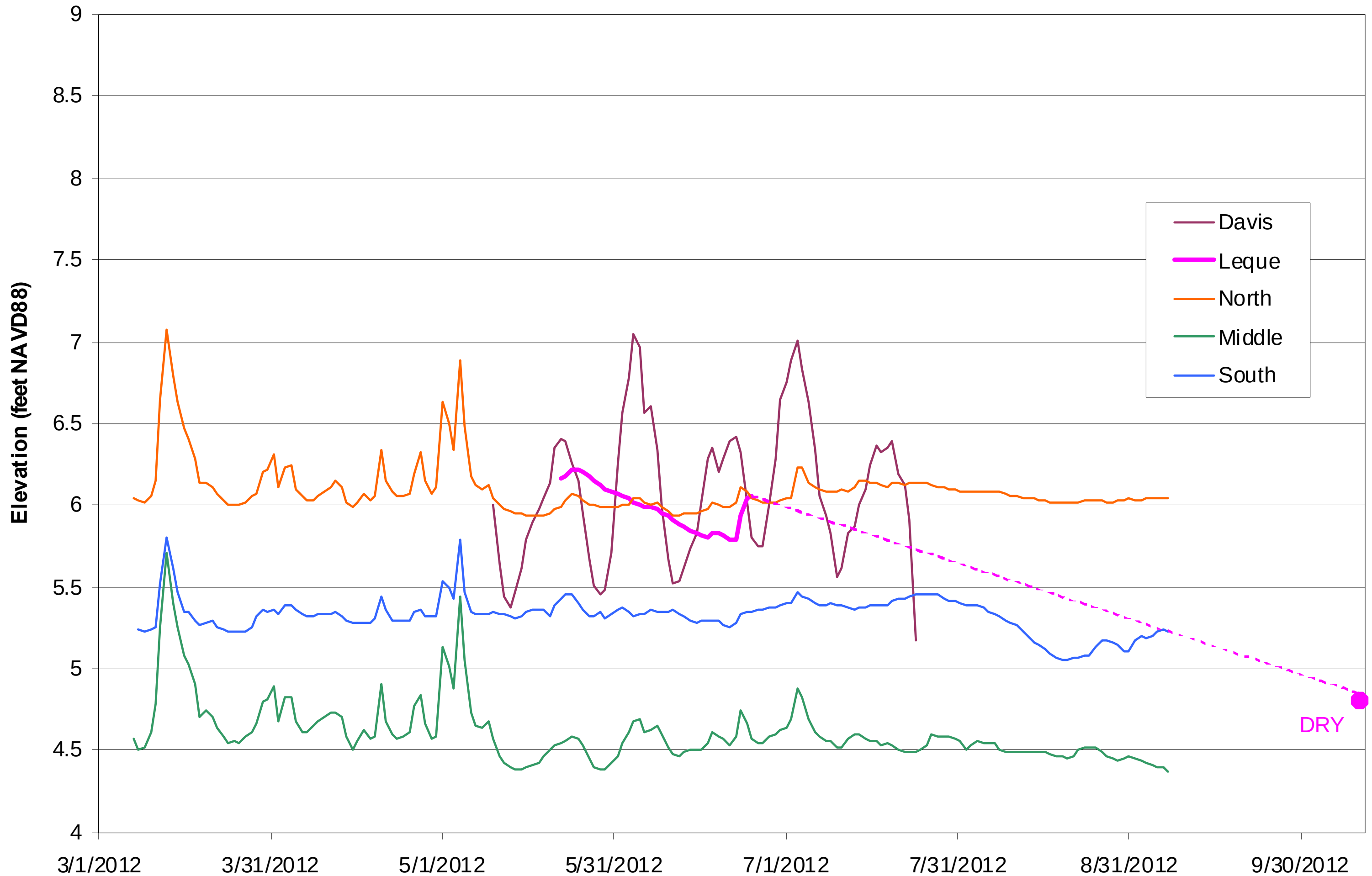


Figure 3-3
Water-Level Elevations in Ditches and Davis Slough

Ducks Unlimited
Leque Island Restoration

PGG



NOTES:
The “Leque” monitoring ditch was observed dry in early October 2012. The ditch bottom elevation is approximately 4.8 feet NAVD88.

Figure 3-4
Average Daily Water-Level Elevations in Monitored Ditches

Ducks Unlimited
Leque Island Restoration

PgG

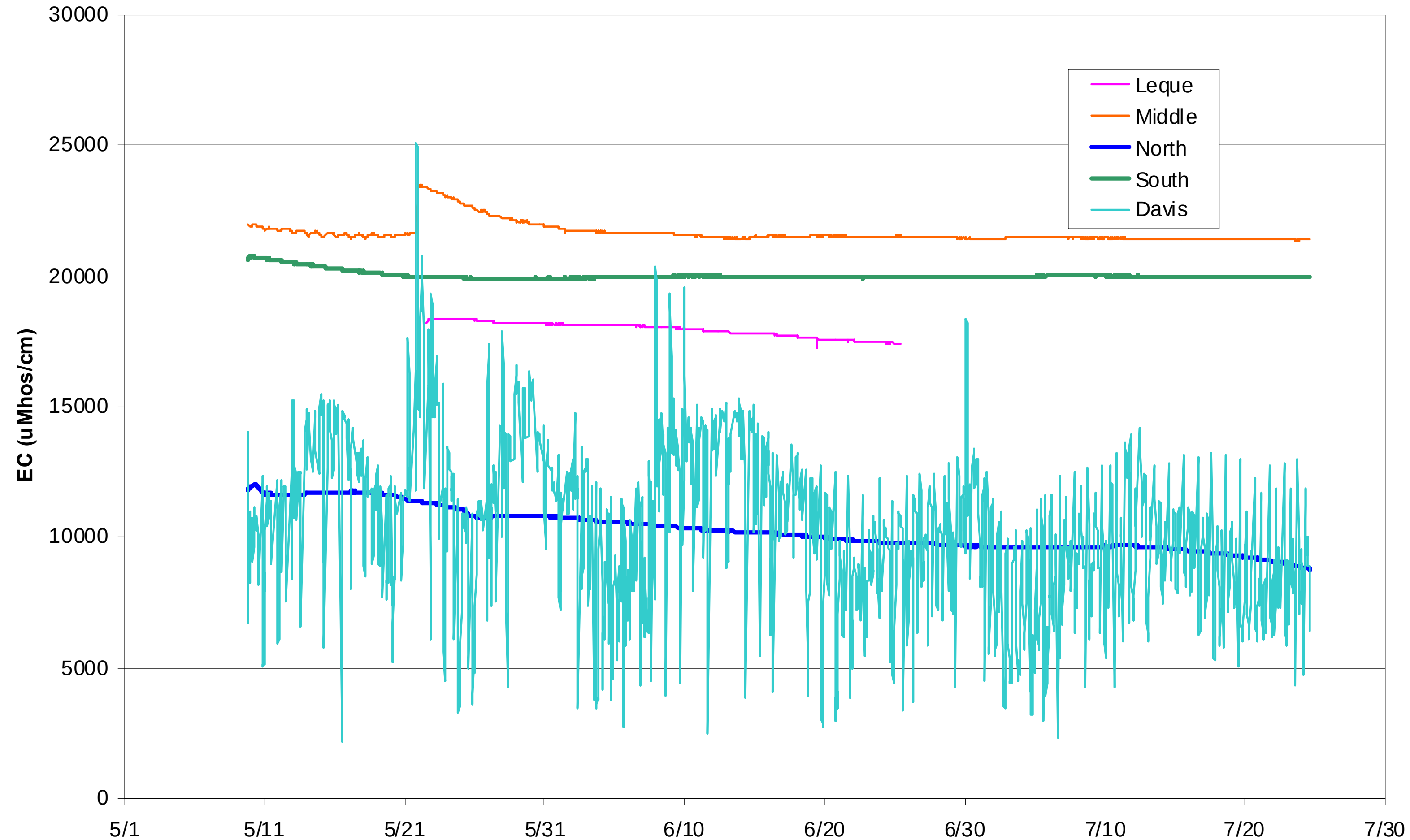
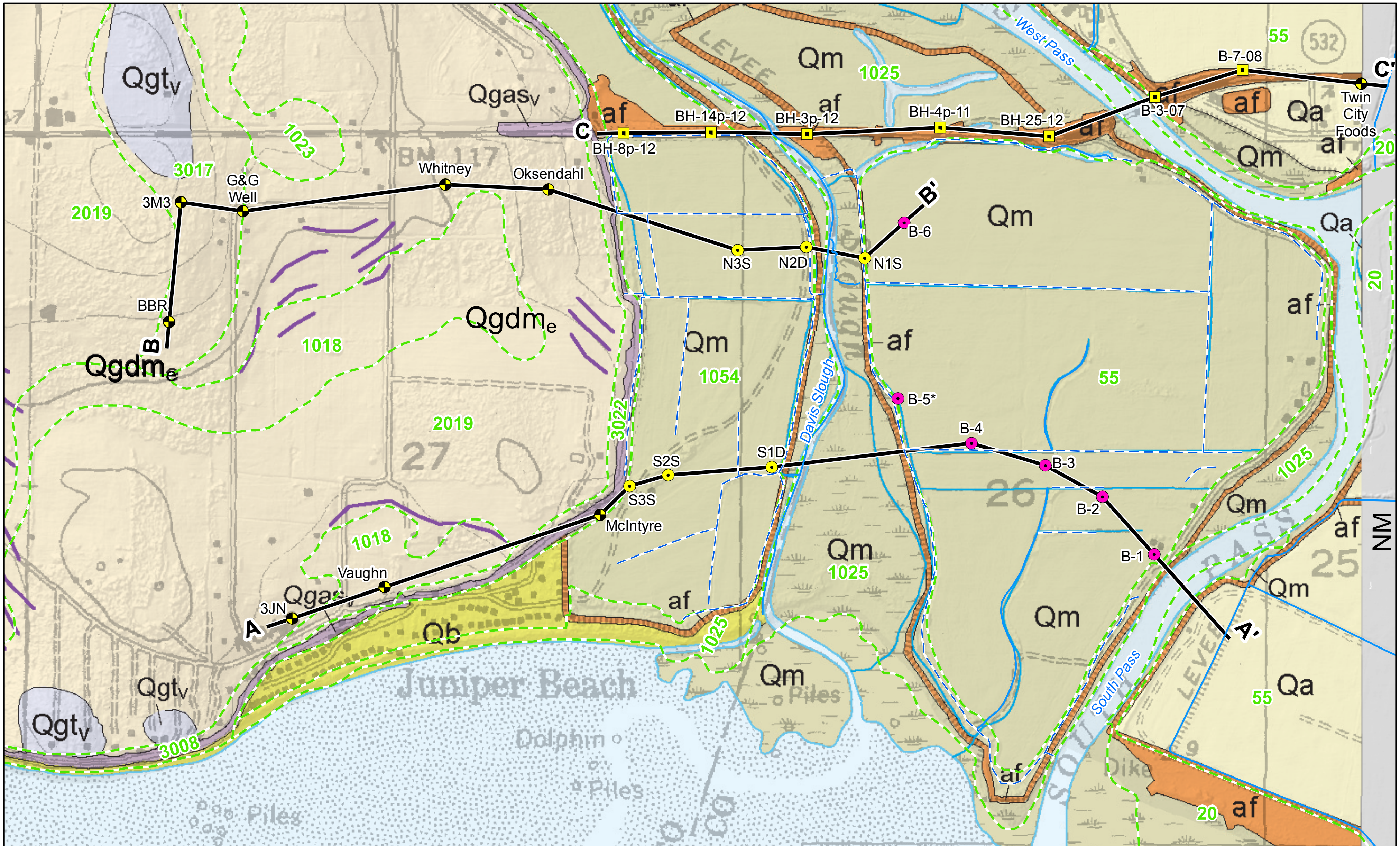


Figure 3-5
EC Trends at Surface-Water Monitoring Points

Ducks Unlimited
Leque Island Restoration

PgG



Cross Section Alignments		PGG Monitoring Well	
Ditch		Private Well	
Stream Channel		GeoDesign Temporary Boring	
55 Soil Unit & ID Number		WSDOT Boring/Piezometer	

* Well not used in Cross Sections

See Table 3-3 for Soil Descriptions

See Table 3-4 for Geologic Descriptions

Geology from from Schasse et al 2009

Surficial Geology

- af - Fill
- Qb - Beach deposits
- Qa - Alluvium and estuarine deposits
- Qm - Marsh deposits
- Qgdm$_e$ - Everson Glaciomarine Drift, undivided
- Qgt$_v$ - Till
- Qgas$_e$ - Advance outwash sand
- NM - Geology not included on map
- Former Strand

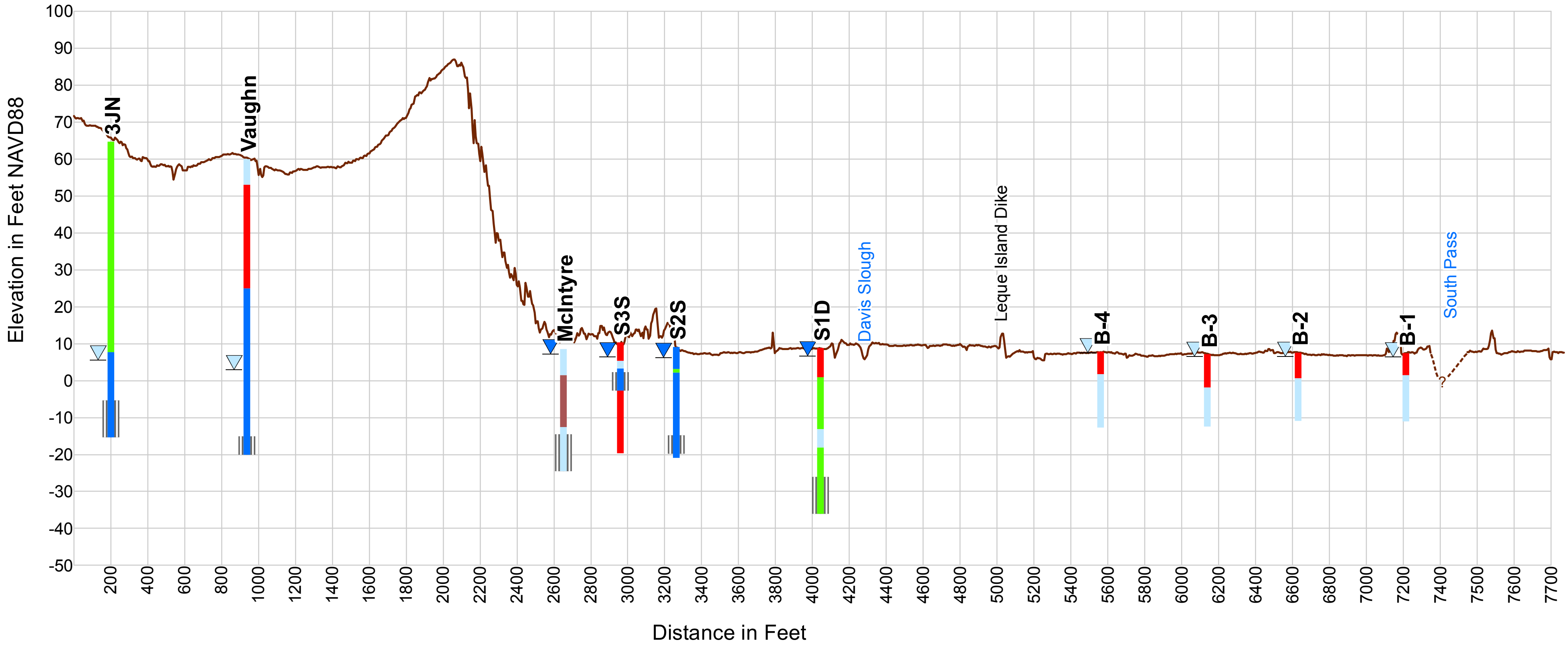
N

0 Feet 1,000

Figure 3-6

Surficial Geology & Soils

PGG



Sedimentary Texture
- Sand/Gravel
- Sand
- Sand/Silt (may also include some gravel)
- Silt/Gravel
- Silt/Clay
- Till

Land Surface (LiDAR)
Screen Interval
Water Level With Established Survey Control
Water Level Without Established Survey Control

Well locations and section traces on figure 3-6

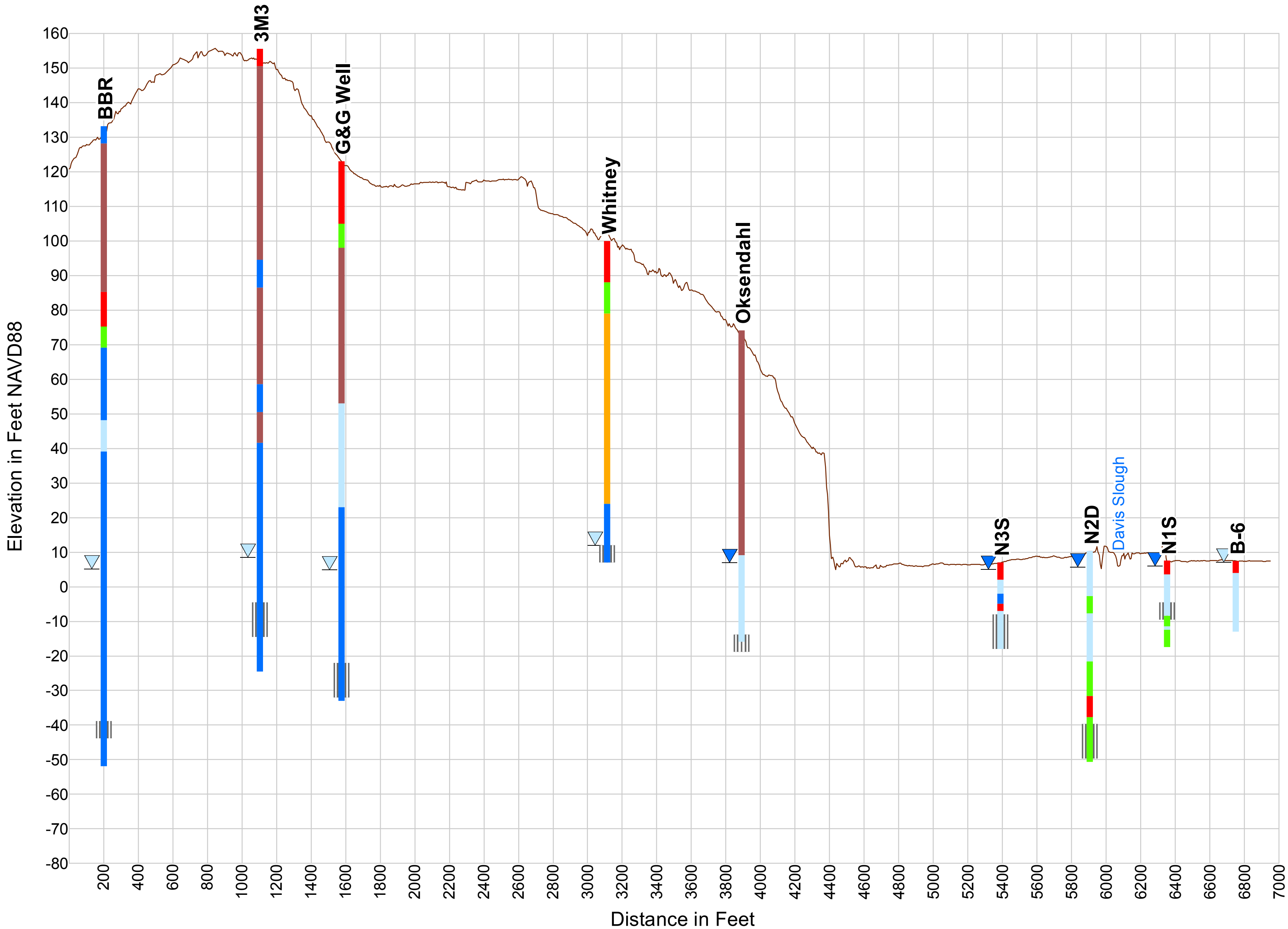
20x Vertical Exageration

Figure 3-7

Cross Section A-A'

Ducks Unlimited
Leque Island Restoration

PGG



Sedimentary Texture
- Sand/Gravel
- Sand
- Sand/Silt (may also include some gravel)
- Silt/Gravel
- Silt/Clay
- Till

- Land Surface (LiDAR)
- Screen Interval
- Water Level With Established Survey Control
- Water Level Without Established Survey Control

Well locations and section traces on figure 3-6

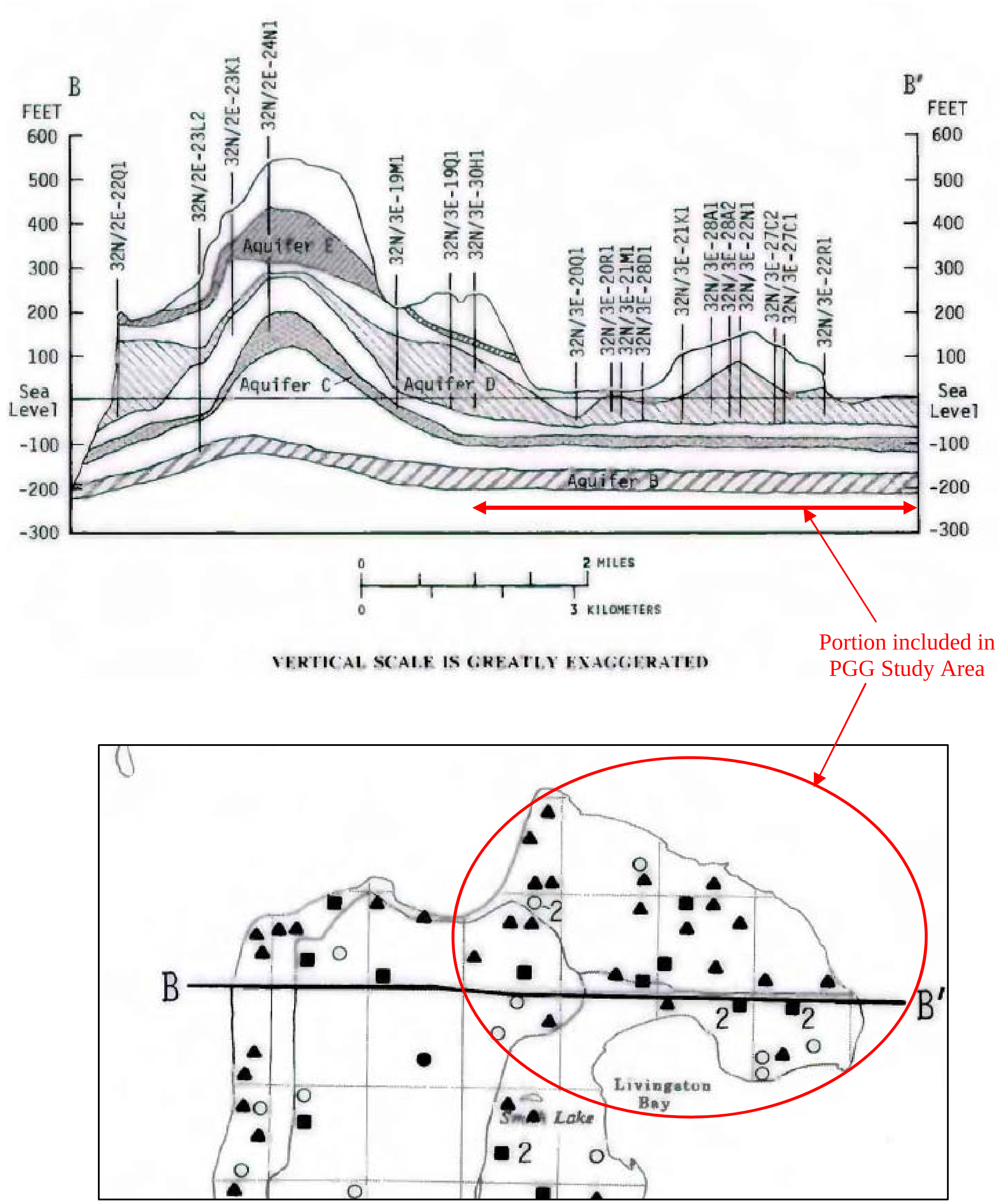
20x Vertical Exageration

Figure 3-8

Cross Section B-B'

Ducks Unlimited
Leque Island Restoration

PGG



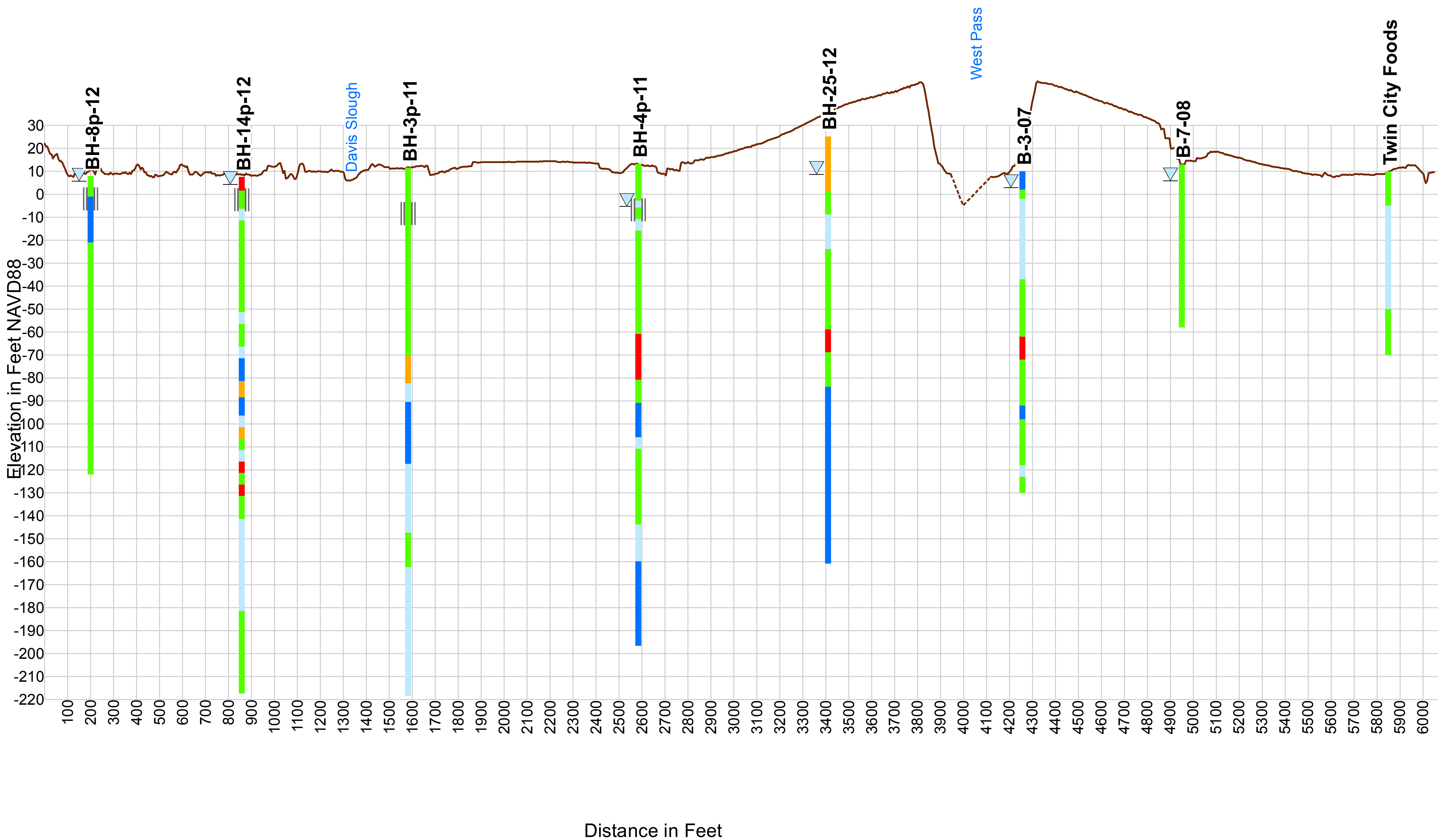
NOTES:

Reproduced and modified from Jones et al, 1985.

Aquitards (shown in white) are named similar to aquifers, with "Aquitard D" representing the low-permeability layer immediately *below* "Aquifer D".

Figure 3-9
Hydrogeologic Cross Section through Northern Camano Island

Ducks Unlimited
Leque Island Restoration



Sedimentary Texture

- Sand/Gravel
- Sand
- Sand/Silt (may also include some gravel)
- Silt/Gravel
- Silt/Clay
- Till

- Land Surface (LiDAR)
- Screen Interval
- Water Level With Established Survey Control
- Water Level Without Established Survey Control

Well locations and section traces on figure 3-6

20x Vertical Exageration

Figure 3-10

Cross Section C-C'

Ducks Unlimited
Leque Island Restoration

PGG

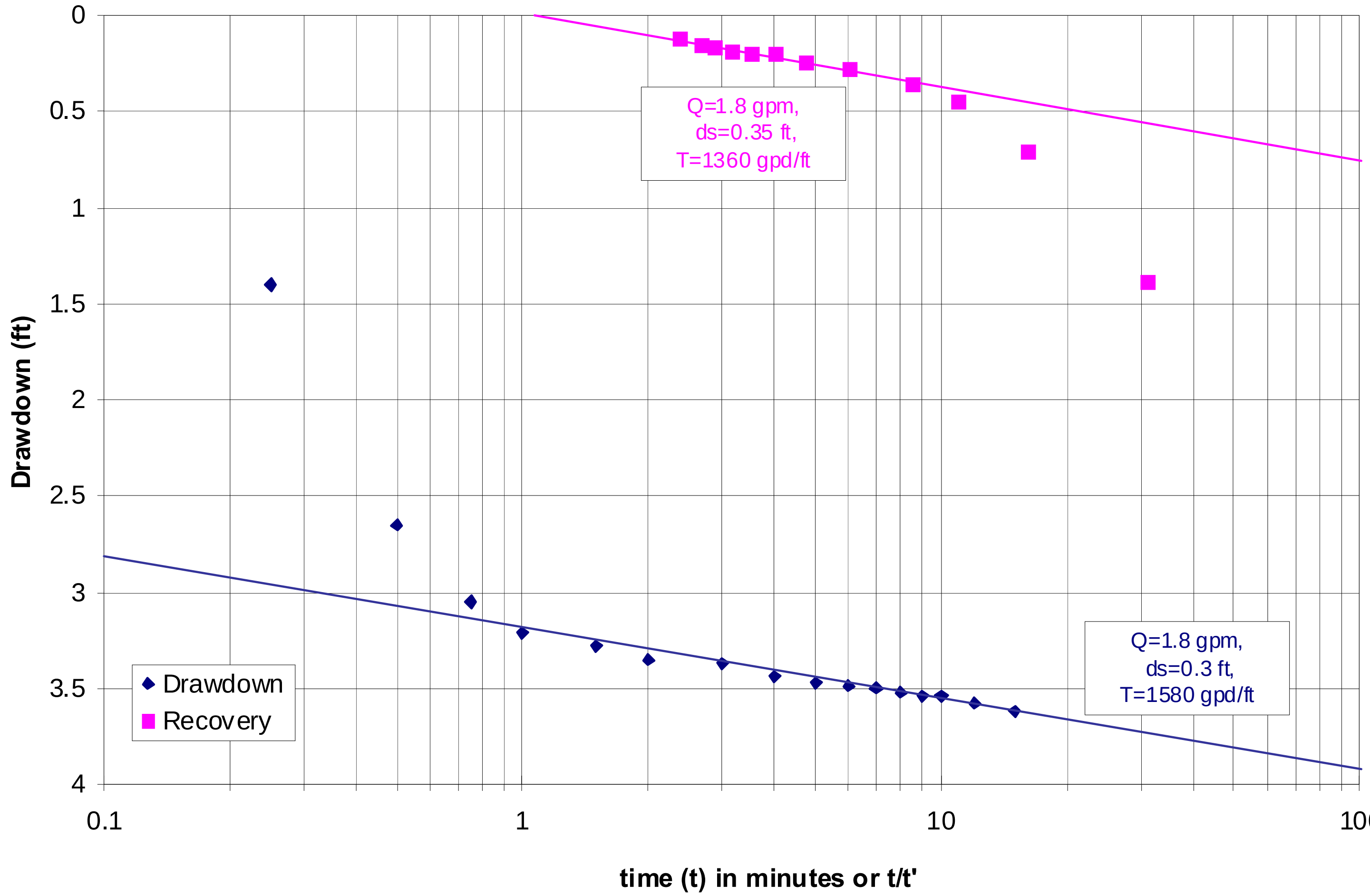
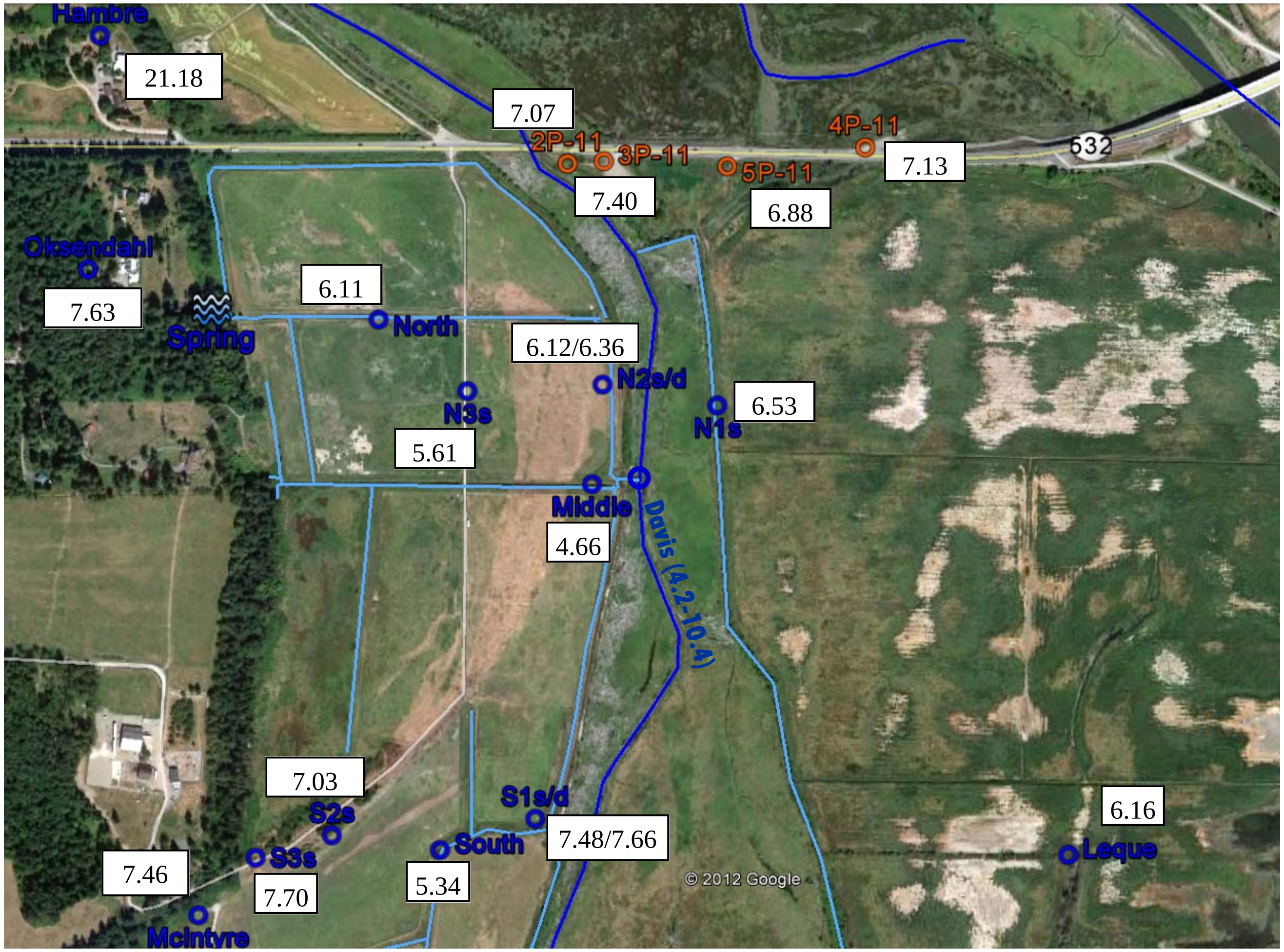


Figure 3-11
Short Term Pumping Test on Well N3s

Ducks Unlimited
Leque Island Restoration

PGG

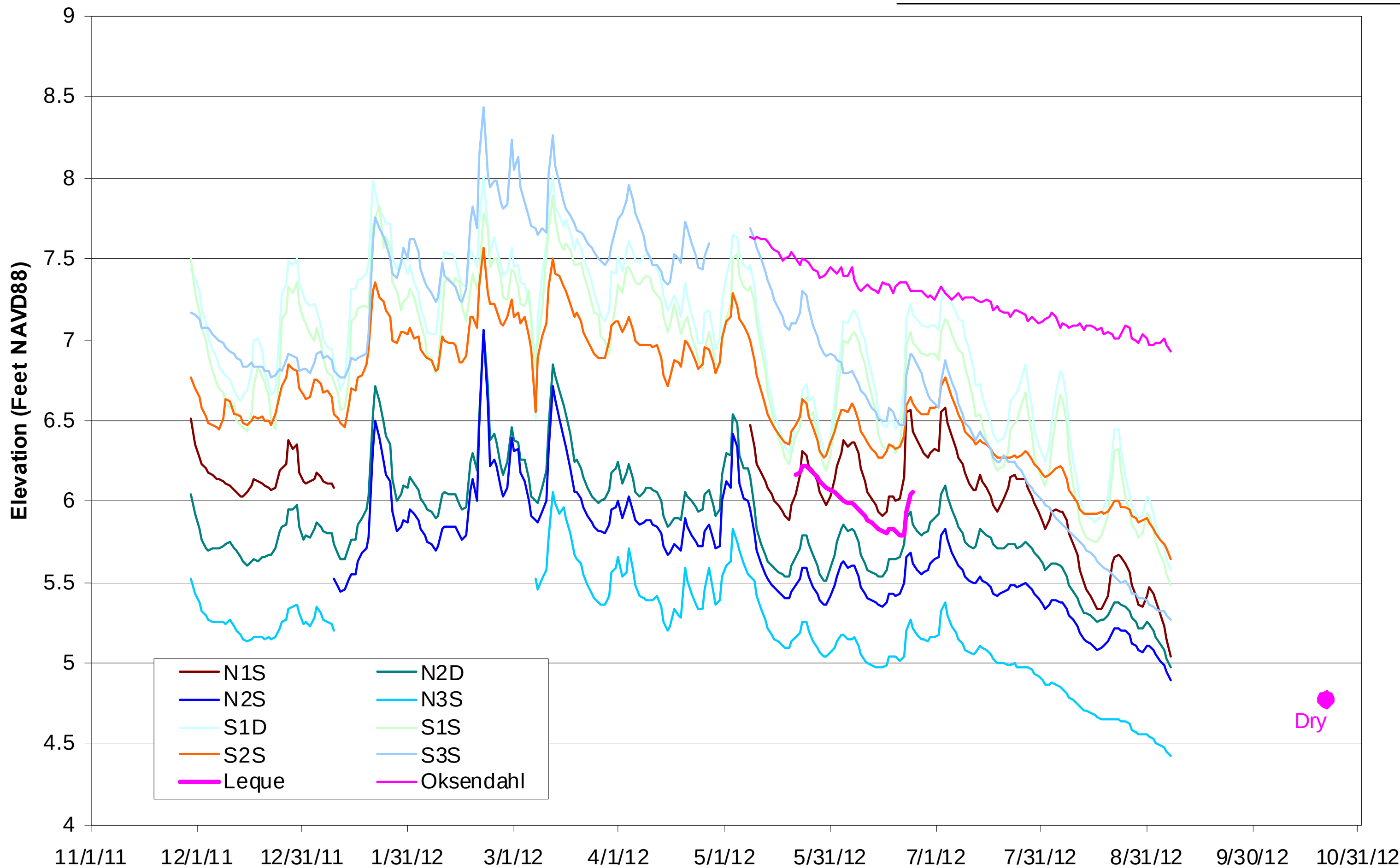


NOTES:
All water level elevations shown as equivalent freshwater head at well screen elevation.
Leque water level taken on 5/22/12.

Figure 3-12
Average Water Level Elevations for 3-Day Period Starting 5/8/12

Ducks Unlimited
Leque Island Restoration

PGG



NOTES:
Data are elevation of water surface in well, and are not corrected to equivalent freshwater head in the well screen.
Oksendal record based on daily maximum water level to counteract affects of pumping

Figure 3-13
Average Daily Groundwater Elevations

Ducks Unlimited
Leque Island Restoration

PgG

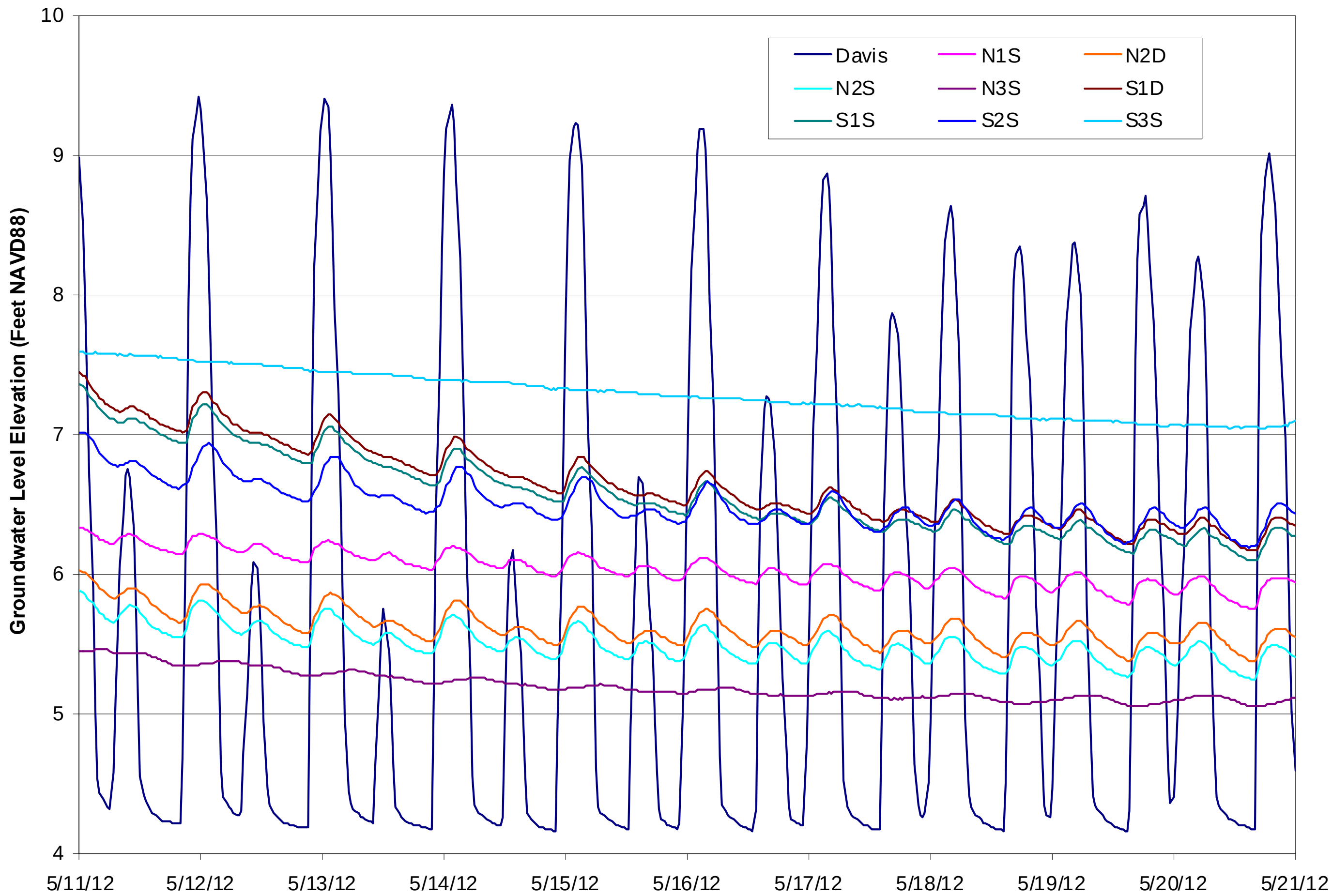


Figure 3-14
Davis Slough Elevations vs. Groundwater Elevations

Ducks Unlimited
Leque Island Restoration

PgG

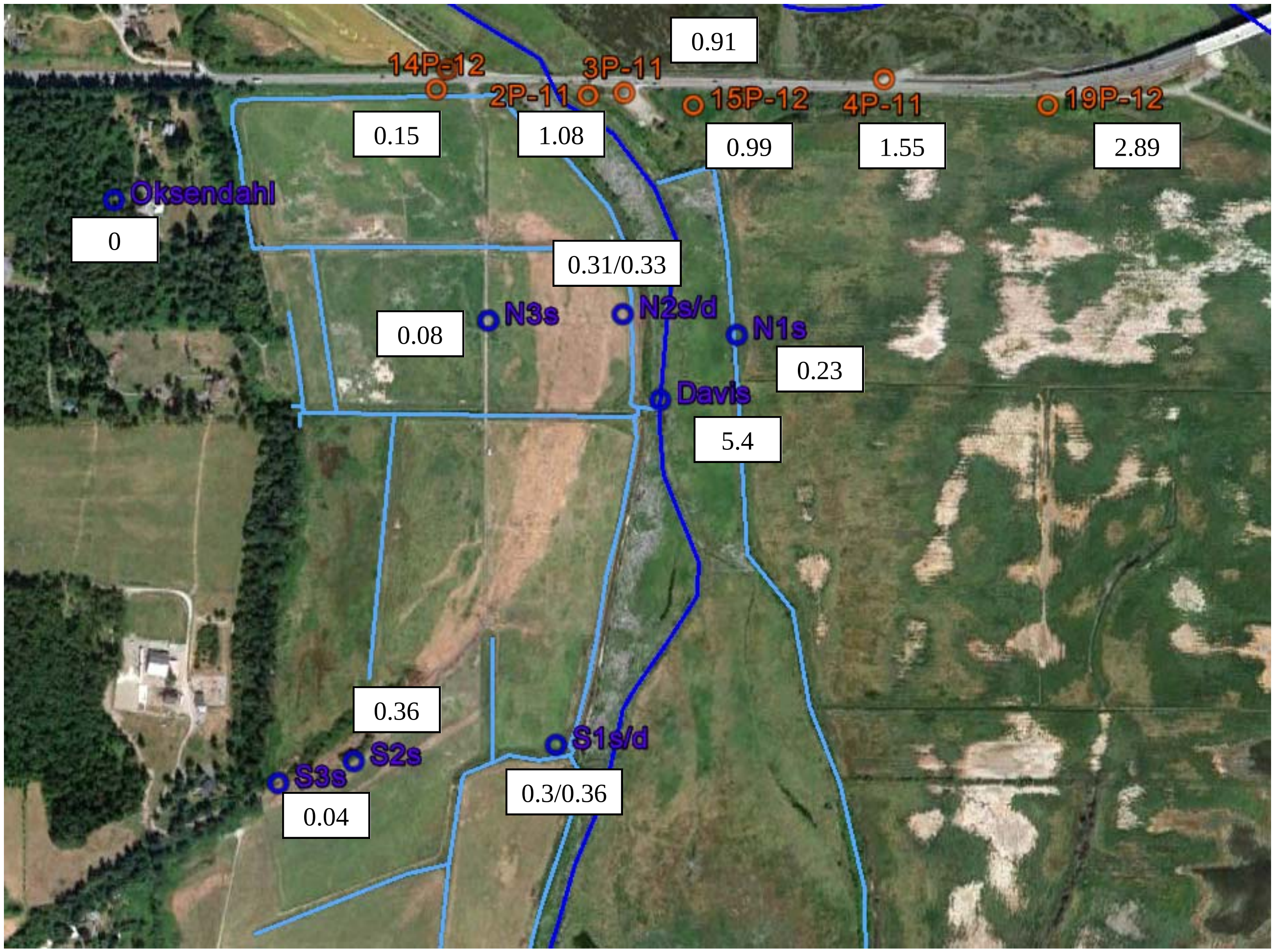


Figure 3-15
Median Daily Water-Level Fluctuations (Tidal Influence)

Ducks Unlimited
Leque Island Restoration

PGG

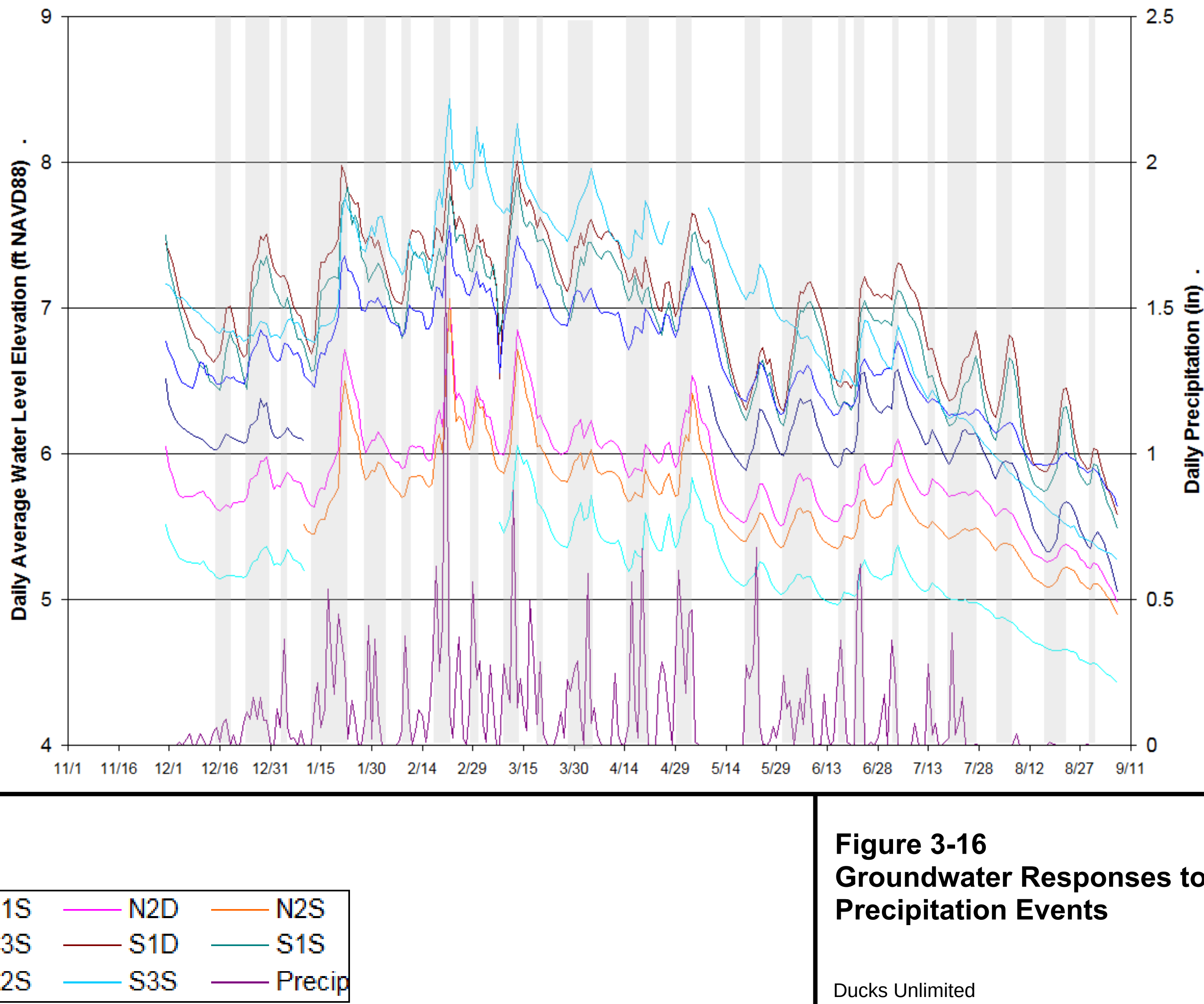


Figure 3-16
Groundwater Responses to Precipitation Events

Ducks Unlimited
Leque Island Restoration

PGG

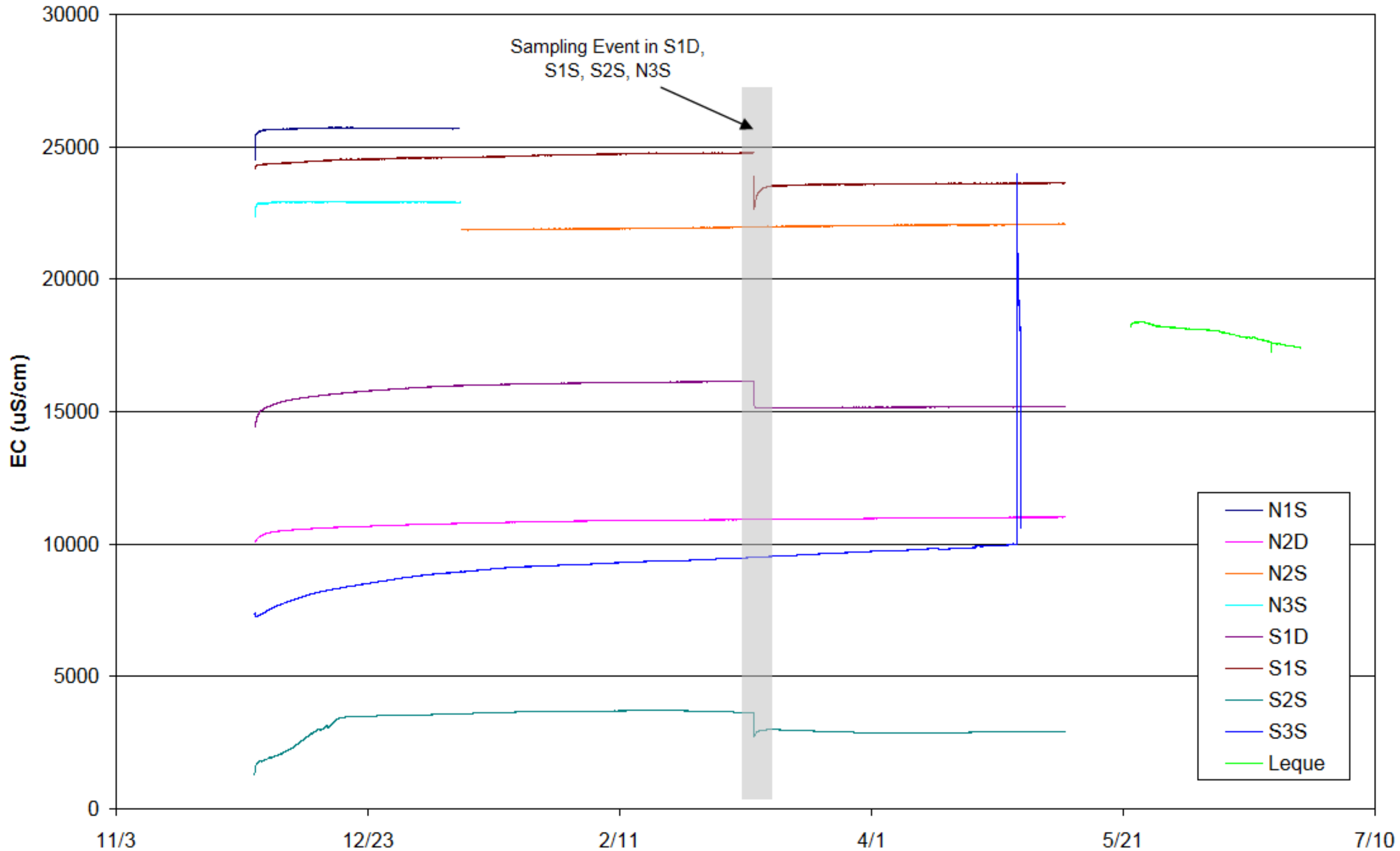
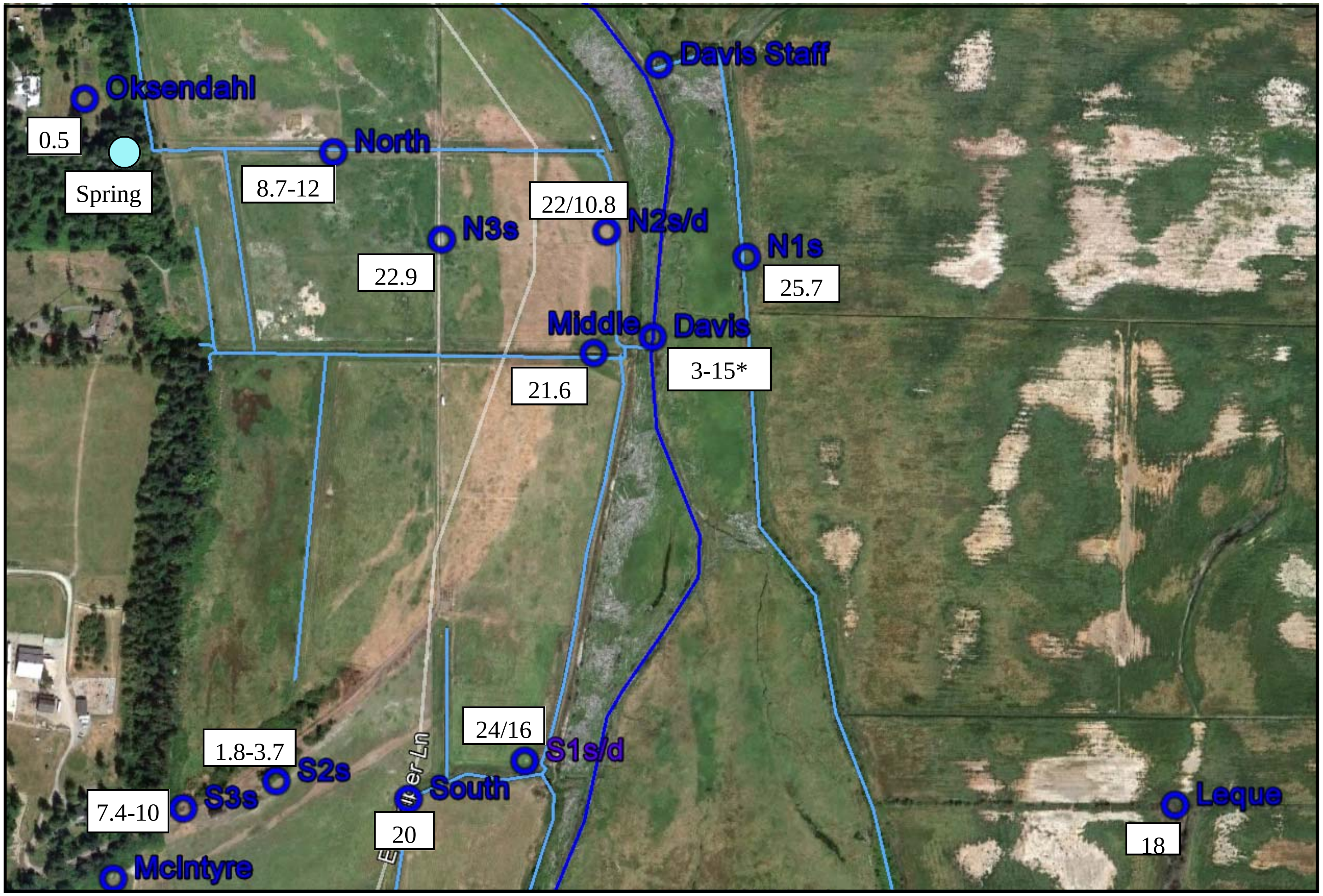


Figure 3-17
EC Trends at Groundwater Monitoring Points

Ducks Unlimited
Leque Island Restoration

PgG



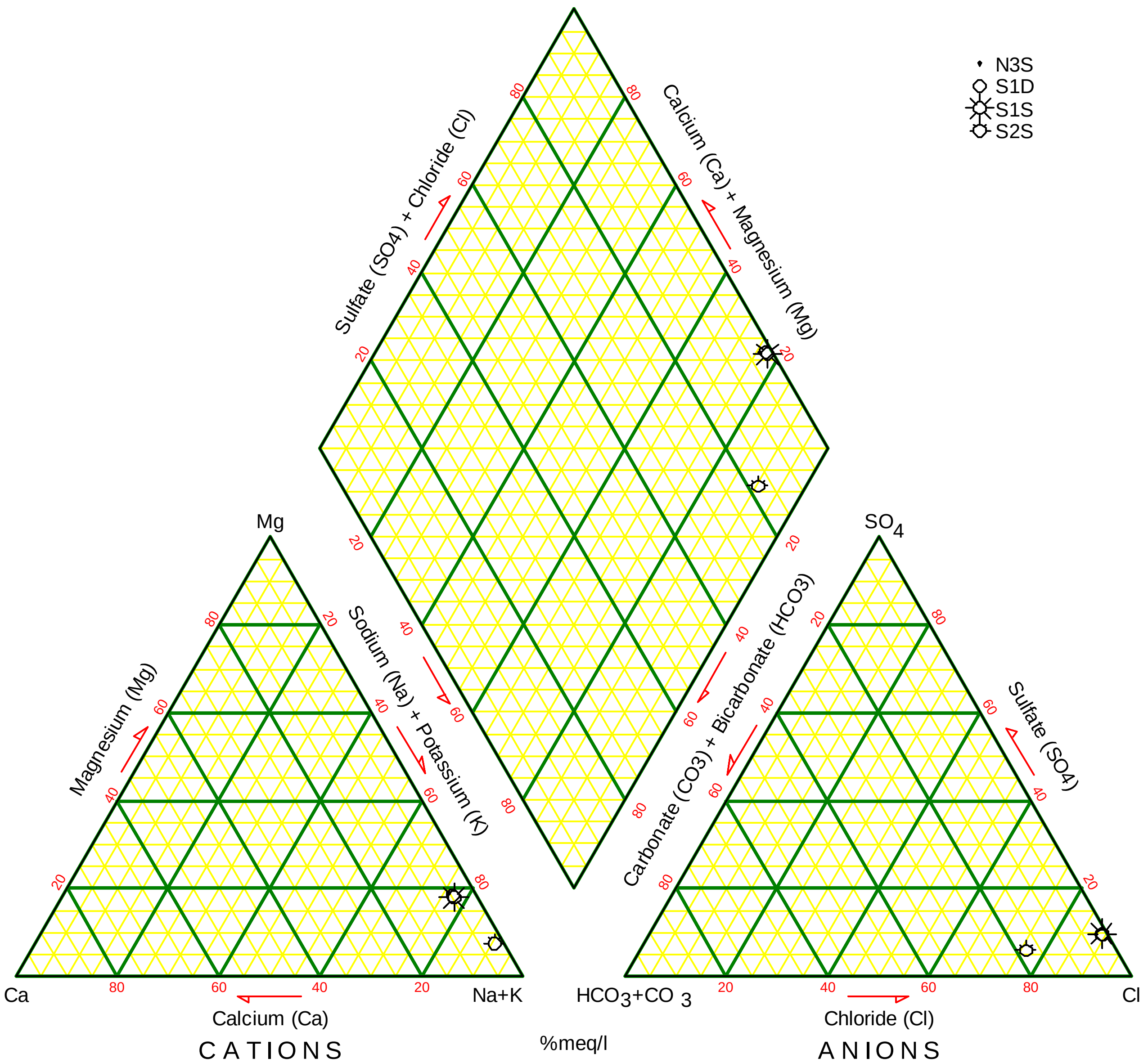
NOTES:
All values in mS/cm
EC reported as single value where range is fairly tight, reported as range otherwise.
Data period for groundwater sites: 11/30/11—5/9/12
Data period for surface-water sites: 3/7/12-9/7/12

* EC for Davis Slough exhibits spikes as high as 25 mS/cm.

Figure 3-18
EC Ranges at Monitoring Points

Ducks Unlimited
Leque Island Restoration

PgG



NOTE:
Plotting symbols may overlay and obsure others.

Figure 3-19
Trilinear Diagram of Groundwater Samples

Ducks Unlimited
Leque Island Restoration

Current Condition

- Tide Gate
- Area with Seepage through dike
- Plugged Culvert
- Dikes
- Canal/Ditch
- Stream/River

Schematic Future Condition

- Restored Remnant Channel
- Conceptual Tributaries

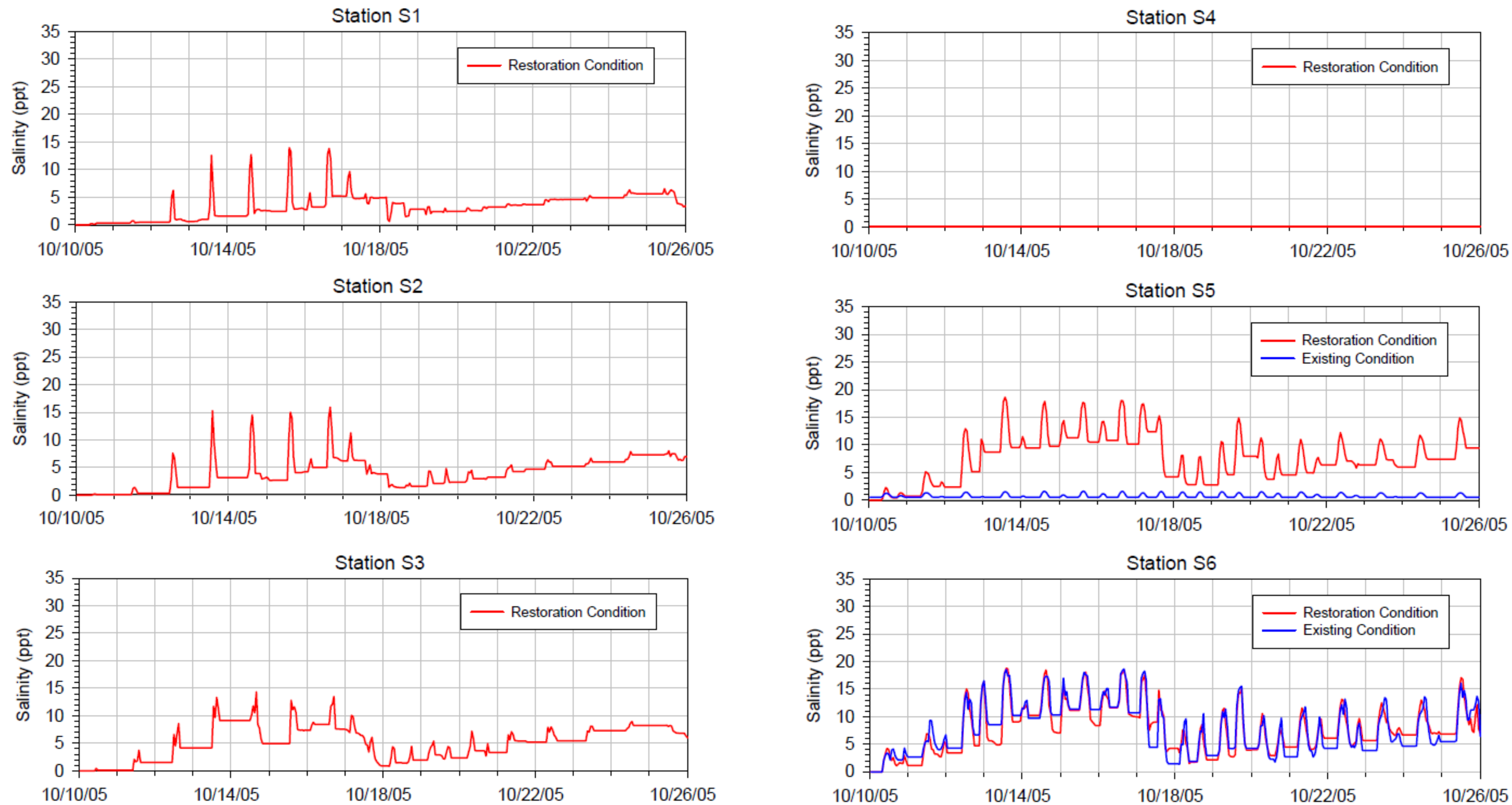
0 Feet 500

N

Aerial Photo from Bing Maps

Figure 4-1
Current Condition and Restoration Schematic

PgG



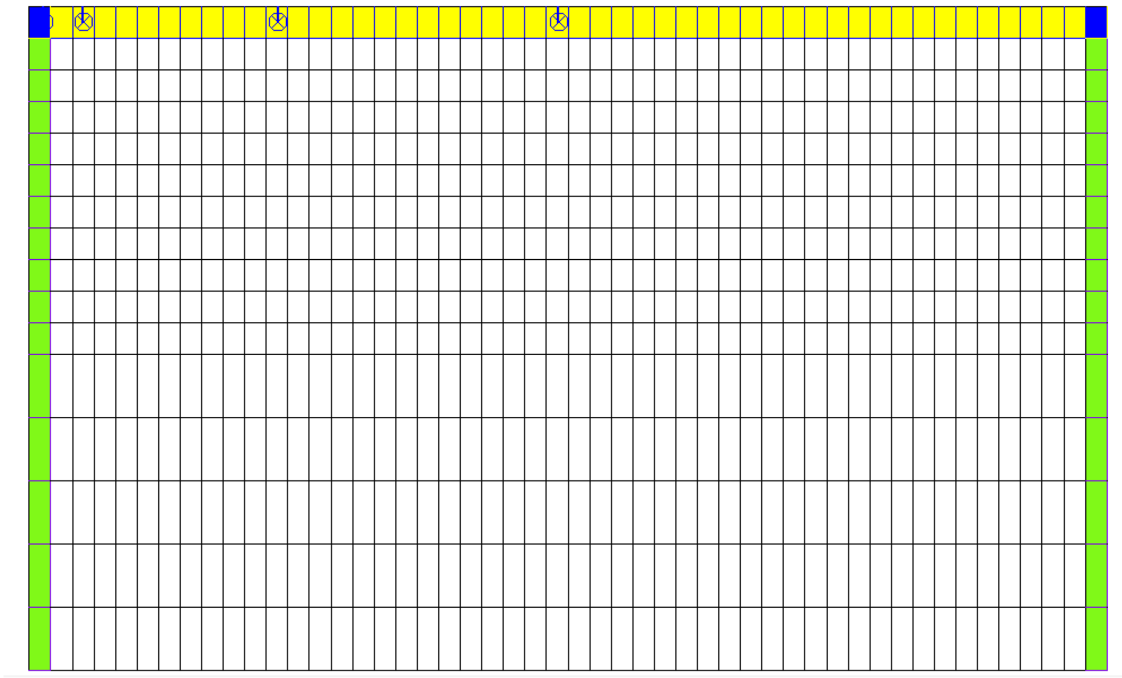
NOTES:
Graphs excerpted from Yang et al, 2008.

STATION LOCATIONS:
S1— Main Leque Island Channel (existing)
S2— East of main channel (lower elevation)
S3— East of main channel (lower elevation)
S4— West of main channel (higher elevation)
S5— South of existing dike (outside of restoration area)
S6— South of existing dike (outside of restoration area)

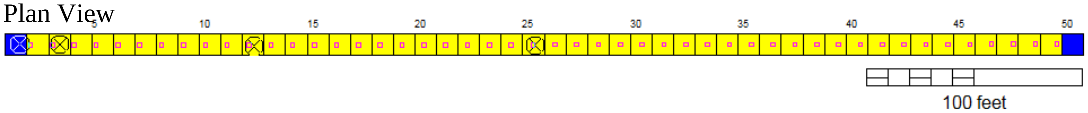
Figure 4-2
Current & Post Restoration Salinities Estimated with Hydrodynamic Model

Ducks Unlimited
Leque Island Restoration

Profile View



Plan View



LEGEND

- Constant Head (CH) Cell
- Drain (DRN) Cell
- General Head Boundary (GHB) Cell
- Model Observation Point

Figure 4-3
2D Model Design

Ducks Unlimited
Leque Island Restoration

PgG

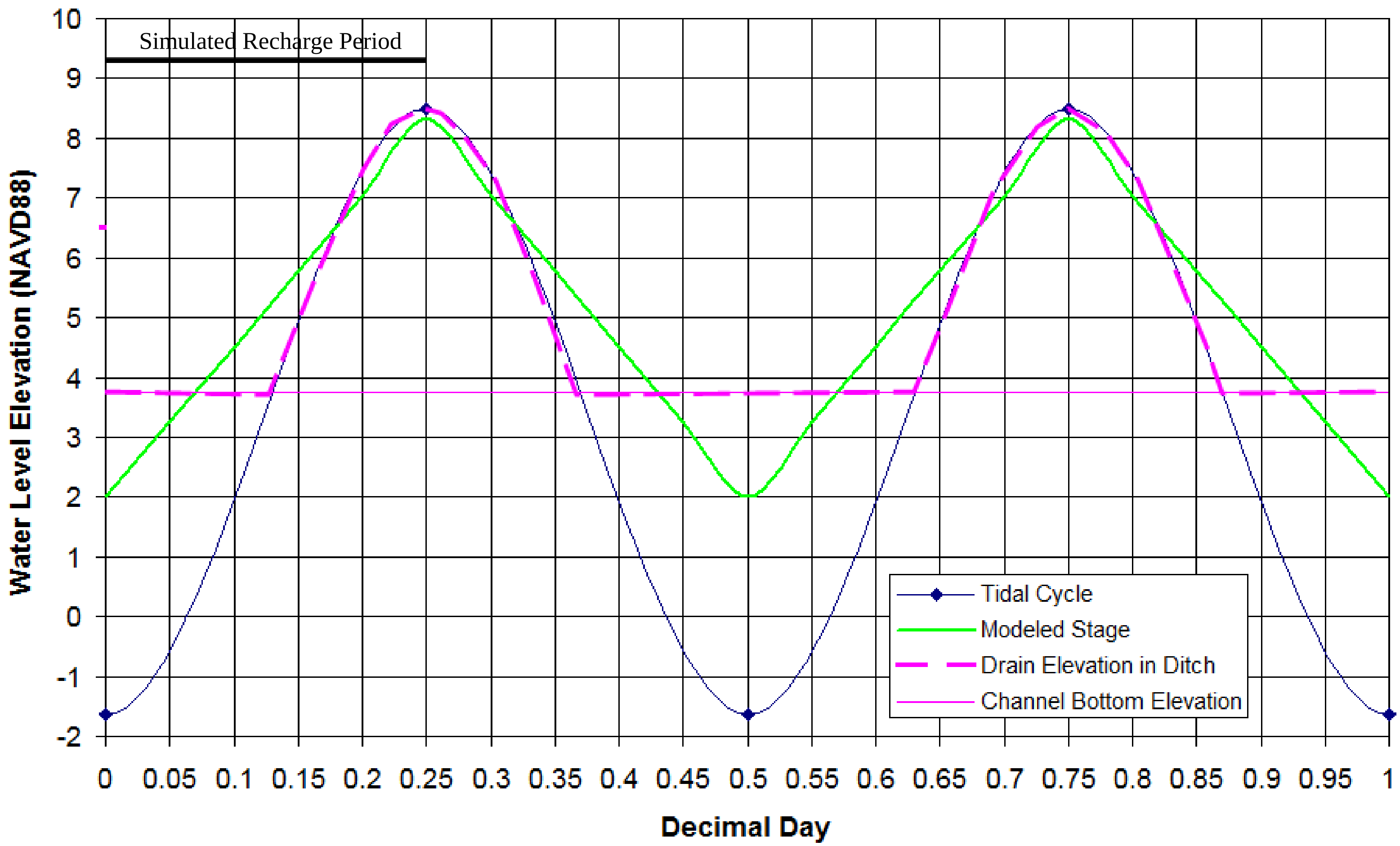
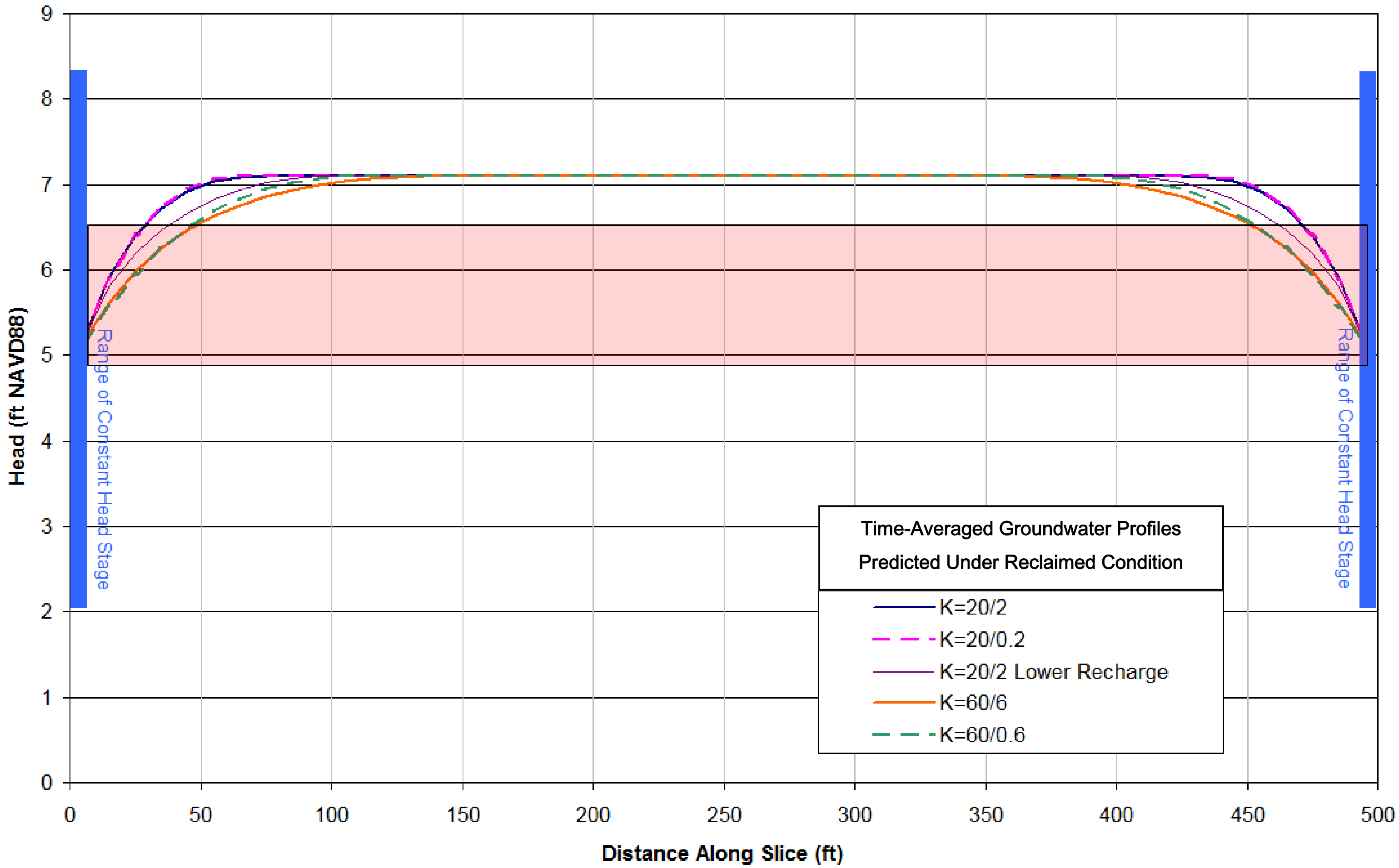


Figure 4-4
Modeled Stage of Constant Head Boundary Conditions

Ducks Unlimited
Leque Island Restoration



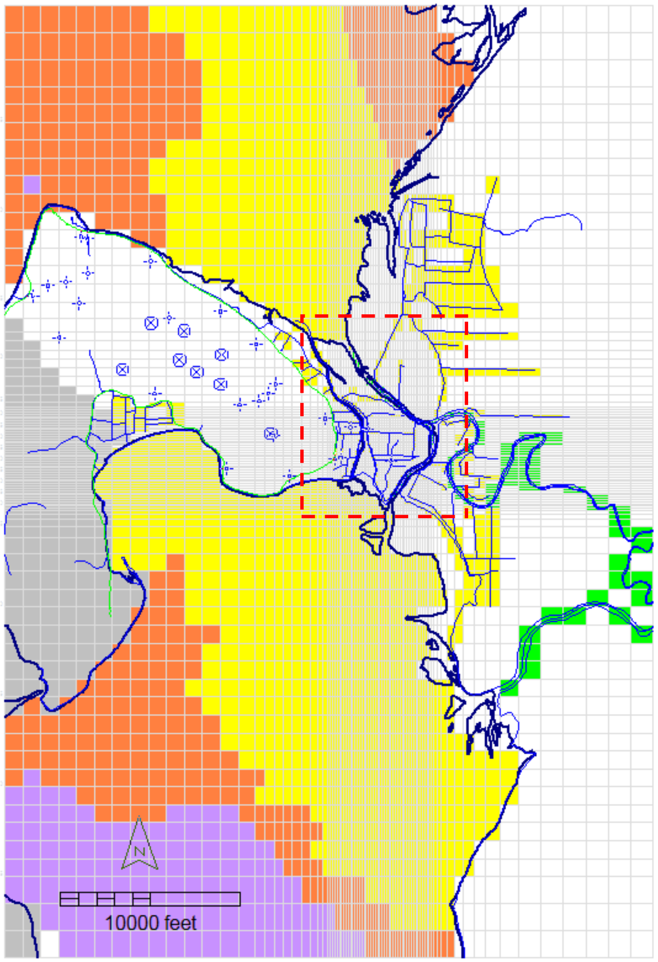
LEGEND

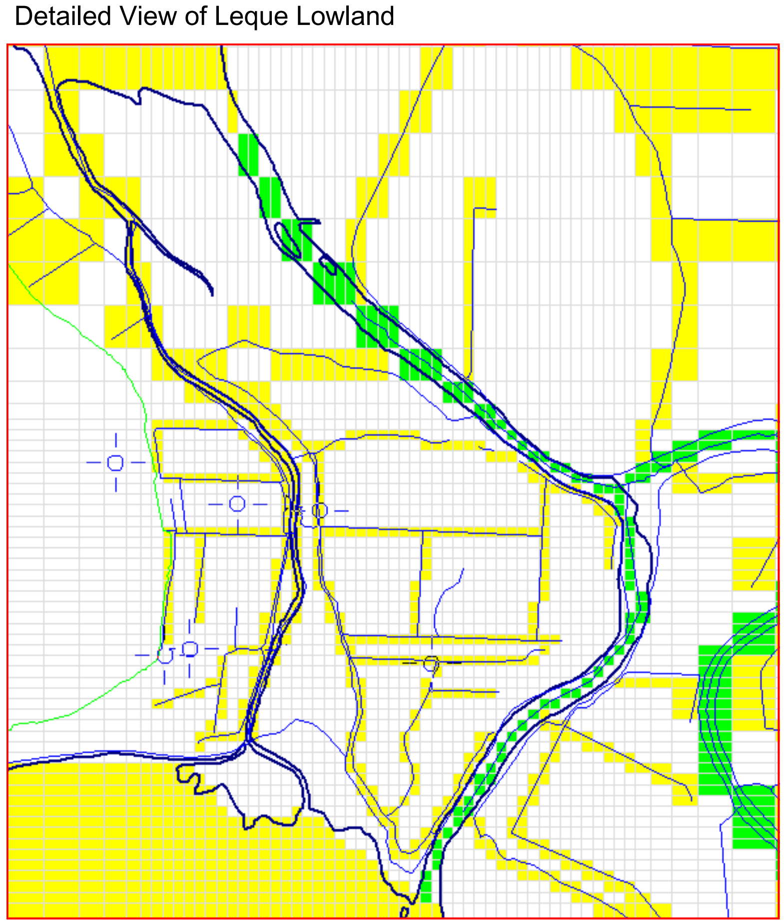
Approximate range of groundwater levels under current condition

Figure 4-5
Modeled Average Daily Head Distribution Along 2D Slice

Ducks Unlimited
Leque Island Restoration

PGG





NOTES:

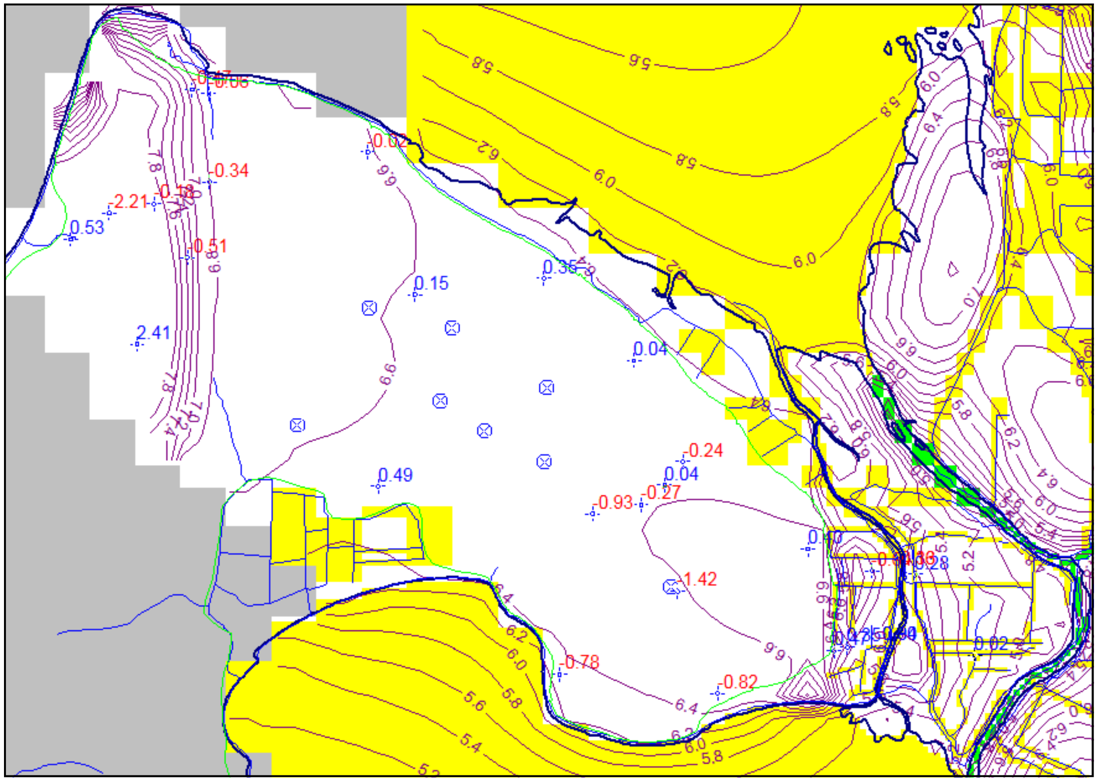
- Inactive Model Cell
- River Cell
- Layer 1 Drain Cell
- Layer 2 Drain Cell
- Calibration Target
- Well
- Upland Escarpment
- Drain Cell in Layers 3-16

Figure 5-1
3D Groundwater Model Grid and Boundary Conditions

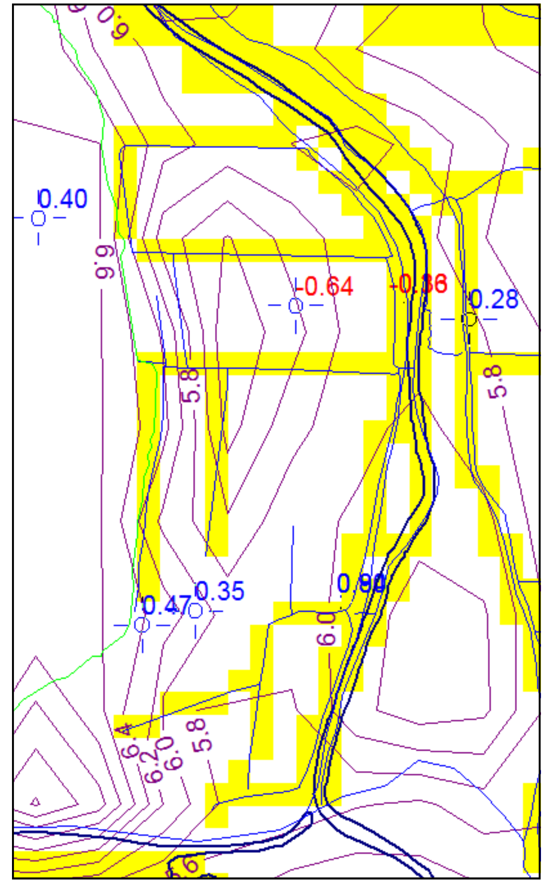
Ducks Unlimited
Leque Island Restoration

PgG

All Calibration Targets — Model Version GS-C



Detailed View of Monitoring Site (V. GS-C)



NOTES:

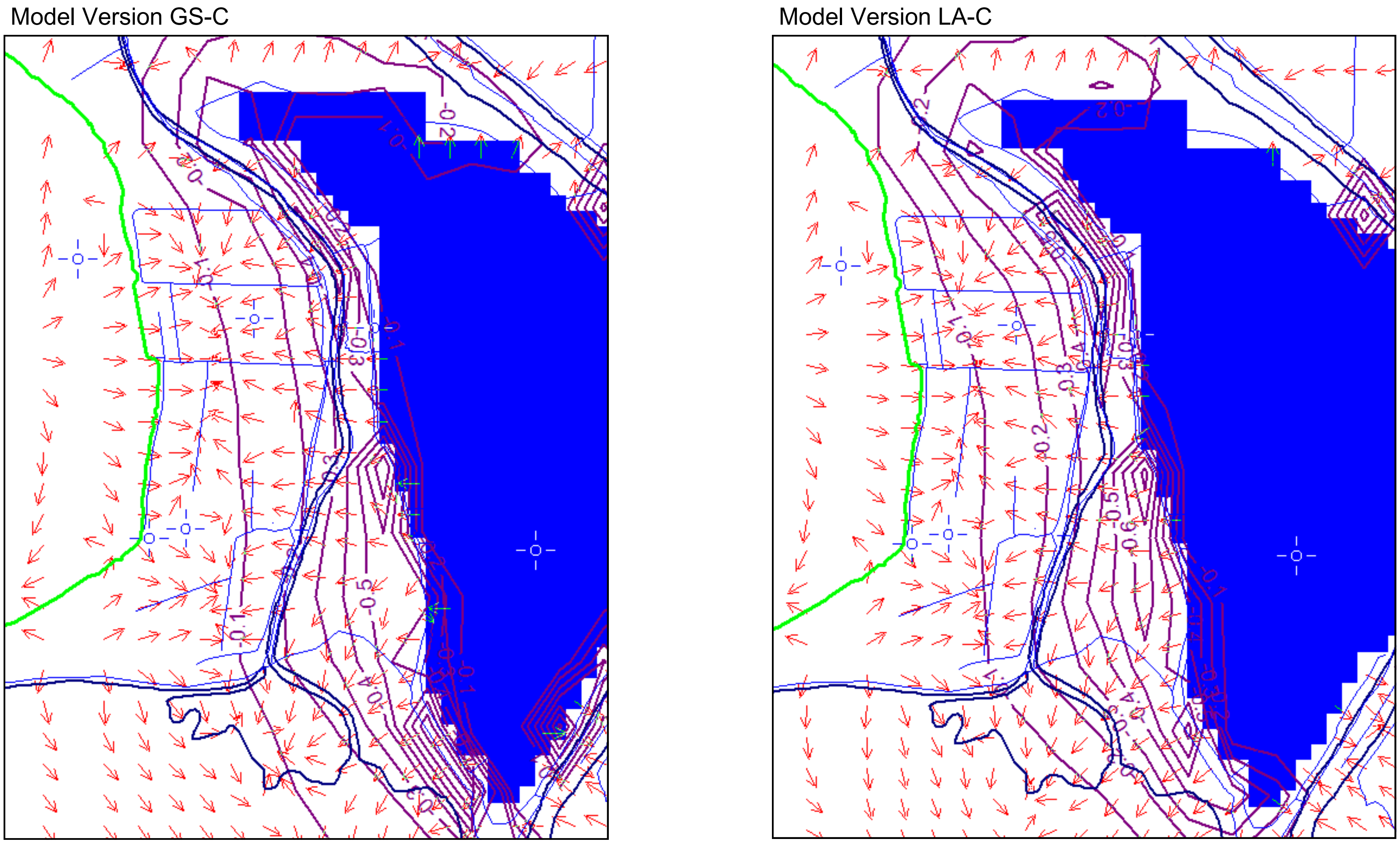
- Inactive Model Cell
- Drain Cell
- River Cell
- Well
- 6.51 Calibration Target and Residual
- Groundwater Level Contour (Interval = 0.2 ft)
- Camano Island Upland Escarpment

Residual = observed minus predicted (negative values are too high).
All values from model layer 1.

Figure 5-2
Prediction of Groundwater Heads and Calibration Residuals

Ducks Unlimited
Leque Island Restoration

PgG



NOTES:

- Constant Head Cell
- Layer 1 Drawdown (Contour (Interval = 0.1 ft)
- Calibration Target
- Camano Island Upland Escarpment
- Layer 1 Modeled Groundwater Flow Direction

Negative Drawdown Indicates Water Level Rise

Figure 5-3
Prediction of Post-Restoration Groundwater Flow Patterns and Drawdowns

Ducks Unlimited
Leque Island Restoration

PGG

APPENDIX A
MONITORING SYSTEM DESIGN AND PROTOCOLS

MONITORING SYSTEM DESIGN AND PROTOCOLS

This appendix describes the installation of 8 monitoring wells on the monitoring site, the installation of 5 surface-water monitoring stations, and PGG's approach to data collection and management.

INSTALLATION OF MONITORING WELLS

PGG installed 8 monitoring wells on the monitoring site: 7 on the west side of Davis Slough and one east of Davis Slough. The wells were installed in late October 2011. Well locations are shown on **Figure 1-1** and well construction information is summarized on **Table 3-1** of the main report. The wells are located in 2 east-west transects across the monitoring site. Each transect has 3 locations, with shallow wells installed at each location (depths ranging from 25 to 30 feet) and a deep well installed at one site (depths of 45 and 61 feet).

All 6 of the shallow wells were installed with a Geoprobe drilling rig. After drilling a 3.5-inch diameter borehole to total depth, a completion interval was selected based on geologic conditions. In some cases, the screen assembly was installed at the bottom of the hole, while in other cases the geoprobe casing was pulled back while the bottom of the hole was backfilled with bentonite pellets. A screen assembly, typically consisting of a 2-inch PVC tailpipe, 5 or 10 feet of 2-inch 10-slot PVC well screen and a 2-inch PVC riser pipe to land surface, was then installed in the geoprobe casing. As the casing was pulled back, a sand pack (2/12 silica sand) was installed alongside the well screen (to 2 or 3 feet above the top of the screen) and bentonite chips were installed up to the land-surface to provide a surface seal for the well. The wellheads were completed with a steel subsurface vault set within a concrete pad on the land surface. The 2 deeper wells were installed with a hollow-stem auger rig using the same procedure and materials. The auger rig was used because the Geoprobes were considered potentially unable to reach desired depths. Borehole diameters varied from 3.5 inches for Geoprobe drilling and 8 inches (6-inch core) for hollow-stem auger.

Geologic logs and as-built diagrams for the 8 monitoring wells are presented on **Figures A-1** through **A-8**. Sedimentary textures were observed during drilling were highly variable, as expected for alluvial deposits. Sand deposits were commonly interbedded with silt/sand and silt/clay deposits. Sand/gravel deposits were also encountered, demonstrating higher-energy fluvial channel deposits. Shells were also commonly observed. Monitoring wells were completed in the coarser-grained deposits and depths consistent with shallow and deep completions.

SURFACE-WATER MONITORING INSTALLATIONS

Ducks Unlimited (DU) installed surface-water level monitoring stations in 4 ditches (3 on the monitoring site and 1 on Leque Island) and in Davis Slough. The stations were installed in early March, 2012 and their locations are shown on **Figure 1-1**. All designs involved driving a steel T-post into the channel bottom and 1 or 2 into the bank. The T-posts were used to support PVC pipes in which the equipment was installed. Installations typically included a 4-inch PVC pipe set into the ditch to house the probe and a 6-inch PVC set on the bank to house the probe cable. The 4-inch pipe was installed vertically at one site (South Ditch), but was installed diagonally from the bank to the ditch bottom in all other locations. Each 4-inch pipe was attached to either 2 vertical T-posts or had a steel angle-iron attached to the side and protruding beyond the bottom to act as a "spear" in order to affix the pipe in the ditch bottom. Each 4-inch pipe had an end cap and was slotted to allow water exchange. DU also installed geotextile around the slotted pipe to exclude silt from the ditch water.

Graduated staff gages were attached to the vertical T-posts installed in each ditch. Because the Davis Slough installation did not have a vertical T-post in the slough (instead, the "spear" approach was used), DU installed a stage-gage on a piling sunk in the slough approximately 900 feet north of the probe installation.

The 6-inch, non-slotted PVC pipe was attached to one of the T-posts on the bank with a PVC top and end cap to contain the probe cable and protect it from the elements.

If desired, more information about the surface-water monitoring assemblies is available from DU.

INSTALLATION AND OPERATION OF MONITORING EQUIPMENT

Datalogging probes were installed in the monitoring wells on November 21, 2011. The probes were Instrumentation Northwest Model CT2X, which measure conductivity (EC), temperature (T) and pressure (water level above probe). The probes were vented to the atmosphere to avoid the need for barometric compensation. The probes were installed close to the well screens so that measurements of EC and T would be representative of aquifer conditions. Measurements were set for 10-minute intervals.

PGG visited the site for the first data download in early January 10, 2012. All probes were functioning properly, although the probe in Well N1d had not been properly initiated and therefore didn't collect data. On March 9, 2012, PGG installed vented CT2X probes in the 3 monitoring-site ditches and in Davis Slough. However, at that time, 2 of the probes (installed in monitoring wells N1s and N3s) had failed, and PGG replaced one (N3s) with a temporary probe. It was determined that the monitoring well vaults were too humid for the vent tubes such that moisture was conducted to the probe electronics, thus leading to equipment failure. One more monitoring-well CT2X had failed by the third data download on May 9, 2012. PGG therefore returned to the site on May 14, 2012 and replaced all CT2X monitoring-well probes with Solinst, non-vented Levelogger probes. The Leveloggers measure pressure and temperature, but do not measure conductivity. Because they are non-vented, a barometric probe was also installed onsite. Subsequent data downloads on July 13, 2012 and September 7, 2012 encountered no further failures of the monitoring well probes.

Probe installations in Davis Slough and the "Leque" ditch site also encountered problems. The first CT2X probe installed at the Davis Slough site in early March 2012 failed within the first day of operation and was replaced soon thereafter. The May 2012 site visit revealed that the replacement CT2X probe had also failed, and PGG immediately procured a non-vented CT2X probe to replace the failed vented unit. Data collection at Davis Slough proceeded successfully from May 9, 2012 until July 24, 2012, when the probe failed once again. PGG installed a vented CT2X probe at the Leque site on May 22, 2012 which failed on June 25, 2012. Overall, PGG was very disappointed with the performance of the CT2X instruments.

PGG procured and installed a Schlumberger Micro-Diver probe in the Oksendahl Well on May 22, 2012. The Micro-Diver is a non-vented slim-profile probe that can fit through the access hole of a standard domestic wellhead. The probe recorded water levels every half hour and performed without problem through the final site visit, during which all probes were removed and downloaded on September 7, 2012.

DU surveyed the coordinates and elevations of the wellheads and the tops of the surface-water staff gages twice: once in late 2011 and a second time in March 2012. The survey data were reported in the Washington State Plane NAD83/07 horizontal and NAVD88 vertical datums. No significant differences were noted between the two surveys.

During each site visit, prior to downloading data from monitoring-well probes, PGG measured the depth to water in the well with an electronic water-level measuring tape. These manual measurements were accurate to within several hundredths of a foot and were used to translate automated pressure readings (water-level above probe) to water-level elevations based on surveyed wellhead elevations. Similarly, PGG recorded the surface-water levels on the staff gages for translation of probe readings to time-series surface-water elevations.

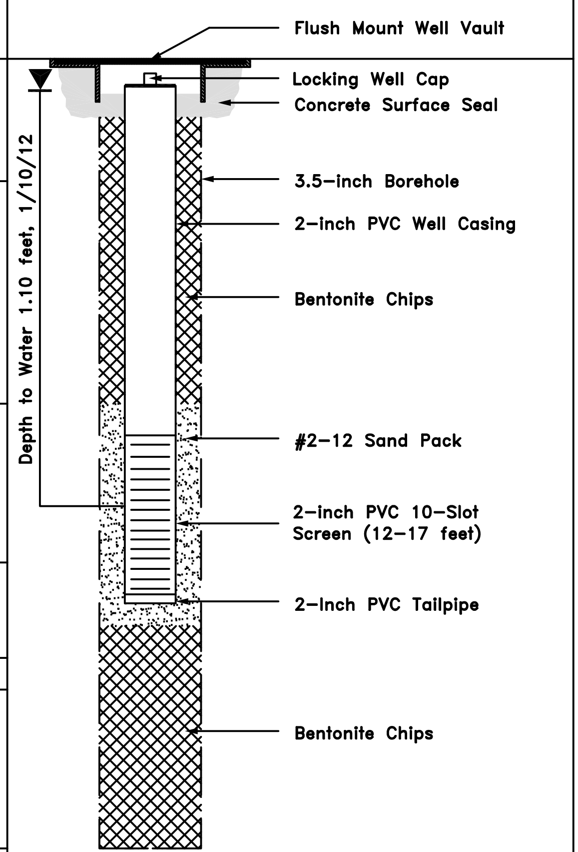
DATA MANAGEMENT

All digital data downloaded from the probes were stored in a Microsoft Access water-level database. Data files from non-vented probes were corrected for barometric pressure variations prior to importing into the database. Surveyed wellhead and staff-gauge elevations, and manual water-level measurements, were also imported into the database. The database translated time-series pressure data from the probes (i.e. water level above probe) to time-series water-level *elevations* by first calculating the elevations of the manual measurement (i.e. measuring point elevation minus depth to water) and then correlating one of the manual measurements to the nearest (in time) probe measurement. The database creates graphs of the time-series water-level elevations calculated from the probe data and the water-level elevations calculated from manual measurements. PGG compared the probe-derived elevations and manual elevations to confirm that there was no drift in the data. Drift was noted only in one case: the probe at the "North" ditch monitoring site instantaneously shifted position – likely because it was not originally resting on the bottom of the PVC pipe. PGG made corrections for this shift, after which all manual and probe data showed good correspondence.

Figure A-1 Geologic Log & Construction of Well N1S

DEPTH (ft)	GEOLOGIC LOG
0	Greyish green silty CLAY with organics, damp
5	Grey medium SAND, tr silt, wet
10	
	Grey medium fins SAND with several thin (2") silty clay layers
15	
	Dark grey sandy SILT and silty sand with shells
	Dark grey medium fine SAND, wet
20	Dark grey sandy SILT with shells, wet
25	Bottom of Hole @25'
30	
35	
40	

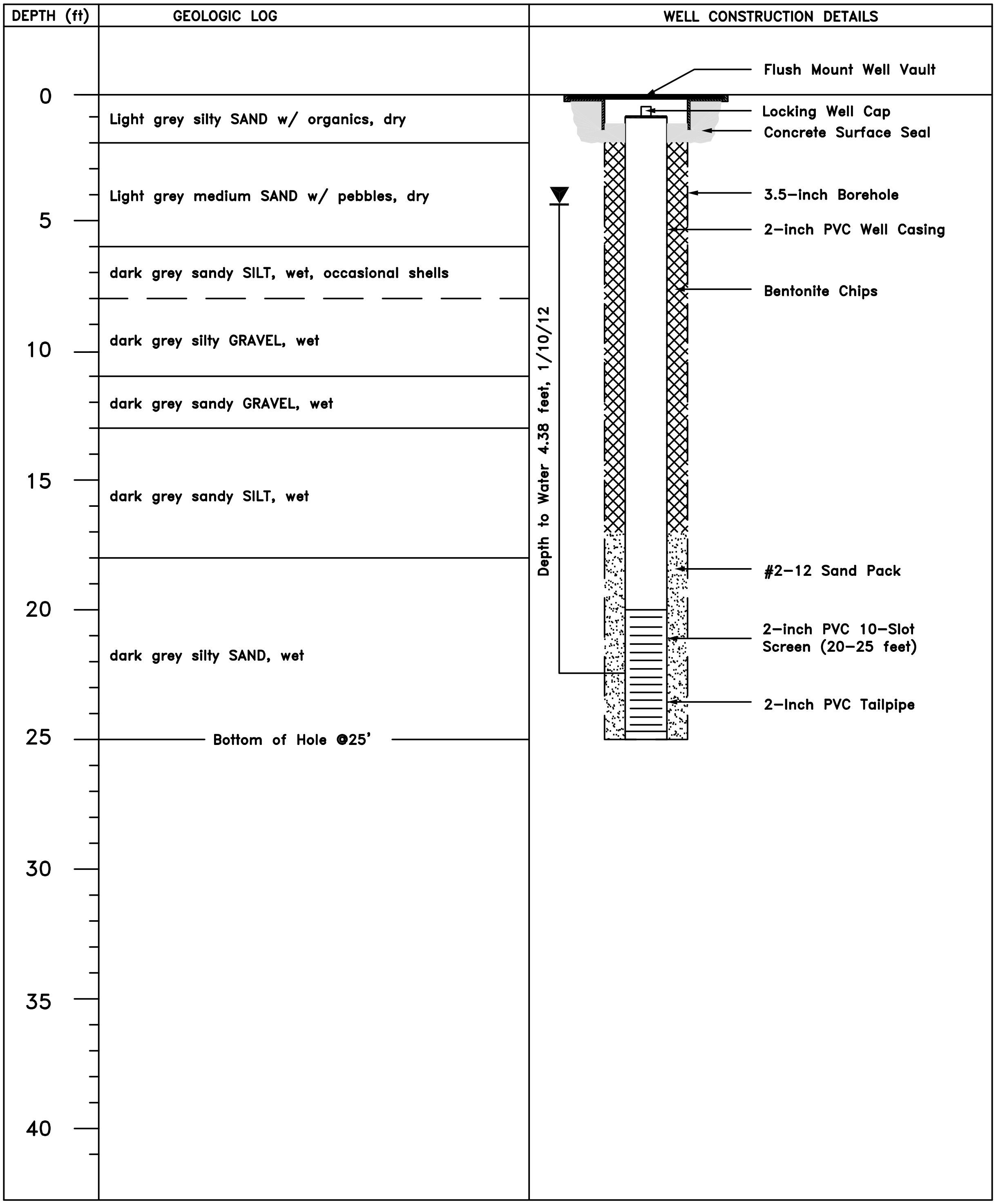
WELL CONSTRUCTION DETAILS



PROJECT NAME: Leque Island Hydrogeologic Study
WELL INDENTIFICATION NUMBER: N1S
DRILLING METHOD: Geoprobe
DRILLER: Elijah Floyd
FIRM: Cascade Drilling
CONSULTING FIRM: Pacific Groundwater Group, Inc.
REPRESENTATIVE: Doug Kelly

LOCATION: 48ø14'13.87651"N,122ø23'29.74989"W
LAND SURFACE ELEVATION 7.04 feet (NAVD 88)
DEPTH TO WATER: 1.10 feet
WATER LEVEL ELEVATION: 5.94 feet (NAVD 88)
WATER LEVEL DATE: 1/10/12
INSTALLED: 10/27/11
DOE TAG: BHK-021

Figure A-2 Geologic Log & Construction of Well N2S



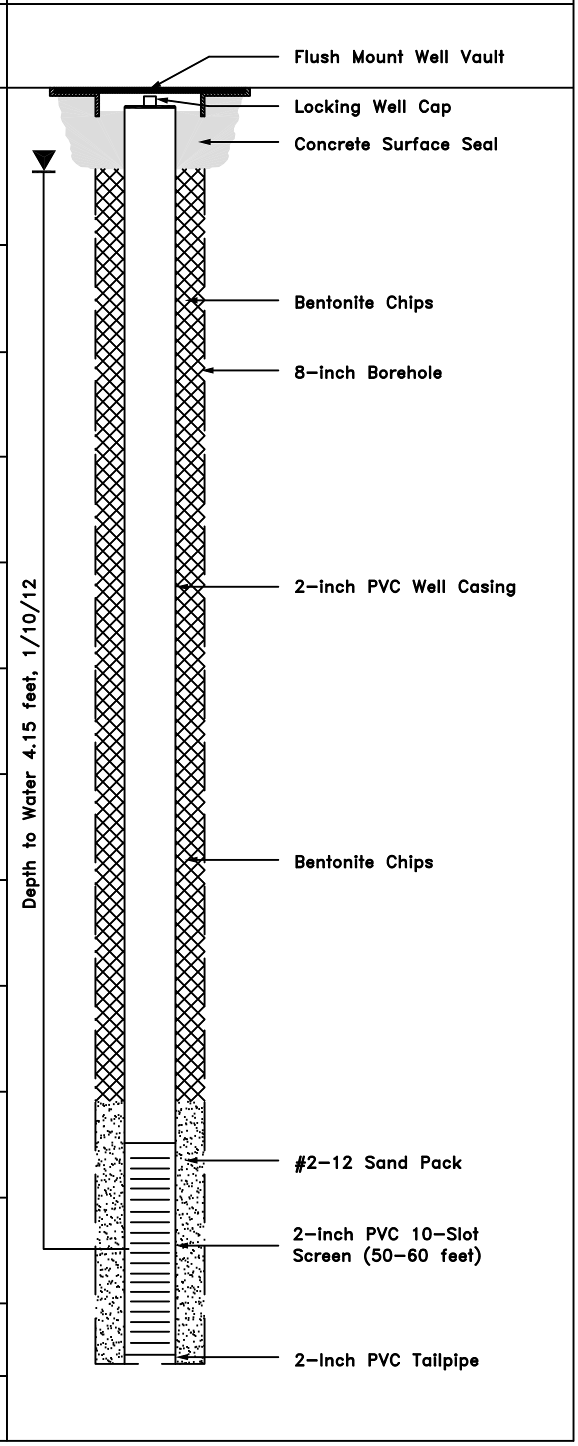
PROJECT NAME: Leque Island Hydrogeologic Study
WELL INDENTIFICATION NUMBER: N2S
DRILLING METHOD: Geoprobe
DRILLER: Elijah Floyd
FIRM: Cascade Drilling
CONSULTING FIRM: Pacific Groundwater Group, Inc.
REPRESENTATIVE: Doug Kelly

LOCATION: 48ø14'14.66439"N,122ø23'36.24531"W
LAND SURFACE ELEVATION 9.84 feet (NAVD 88)
DEPTH TO WATER: 4.38 feet
WATER LEVEL ELEVATION: 5.46 feet (NAVD 88)
WATER LEVEL DATE: 1/10/12
INSTALLED: 10/27/11
DOE TAG: BHK-018

Figure A-3 Geologic Log & Construction of Well N2D

DEPTH (ft)	GEOLOGIC LOG
0	
5	Light grey fine SAND, dry
10	Grey medium to fine SAND, wet
15	Grey medium SAND w/ some silt, wet
20	Dark grey medium to coarse SAND with silt layers
25	Grey SAND with shells, heaving
30	Grey medium to fine SAND, with shells
35	Dark grey fine silty SAND, occasional shells
40	Dark grey medium fine silty SAND, occasional shells
45	Grey SILT, organic (H2S) odor, shells
50	Compact sandy SILT with abundant shells
55	Grey silty CLAY interbedded with sandy silt and SAND
60	Grey SAND with some silt
	Bottom of Hole @61'

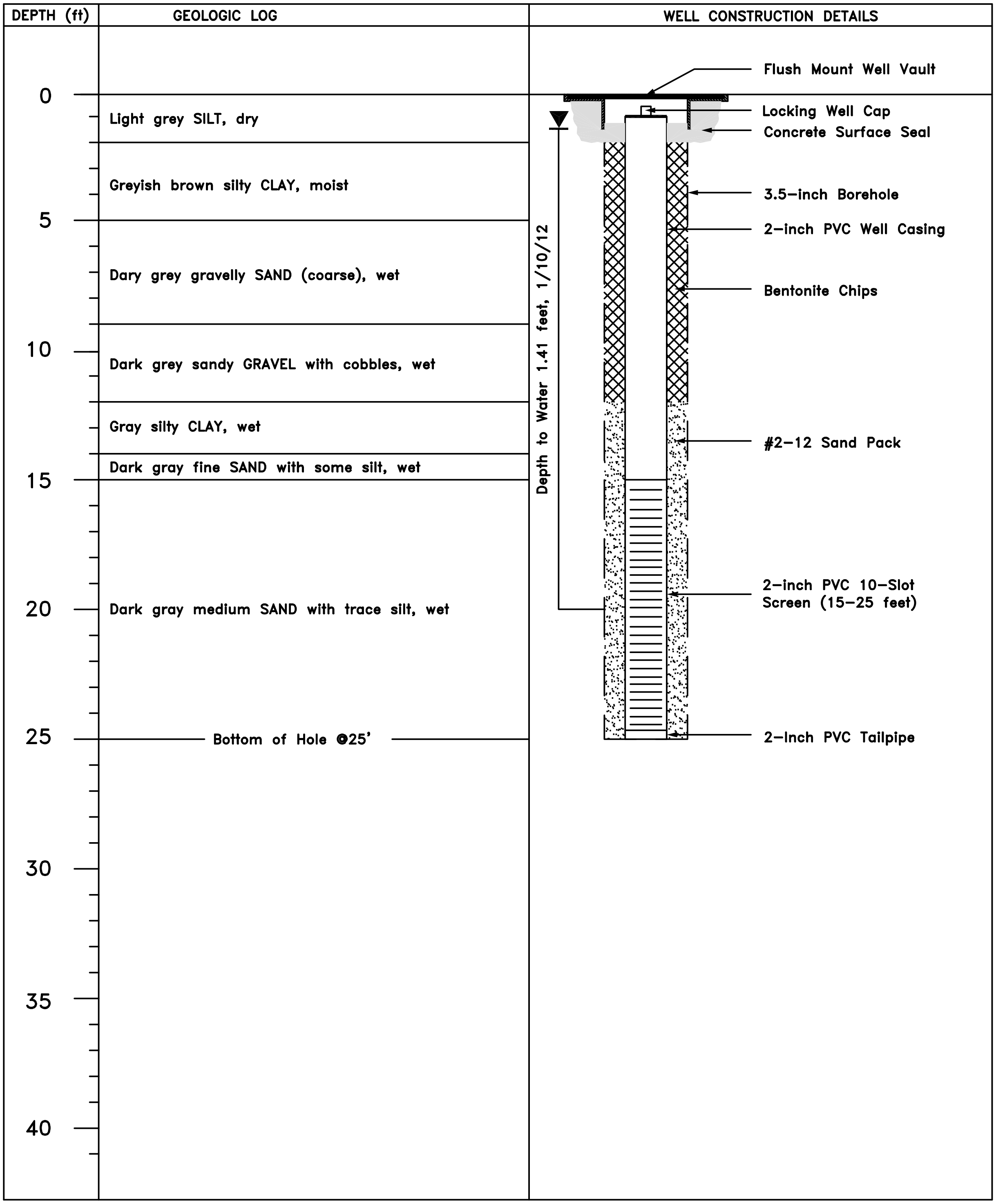
WELL CONSTRUCTION DETAILS



PROJECT NAME: Leque Island Hydrogeologic Study
WELL INDENTIFICATION NUMBER: N2D
DRILLING METHOD: Hollow Stem Auger
DRILLER: Jim Goeble
FIRM: Cascade Drilling
CONSULTING FIRM: Pacific Groundwater Group, Inc.
REPRESENTATIVE: Doug Kelly

LOCATION: 48ø14'14.66439"N,122ø23'36.24531"W
LAND SURFACE ELEVATION 9.84 feet (NAVD 88)
DEPTH TO WATER: 4.15 feet
WATER LEVEL ELEVATION: 5.69 feet (NAVD 88)
WATER LEVEL DATE: 1/10/12
INSTALLED: 10/20/11
DOE TAG: BHJ-589

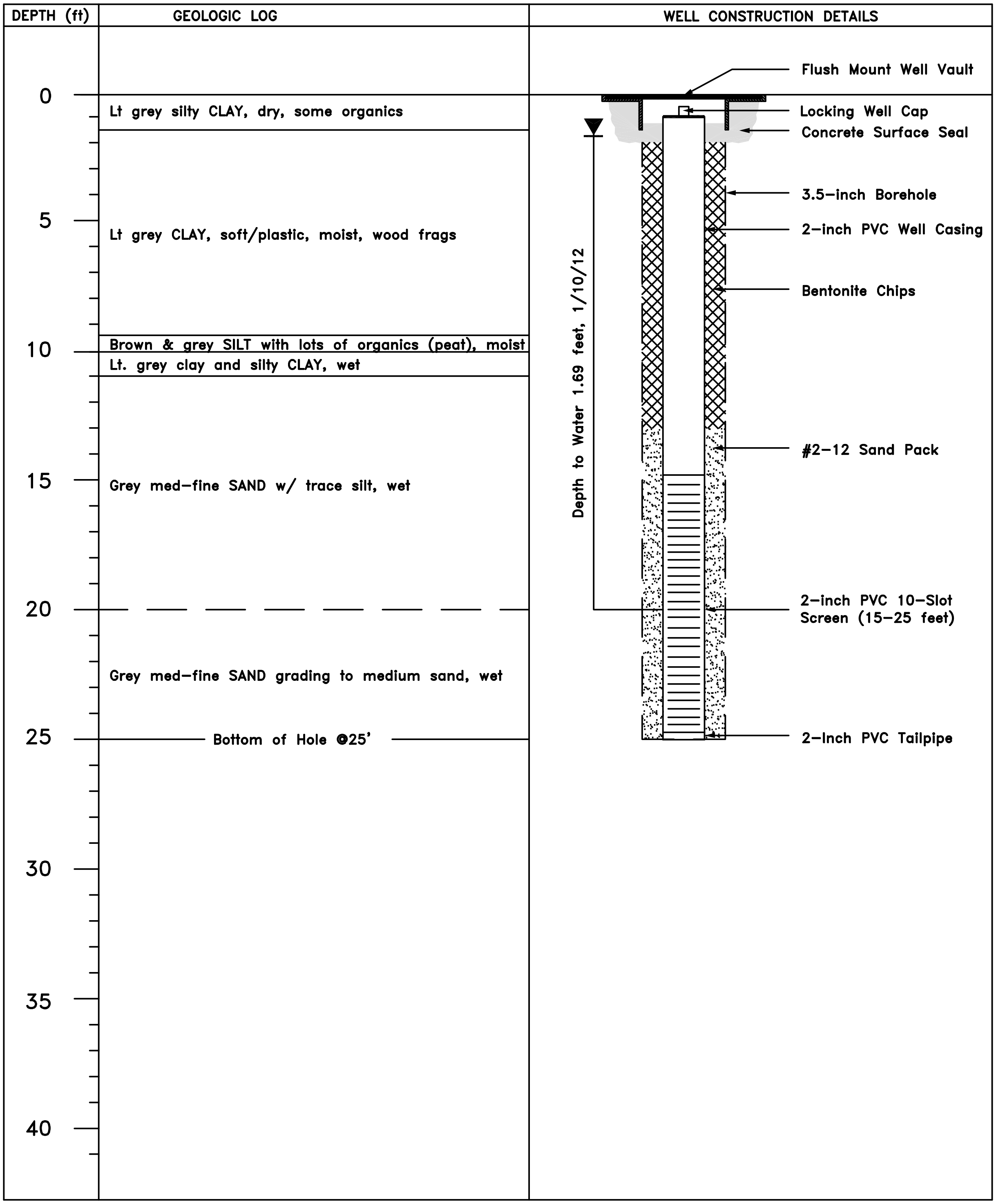
Figure A-4 Geologic Log & Construction of Well N3S



PROJECT NAME: Leque Island Hydrogeologic Study
WELL INDENTIFICATION NUMBER: N3S
DRILLING METHOD: Geoprobe
DRILLER: Elijah Floyd
FIRM: Cascade Drilling
CONSULTING FIRM: Pacific Groundwater Group, Inc.
REPRESENTATIVE: Doug Kelly

LOCATION: 48ø14'14.41635"N,122ø23'43.88270"W
LAND SURFACE ELEVATION 6.60 feet (NAVD 88)
DEPTH TO WATER: 1.41 feet
WATER LEVEL ELEVATION: 5.19 feet (NAVD 88)
WATER LEVEL DATE: 1/10/12
INSTALLED: 10/27/11
DOE TAG: BHK-019

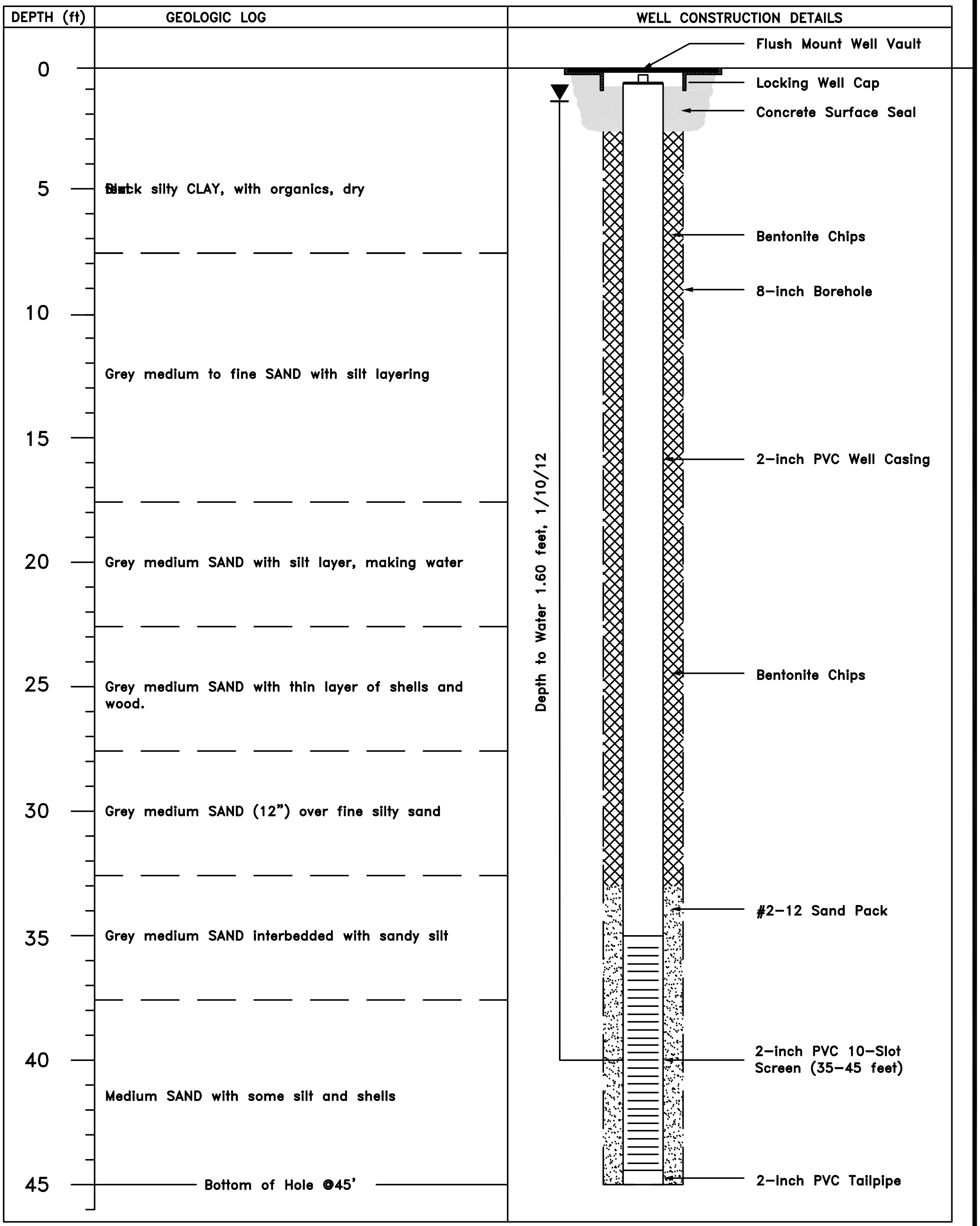
Figure A-5 Geologic Log & Construction of Well S1S



PROJECT NAME: Leque Island Hydrogeologic Study
WELL INDENTIFICATION NUMBER: S1S
DRILLING METHOD: Geoprobe
DRILLER: Elijah Floyd
FIRM: Cascade Drilling
CONSULTING FIRM: Pacific Groundwater Group, Inc.
REPRESENTATIVE: Doug Kelly

LOCATION: 48ø13'58.31920"N,122ø23'40.04967"W
LAND SURFACE ELEVATION 8.36 feet (NAVD 88)
DEPTH TO WATER: 1.69 feet
WATER LEVEL ELEVATION: 6.67 feet (NAVD 88)
WATER LEVEL DATE: 1/10/12
INSTALLED: 10/27/11
DOE TAG: BHK–020

Figure A-6 Geologic Log & Construction of Well S1D



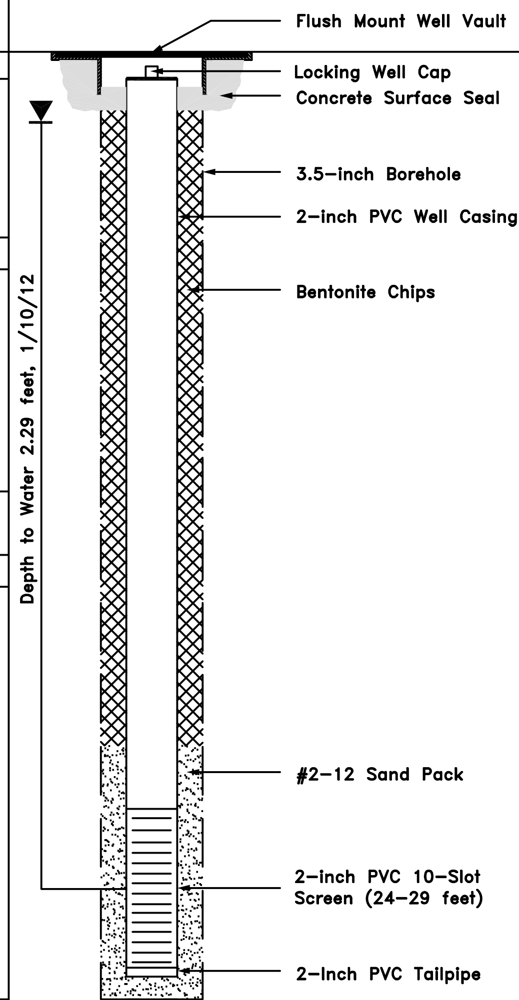
PROJECT NAME: Leque Island Hydrogeologic Study
WELL INDENTIFICATION NUMBER: S1D
DRILLING METHOD: Hollow Stem Auger
DRILLER: Jim Goeble
FIRM: Cascade Drilling
CONSULTING FIRM: Pacific Groundwater Group, Inc.
REPRESENTATIVE: Doug Kelly

LOCATION: 48ø13'58.31920"N,122ø23'40.04967"W
LAND SURFACE ELEVATION 8.43 feet (NAVD 88)
DEPTH TO WATER: 1.60 feet
WATER LEVEL ELEVATION: 6.83 feet (NAVD 88)
WATER LEVEL DATE: 1/10/12
INSTALLED: 10/21/11
DOE TAG: BHJ-590

Figure A-7 Geologic Log & Construction of Well S2S

DEPTH (ft)	GEOLOGIC LOG
0	Brownish–grey SILT with organics, dry
	Brown SAND and GRAVEL, dry to 4 feet
5	
	Brown grading to grey sandy SILT, wet
10	Grey sandy GRAVEL w/ 3" silt layer, wet
15	Brown sandy GRAVEL with small cobbles
	Grey medium SAND, wet
20	
	Brownish grey sandy GRAVEL w/ sand layers
25	
30	Bottom of Hole @30'
35	
40	

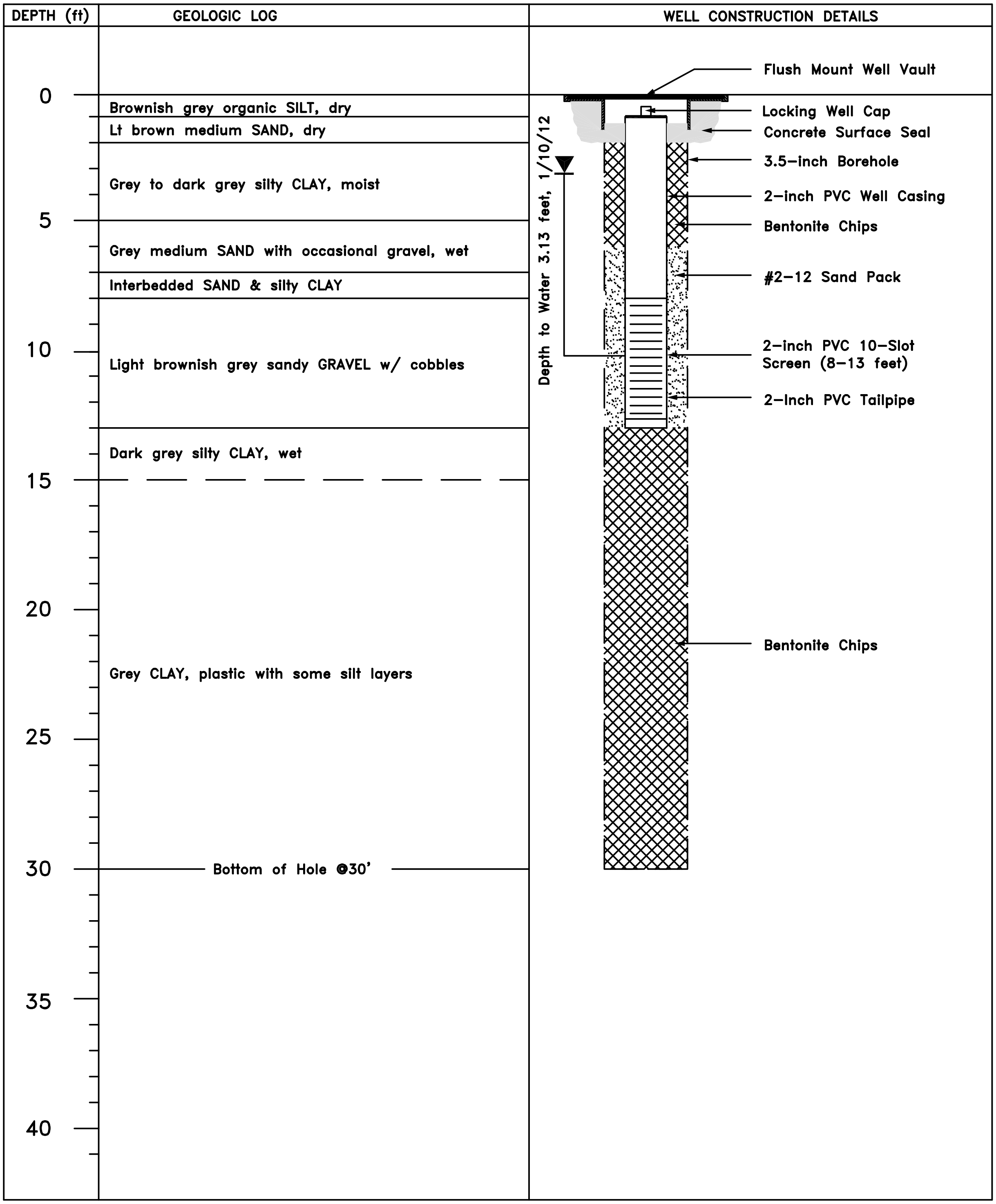
WELL CONSTRUCTION DETAILS



PROJECT NAME: Leque Island Hydrogeologic Study
WELL INDENTIFICATION NUMBER: S2S
DRILLING METHOD: Geoprobe
DRILLER: Elijah Floyd
FIRM: Cascade Drilling
CONSULTING FIRM: Pacific Groundwater Group, Inc.
REPRESENTATIVE: Doug Kelly

LOCATION: 48ø13'57.70625"N,122ø23'51.55699"W
LAND SURFACE ELEVATION 8.83 feet (NAVD 88)
DEPTH TO WATER: 2.29 feet
WATER LEVEL ELEVATION: 6.54 feet (NAVD 88)
WATER LEVEL DATE: 1/10/12
INSTALLED: 10/28/11
DOE TAG: BHK–022

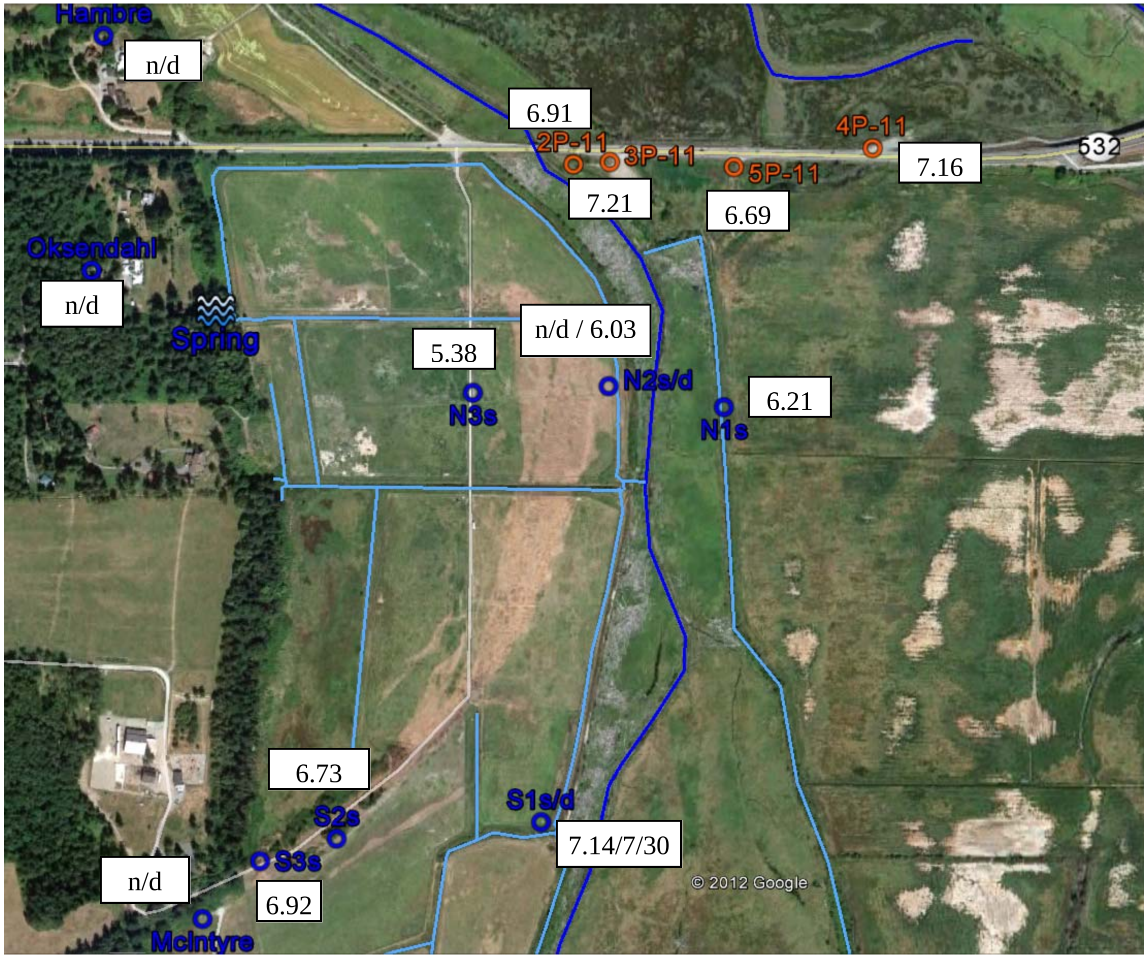
Figure A-8 Geologic Log & Construction of Well S3S



PROJECT NAME: Leque Island Hydrogeologic Study
WELL INDENTIFICATION NUMBER: S3S
DRILLING METHOD: Geoprobe
DRILLER: Elijah Floyd
FIRM: Cascade Drilling
CONSULTING FIRM: Pacific Groundwater Group, Inc.
REPRESENTATIVE: Doug Kelly

LOCATION: 48ø13'56.87370"N,122ø23'55.83387"W
LAND SURFACE ELEVATION 9.94 feet (NAVD 88)
DEPTH TO WATER: 3.13 feet
WATER LEVEL ELEVATION: 6.81 feet (NAVD 88)
WATER LEVEL DATE: 1/10/12
INSTALLED: 10/28/11
DOE TAG: BHK-023

APPENDIX B
SYNOPTIC WATER-LEVEL MAPS

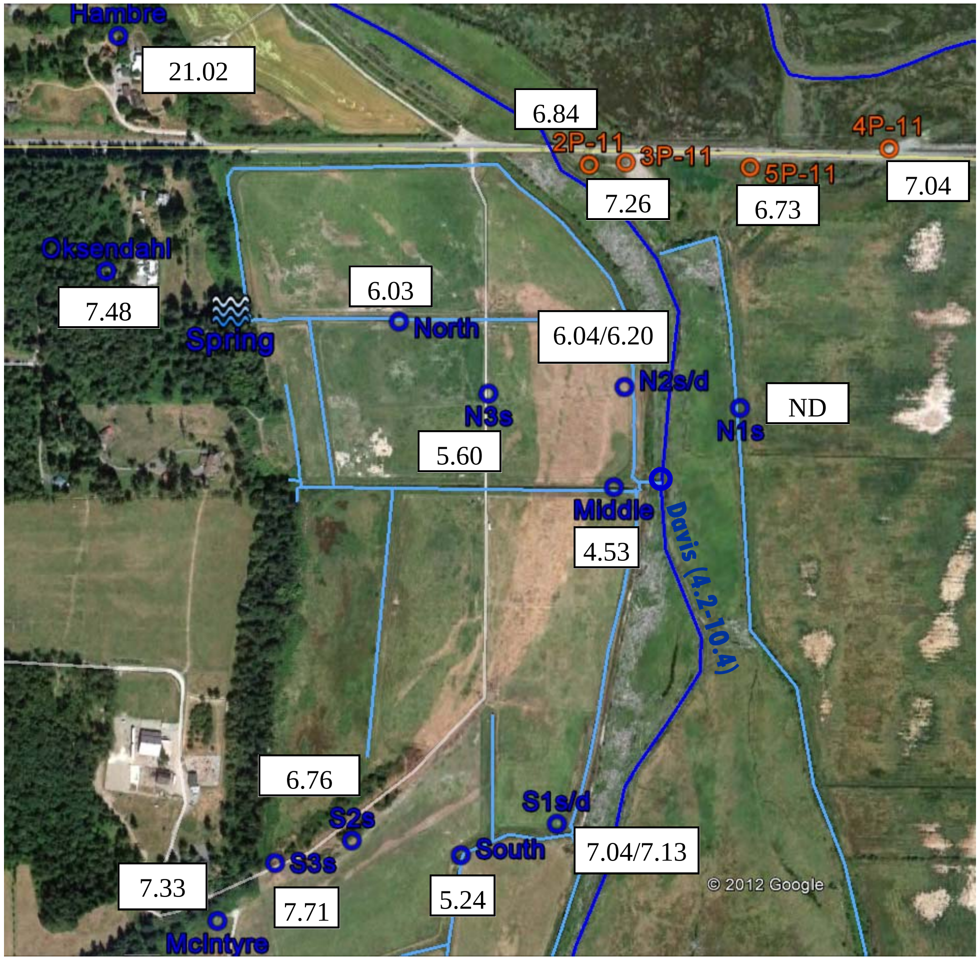


NOTES:
All water level elevations shown as equivalent freshwater head at well screen elevation.
ND = no data available

Figure B-1
Average Water Level Elevations for 3-Day Period Starting 1/5/12

Ducks Unlimited
Leque Island Restoration

PgG

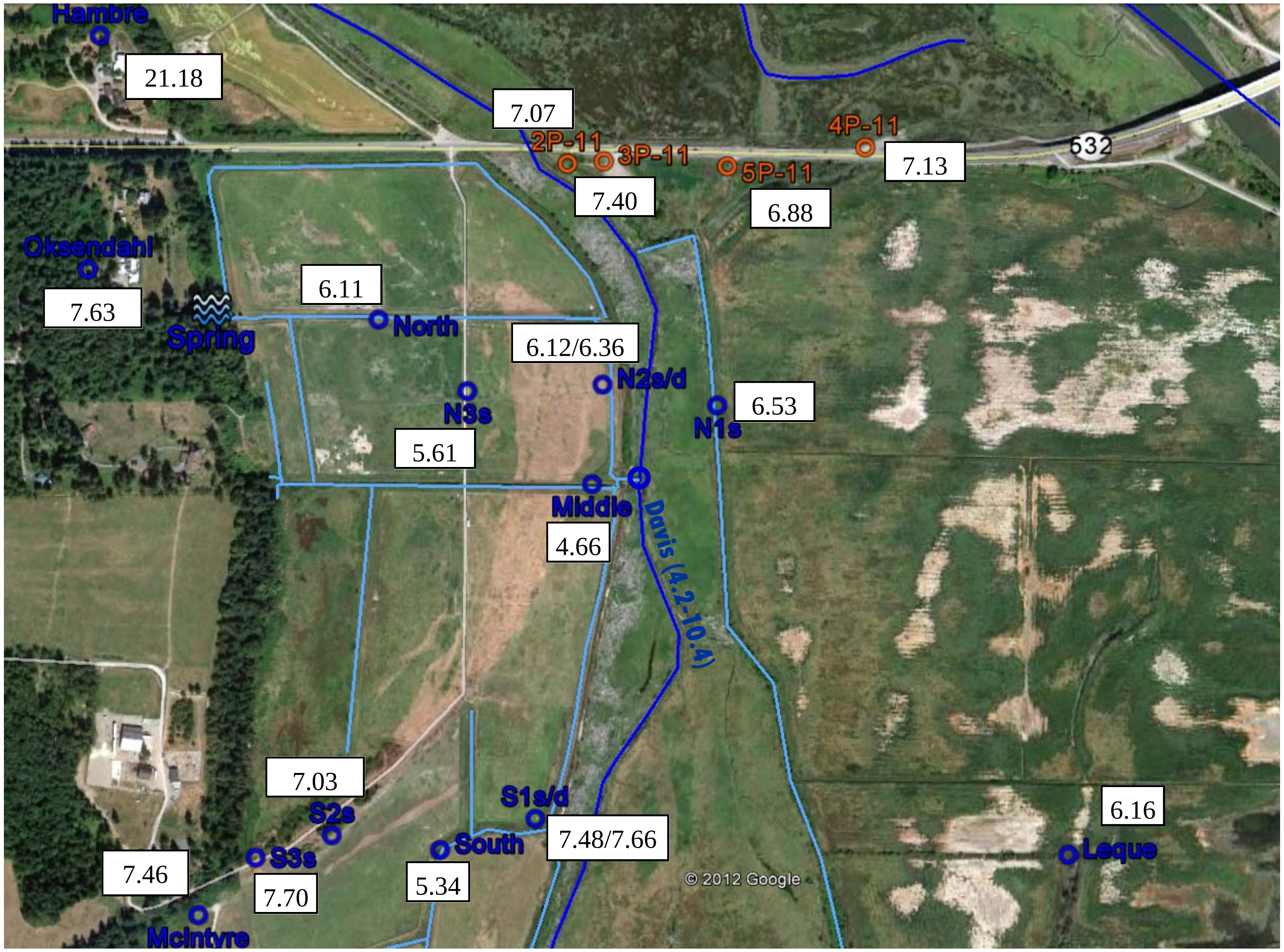


NOTES:
All water level elevations shown as equivalent freshwater head at well screen elevation.
ND = no data available

Figure B-2
Average Water Level Elevations for 3-Day Period Starting 3/7/12

Ducks Unlimited
Leque Island Restoration

PgG

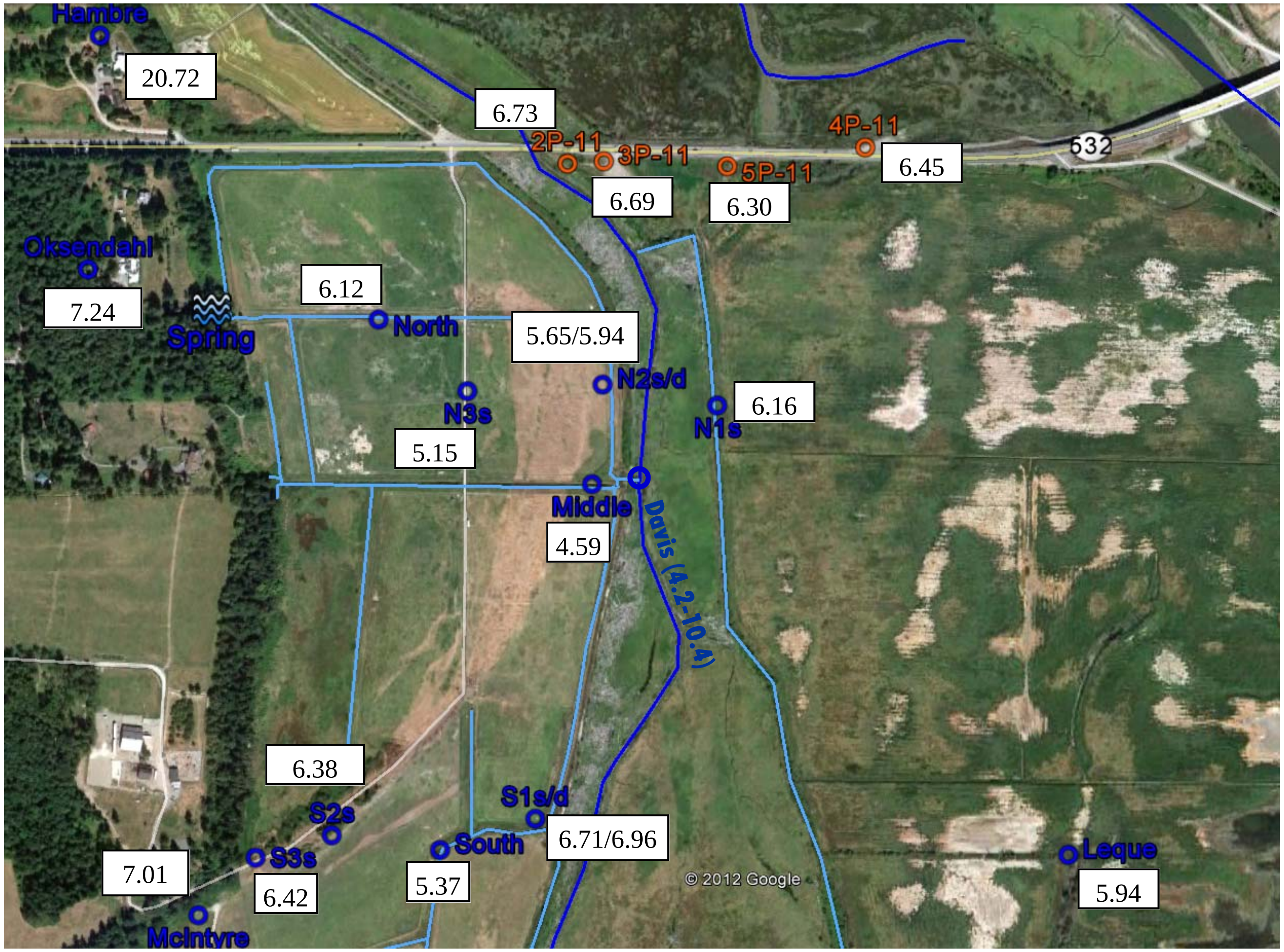


NOTES:
All water level elevations shown as equivalent freshwater head at well screen elevation.
Leque water level taken on 5/22/12.

Figure B-3
Average Water Level Elevations for 3-Day Period Starting 5/8/12

Ducks Unlimited
Leque Island Restoration

PGG

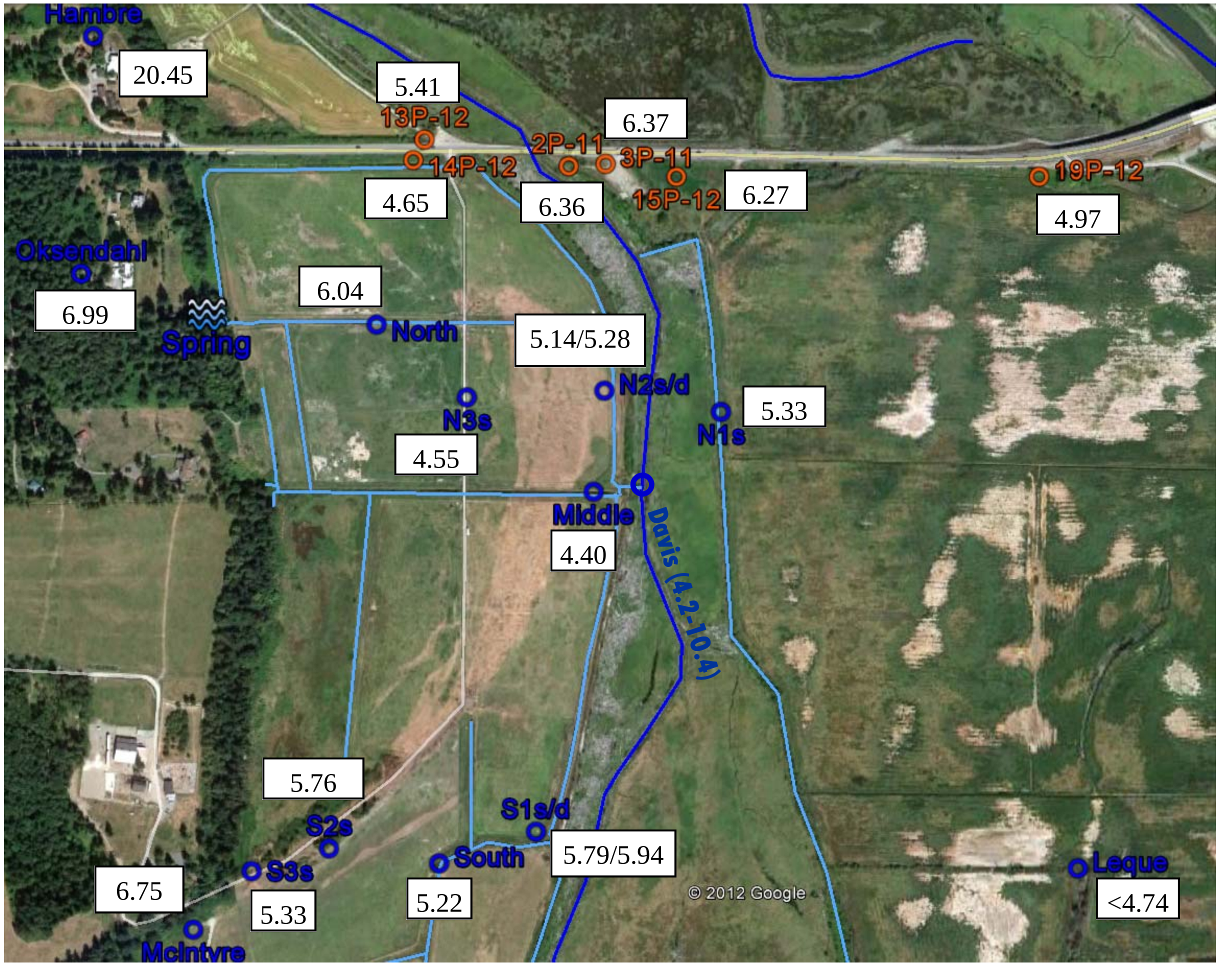


NOTES:
All water level elevations shown as equivalent freshwater head at well screen elevation.

Figure B-4
Average Water Level Elevations for 3-Day Period Starting 7/12/12

Ducks Unlimited
Leque Island Restoration

PgG



NOTES:
All water level elevations shown as equivalent freshwater head at well screen elevation.
Leque ditch dry in early October, assumed same for early September
Accuracy of WDOT elevations????
Davis Slough range based on record from XX—YY.

Figure B-5
Average Water Level Elevations for 3-Day Period Starting 9/4/12

Ducks Unlimited
Leque Island Restoration

PgG

APPENDIX C
DOCUMENTATION OF 3D GROUNDWATER FLOW MODEL

DOCUMENTATION OF 3-D GROUNDWATER FLOW MODEL

This section describes the design, construction, calibration and employment of a three dimensional groundwater flow model prepared to evaluate the impacts of the proposed Leque Island restoration on groundwater levels below Camano Island. Predicted changes in groundwater levels and groundwater flow directions are then interpreted in the context of potential effects on saltwater intrusion susceptibility of the groundwater system beneath Camano Island.

CONCEPTUAL MODEL AND APPROACH

Hydrogeologic conditions in the study area are described in Section 3.3 of the main report. Layered glacial/interglacial units have been characterized beneath the northeast lobe of Camano Island ("Camano Upland"), although local wells typically do not penetrate below about -50 feet NAVD88 and therefore do not document regional units below Aquifer D. The lowland between Camano Island and the mainland ("Leque Lowland") exhibits silty alluvial/marsh sediments near the land surface, gravelly sediments below about -90 feet NAVD88, and intervening silty or sandy alluvial sediments. Within the study area, much of the mainland is occupied by alluvium associated with the Stillaguamish River, although upland areas are underlain by a sequence of glacial/interglacial units that have been defined on a regional scale. The extent to which stratified glacial units below the Camano Island and mainland uplands extend beneath the Leque Lowland is unknown.

Groundwater recharge occurs largely from precipitation. Groundwater discharges predominantly to drainage ditches, other surface-water bodies (Stillaguamish River and Davis Slough), submarine springs in Port Susan and Skagit Bay, evapotranspiration (where groundwater levels are within several feet of the land surface) and pumping wells. Groundwater levels beneath Camano Island are documented in Aquifer D, and while they are only several feet above mean sea level (6 to 7 feet vs. 4.4 feet NAVD88), they are higher than groundwater levels beneath the Leque Lowland. Groundwater levels beneath the lowland are depressed due to discharge to ditches and other surface-water features. Groundwater levels on the mainland are expected to be higher than the Stillaguamish River, as the river is expected to function as a discharge boundary.

Leque Island restoration is estimated to raise groundwater heads beneath the island by an average of 1.2 feet. Groundwater mounding beneath Leque Island will also raise groundwater levels in adjacent areas. The geographic extent of overall mounding will depend on aquifer properties and the extent to which surface-water features surrounding Leque Island (Stillaguamish River, Davis Slough and monitoring-site drainage ditches) will "intercept" the increased head, thus exhibiting increased groundwater discharge. In general, increased heads in the Leque Lowland are expected to be beneficial to groundwater conditions below Camano Island. This is because increased heads in the lowland "discharge area" will cause increased heads in the upland "recharge area". Saltwater intrusion theory dictates that higher freshwater head will result in deepening of the saltwater/freshwater interface (i.e. Ghyben-Herzberg relationship). However, groundwater elevations beneath the eastern portions of Camano Island are relatively low, and theoretically, increased heads beneath Leque Island could locally reverse the flow direction of shallow groundwater such that brackish water beneath the lowlands is carried beneath local portions of eastern Camano Island. Groundwater modeling was performed to evaluate whether such reversed flows are possible or significant beneath the eastern edge of Camano Island.

PGG developed a 3D calibrated model that includes the northeast lobe of Camano Island, the Leque Lowland and the adjacent coastal portion of the mainland (the Stillaguamish Delta and glacial uplands). Whereas the south and west passes of the Stillaguamish River are expected to function as a major hydraulic boundary condition (east of which the impacts of Leque Island restoration are minor), PGG included the mainland areas in case associated hydrogeologic conditions affect model calibration and function. Mainland areas are represented to generally reproduce hydrogeologic conditions (and heads) east of the passes; however, formal model calibration did not extend to these areas.

Because deeper hydrostratigraphy is not well defined beneath the Leque Lowland, PGG created two versions of the model to function as "end members" for likely hydrogeologic interpretation. The "glacial stratigraphy" (GS) version of the model extends the deeper glacial and interglacial units identified beneath Camano Island across the entire model domain. The "lumped anisotropy" (LA) version of the model represents observed textural variation in the alluvial sediments that underlie the lowland areas, but does not attempt to differentiate aquifers or aquitards within these sediments, instead acknowledging the presence of interbedded coarse- and fine-grained sediments based on anisotropy (the ratio of horizontal to vertical hydraulic conductivity).

The impact of Leque Island restoration on Camano Island groundwater conditions may be sensitive to the degree of hydraulic connection between shallow groundwater beneath the island to immediately adjacent surface-water features. The greater these hydraulic connections, the greater the extent to which increased post-restoration heads beneath Leque Island will be "intercepted" and "relieved" due to increased discharge to these features, and will therefore have a lesser affect on Camano Island. For this reason, for each version of the model, PGG created two further model "realizations" over a range of hydraulic connection to these key surface-water features (the "C" versions have more hydraulic connection than the "D" versions). All four versions of the model (GS-C, GS-D, LA-C, LA-D) were run to evaluate hydraulic impacts on Camano Island groundwater due to Leque Island restoration.

GROUNDWATER FLOW MODEL DESIGN

Model Code, Domain and Discretization

The groundwater flow model was developed using the U. S. Geological Survey's finite difference modeling code "MODFLOW-2005" (Harbaugh, 2005). This code was selected it is widely accepted, well validated and technically defensible. PGG used Groundwater Vistas 6.0, a Graphical User Interface (GUI), for processing and viewing input and output MODFLOW files (ESI, 2012).

The total model domain covers approximately 69 square miles, with a north-south dimension of 10 miles and an east-west dimension of 6.8 miles. As shown in **Figure C-1**, the model domain includes the northeast lobe of Camano Island, the Leque Lowland, coastal portions of the mainland and portions of Port Susan Bay, Skagit Bay. The model coordinate system is State Plane North NAD 83 and the vertical datum is NAVD 88 (where mean sea level occurs at an elevation of 4.4 feet).

The model consists of 98 rows and 85 columns with a horizontal grid spacing that ranges from 125x125 foot cells in the Leque Island lowland to 1250x1500 foot cells towards the outer edges of the model domain. The top of the model is the land surface in terrestrial areas (as defined by LiDAR) and mean sea level in marine areas. The model includes 16 horizontal layers: layer 1 has a bottom elevation of -3 feet; layers 2 through 11 are all 10 feet thick and extend down to an elevation of -103 feet; and layers 12 through 16 are all 20 feet thick (extending down to an elevation of -203 feet). The use of horizontal layering allows layers (or portions of layers) to be assigned to specific hydrostratigraphic units (HSU's) where layer elevations and HSU elevations approximately coincide.

Model layer 1 was represented as unconfined, whereas all underlying layers are always fully saturated and were therefore represented as confined. The model was run in steady-state mode to represent long-term average conditions.

Boundary Conditions.

The model uses a variety of MODFLOW packages to represent recharge, evapotranspiration from plants with roots tapping the shallow water table, groundwater withdrawals, drainage ditches, inland surface-water features such as Davis Slough and the Stillaguamish River, and marine surface-water conditions such as Port Susan Bay and Skagit Bay.

Recharge was simulated with MODFLOW's recharge package, which assigns recharge to each cell in the top model layer. **Figure C-2** presents the modeled recharge distribution. Model cells on the Camano Island upland were assigned recharge rates consistent with the distribution estimated by the USGS for Whidbey and Camano Islands (Sumioka & Bauer, 2004). It should be noted that the USGS predict a small area on the southeast corner of the northeast lobe of Camano Island with a dramatically higher recharge rate of 18 in/yr. Model cells on the fine-grained (Qm) sediments of the Leque Lowland were assigned a rate of 6 in/yr, consistent with the USGS estimate of local recharge to fine-grained soils (ibid). Model cells on the coarser-grained (Qa) sediments of the Leque Lowland and the mainland were assigned a rate of 16 in/yr, consistent with recharge estimates in the USGS Snohomish County groundwater evaluation (Thomas et al, 1997). The same rate was assigned to the upland portions of the mainland which are occupied by glacial sediments.

Evapotranspiration was simulated with MODFLOW's "ET" package, which removes groundwater at rates inversely proportional to depth to groundwater beneath the top of the model layer. The ET condition was specified for all terrestrial cells within model layer 1 with an extinction depth of 3.5 feet[5] and a maximum annual ET rate of 16 in/yr. This means that ET will vary linearly between 16 in/yr (where groundwater occurs at the land surface) to zero (where groundwater is at or below 3.5 feet below land surface). Based on this relationship, the model will functionally apply the ET condition only to lowland areas, as the land surface in upland areas is far above simulated water-table elevations. The 16 in/yr maximum ET rate is based on the difference between USGS estimates of actual ET and potential ET in the absence of shallow groundwater (Sumioka & Bauer, 2004). In the presence of shallow groundwater, PGG assumed that the USGS recharge modeling would estimate actual ET as equal to potential ET rather than the (lower) actual ET value which is diminished by reduced soil-water availability during summer months.

Groundwater pumping was simulated with MODFLOW's "Well" package. Because PGG did not attempt to calibrate the model to mainland conditions, pumping was not simulated in mainland areas. Pumping in the rest of the model domain occurs predominantly on Camano Island. Domestic pumping on the island is assumed to be largely non-consumptive due to septic effluent returns; therefore, PGG only simulated pumping withdrawals for irrigation and Juniper Beach Water District (the largest public water system on the modeled portion of the island). **Figure C-1** shows the locations of pumping wells simulated by the model and **Table C-1** summarized modeled pumping rates. A single well was used to represent the 9 gpm average-annual withdrawal by Juniper Beach Water District, and 7 individual wells were used to represent an estimated 213 gpm of annual average irrigation withdrawals. The irrigation withdrawals were specified at irrigation well locations defined by Sapik et al (1988). Irrigation pumping rates were estimated by PGG based on place-of-use polygons associated with irrigation certificates in Ecology's water-right

[5] Although plant roots do not extend as deep as 3.5 feet, capillary action may "wick" water from this depth into the root zone.

database (also shown on **Figure C-1**), an assumed irrigation application of 1.04 feet based on the Washington Irrigation Guide (USDA, 1985), and associating places of use with the 7 wells. All wells were modeled in the upper portion of Aquifer D (model layers 1 through 4).

The Stillaguamish River was represented with MODFLOW's "River" boundary condition. The river condition specifies a river-stage elevation for each cell in the model and a conductance value used to calculate the seepage rate between groundwater and surface-water based on the difference between groundwater and surface-water levels. Seepage rate is linearly proportional to this head difference[6]. Conductance is calculated as riverbed area times riverbed hydraulic conductivity (K_r) divided by riverbed thickness (B). For calculating riverbed area, Groundwater Vistas calculated the length of the river crossing the model cell and PGG employed river widths ranging from 80 to 250 feet based on measurements made in Google Earth. All river cells were assigned a riverbed thickness of 1 foot, and model simulations employed K_r values of 0.1 and 1 ft/d. River stage elevations were specified based on Google Earth and range from sea level (4.4 feet NAVD88) at the mouth to 9.8 feet NAVD88 in the uppermost simulated river cell. Riverbed K_r and B values are summarized on **Table C-2** and model river cells are shown on **Figure C-1**.

Davis Slough and drainage ditches on the monitoring site, Leque Island, and other lowland areas were all represented with MODFLOW's "Drain" boundary condition (**Figure C-1**). The drain condition is similar to the river condition except that seepage can only occur from groundwater *into* the drain (i.e. seepage is zero if groundwater levels are below specified drain elevations). Conductance is calculated as drainbed area times drainbed hydraulic conductivity (K_{dr}) divided by drainbed thickness (B). For calculating drainbed area, Groundwater Vistas calculated the length of the ditch (or slough) crossing the model cell and PGG employed drain widths ranging from 5 to 10 feet for drainage ditches and 20 feet for Davis Slough. All drain cells were assigned a drainbed thickness of 3 feet, and model simulations employed K_{dr} values ranging from 0.01 to 2 ft/d (**Table C-2**). Stage elevations for drains on the monitoring site, Leque Island and Davis Slough were all based on average values derived from monitoring (discussed in Section 3.2 and shown on **Table C-2**). It should again be noted that a 1.7-foot range of drain stages was noted across the monitoring site and a continuous distribution of drain stage was not surveyed; therefore, there is potential error in the modeled distribution of drain stages. In some cases, PGG varied drain stages locally within the observed range to achieve better model calibration. Stage elevations of drains on the mainland and in distant areas of Camano Island were assigned values 1 or 1.5 feet below the representative land-surface elevation of the model cell.

MODFLOW's drain package was also used to represent discharge of submarine springs to Port Susan and Skagit Bays. PGG assumed that any cell coinciding with the seafloor could provide a pathway for groundwater discharge to the bays. PGG used LiDAR bathymetry of the seafloor to assign drain cells where the seafloor intersects the model layers. The drainbed area for all marine drains was based on the cell dimensions (row and column widths), B was assumed to be 10 feet, and seafloor permeability (K_{sf}) values ranged from 0.001 to 0.008 ft/d (**Table C-2**). Drain stages were assumed equal to mean sea level (4.4 feet NAVD88) for cells in model layer 1; however, stages for deeper cells were compensated for the density of seawater[7] to yield equivalent freshwater head values ranging from 4.6 to 8.8 feet depending on the bathymetric depth of the model cell. The locations of marine drain cells are shown on **Figures C-1** and **C-3**.

---

[6] MODFLOW's river condition also specifies a "bottom elevation" such that seepage losses from the river occur at a fixed rate if groundwater levels fall below this elevation. PGG specified a bottom elevation below sea level such that seepage rates are always linearly proportional to head difference.

[7] A density of 1.015 gm/cm^3 was assumed for brackish seawater.

A number of model cells are specified as inactive ("no flow"), as shown on **Figure C-1**. The model actively simulates the northeast lobe of Camano Island; however, all other portions of Camano Island within the model domain are specified as inactive. The boundary between inactive and active corresponds to a groundwater sub-basin boundary defined by Island County (2001). Regions of marine model cells in layers 1 and 2 are also specified as inactive. Inactive marine cells in layers 1 and 2 occur where the bottom elevation of the layer occurs above the actual seafloor elevation. Given that layer 1 has a bottom elevation of -3 feet NAVD88, this layer is actually occupied by seawater in all marine locations, including where its bottom elevation occurs above the seafloor. However, at such locations, the hydraulic connection between the seafloor and the bay is represented with drains in an underlying layer, such that explicit representation of seawater is not needed in cells that do not include the seafloor.

Aquifer Properties

The hydrostratigraphic framework of the study area is described in Section 3.3. Distinct hydrostratigraphic units (HSU's) can be differentiated based on their differing sedimentary textures, hydraulic properties and position in the 3-D framework. The two versions of the model both distribute HSU's to model layers based on representative profiles within sub-regions of the model domain. The model includes the following sub-regions:

- Upland – Camano Island
- Lowland – Monitoring Site
- Lowland – Leque Island
- Lowland – Mainland (Stillaguamish River Delta)
- Upland – Mainland
- Bays

Table C-3 summarizes the HSU profiles within each sub-region and **Figures C-4** through **C-11** show the geographic distribution of associated K values. The GS model projects the glacial stratigraphy defined beneath the Camano Island Upland across the model domain. That is, all Camano Upland HSU's from Aquitard D downward through Aquifer B, are assumed present in all locations. K values are homogeneous within individual layers from model layer 8 through 16. Only the uppermost layers (1 through 7) portray variable HSU's and K values within individual layers. The lowland sub-regions are assigned "silty alluvium" and "sandy alluvium" HSU's, which are distributed according to field observations. Whereas the monitoring site is represented as "silty alluvium" throughout the entire 7-layer upper profile, Leque Island is represented with silty sediments in the top layer (10 feet) above 2 layers (20 feet) of sandy alluvium above 4 layers (40 feet) of silty alluvium. The Stillaguamish River delta on the mainland is represented as approximately 30 feet of sandy sediments over 40 feet of silty sediments. Layers 1 through 7 of the mainland upland are all represented as glacial outwash. Bay sediments are represented as finer-grained (silty) in the upper two layers and coarser-grained within the underlying 5 layers, the entire sequence overlying Aquitard D.

The LA model does not extend the glacial stratigraphy beneath the Camano Island Upland to other model sub-regions. Instead, beneath the mainland upland, the model depicts a glacial sequence of outwash (layers 1-6) over transitional beds (layers 7-13) over undifferentiated glacial sediments (layers 14-16). This stratified sequence is consistent with regional characterization performed by the USGS (Thomas et al, 1997). For the lowland sub-regions, the distribution of alluvium in layers 1-7 is the same as for the GS model, with silty alluvium continuing downward through layer 11. Layers 12-16 are all represented by gravelly alluvium, as observed in the deep WSDOT borings (Section 3.3). The bays are generally represented as fine-grained sediment in the upper two layers overlying coarser-grained sediment in the underlying 14 layers; however, western portions of the shallow Port Susan Bay sediments are represented as coarser-grained.

Each HSU was represented with a hydraulic conductivity "zone" in Groundwater Vistas. Each zone has constant values of horizontal hydraulic conductivity (K_h) and vertical hydraulic conductivity (K_v). **Table C-2** presents the K_h and K_v values assigned to each zone. The model sensitivity to ranges of key K_h and K_v values in each zone was evaluated during sensitivity analysis, and values were selected that yielded acceptable calibration.

MODEL CALIBRATION AND SENSITIVITY ANALYSIS

Calibration is the process of adjusting model parameters within reasonable ranges to achieve acceptable representation of existing conditions with the computer model. Existing conditions are typically defined as a set of calibration targets, which may include: groundwater levels (heads), flows (such as groundwater discharge fluxes to ditches or drains), and gradients (e.g. the upward vertical gradient observed on the monitoring site). Departures from observed calibration targets are called "residuals". The calibration process often includes a sensitivity analysis, to identify which parameters the model is most sensitive to so they can be adjusted during calibration.

Model Targets and Calibration Goals

Field observations available for calibration are somewhat limited. The steady-state model is intended to represent long-term average conditions; however, long-term monitoring of static water levels is largely absent within the study area. Head data used for calibration were limited to average groundwater elevations recorded in monitoring-site wells between November 2011 and September 2012, and single measurements of groundwater levels recorded in Camano Island wells by Island County (predominantly in August of 2001).

Head data from the monitoring site are averaged over most of a single hydrologic year, but are missing the lowest water levels expected to occur during the end of the dry season (late September and October). In addition, groundwater levels are expected to be locally influenced by water levels in the drainage ditches; however, ditch stages vary by at least 1.7 feet across the site and have only been recorded in three locations. Because the actual distribution of ditch stage is unknown, the model incorporates a simplified distribution that may affect the quality of calibration.

Surveyed water level elevations from Camano Island wells each represent a single measurement made during the dry/pumping season, and are therefore expected to represent somewhat depressed groundwater levels. Target values are shown on **Figure C-1**. The only available time-series water-level monitoring on the northeast lobe of Camano Island are from PGG's monitoring of the Oksendahl Well (main report **Figure 1-1**), which occurred over a 5-month period and suggested water-level variations on the order of 1 foot (main report **Figure 3-13**). This range of variation might be applicable to the other Camano Island wells.

Both the PGG and Island County data sets suffer from largely being collected during a single annual period (different periods per data set), and therefore are neither simultaneous nor do they provide indication of year-to-year variability.

Data from the monitoring site also define vertically upward gradients in two well "nests" (N2s/N2d, S1s/S1d). As discussed in Section 3.3.3, observed gradients are on the order of 0.006 ft/ft. Monitoring site data did not include measurement of discharge from the ditches; however, visual observations suggest relatively slow moving water.

Given the limited data available for calibration targets, model calibration goals were generalized to reflect the quality of the data. Calibration goals included:

1. Model residuals on the Camano Island upland should generally be within a foot of observed targets, and generally higher than the observed values.
2. Model residuals within monitoring site wells should generally be within 2/3 of a foot of observed period-of-record averages, with most of the variation attributed to uncertainty in actual ditch stage distribution;
3. Gradients should be upward at the site, and not too large. The head difference between layers 1 and 4 should be on the order of several tenths of a foot; and,
4. Flow to the monitoring site ditches should be relatively low (preferably some fraction of a cfs) as visual observations suggested fairly low rates of flow.

In addition to the guidelines, three statistics are generally used to evaluate the success of calibration (i.e. minimization of residuals). The residual mean (RM) is the sum of all residuals divided by the number of targets. Some residuals are positive and some negative and a well calibrated model that balances the two would result in a low RM-value. The Absolute Residual Mean (ARM) is the sum of the absolute values of the residuals divided by the number of targets. The ARM statistic is a measure of the overall average error. Finally, a comparison of the residual standard deviation to the overall range in target values throughout the model ("Scaled Residual Standard Deviation") is assessed, with a value less than 10% generally considered good.

Sensitivity Analysis

PGG performed an analysis of model sensitivity to various key parameters. The analysis was conducted by varying aquifer, riverbed and drainbed K values by a range of multipliers (0.01, 0.1, 0.3, 3, 10, and 100), and ET rates by a range of multipliers (1.5, 1, 0.7, 0.5) and observing how this perturbation affected the sum of squared calibration residuals (SSR). Drains and rivers were grouped together so that groups of *all* drains on the monitoring site, *all* marine drains, and *all* river cells could be conveniently assessed. Sensitivity analysis results are summarized on **Table C-4**. Not all multipliers are realistic for all parameters, and unrealistic multipliers are grayed-out on the table. Notable changes in SSR indicate that a change in parameter is having a significant change on model predicted heads (where heads are known).

For the GS model, sensitivity analysis indicated that:

- Calibration target residuals are most sensitive to changes in K_{dr} of marine drains, Aquifer D K_h, Aquitard D K_v , and K_h of the coarser marine sediments.
- Calibration target residuals are moderately sensitive to the ET rate, K_h of the sandy alluvium and K_v of the finer-grained bay sediments.
- Calibration target residuals are least sensitive to the remaining parameters evaluated: Aquifer C K_h, Aquitard C K_v, Aquifer B K_h, K_h of the finer marine sediments, K_h and K_h of the silty alluvium, K_{dr} of the monitoring-site and Leque Island ditches, and K_r of the Stillaguamish River.

For the LU model, sensitivity indicated that:

- Calibration target residuals are most sensitive to changes in K_{dr} of marine drains and the K_h and K_v of Aquifer D.
- Calibration target residuals are moderately sensitive to the ET rate, K_h of the coarser bay sediments, K_h of the sandy alluvium, K_h and K_v of the silty alluvium, and K_{dr} of the monitoring site drains.

- Calibration target residuals are least sensitive to the remaining parameters evaluated: Aquifer C K_h, Aquitard C K_v, Aquifer B K_h, K_h and K_v of the finer marine sediments, K_h of the gravelly alluvium, K_h of the mainland outwash, K_v of the mainland transitional beds, K_h of the mainland Qu, K_{dr} of the Leque Island ditches, and K_r of the Stillaguamish River.

Calibration Procedure and Results

Calibration was performed by manually adjusting the most sensitive and moderately sensitive parameters, supplemented with automated adjustment of selected parameters, to achieve the calibration goals discussed above. PGG created two calibrated versions of each model ("C" and "D" versions) such the Leque Lowland drain and Stillaguamish riverbed conductances were an order of magnitude lower in the "D" versions of each model. While this variation made little difference in calibrating the models, it was included because PGG identified the hydraulic connection between shallow groundwater and the surface-water features surrounding Leque Island as a potentially significant factor controlling how water-level changes on Leque Island extend outwards to surrounding areas, including the eastern edge of Camano Island.

Aquifer property values (K_h and K_v) were varied over reasonable ranges. For HSU's on Camano Island, PGG either used values directly from the USGS calibrated model of Camano Island (Sapik et al, 1988) or (for aquifers D and C), varied these parameters within similar ranges considered by the USGS. In general, PGG considered the following K ranges for aquifer materials:

- Silty and interbedded sand/silt aquifer materials were allowed K_h values ranging from 1 to 30 ft/d, and anisotropy ratios (K_h/K_v) of 100 or 1000;
- Sandy aquifer materials were allowed K_h values ranging from 30 to 100 ft/d; and,
- Gravelly aquifer materials were allowed K_h values ranging from 100 to 600 ft/d.

Aquitard K_v's for the layered HSU's beneath Camano Island were set to the values developed by the USGS during their full-island model calibration ($9E^{-4}$ for Aquitard C and $9E^{-5}$ for Aquitard D). For the LA model, the transitional beds (an aquitard in the glacial sequence beneath upland portions of the mainland) was assigned a K_v value of $5E^{-3}$ and not varied during calibration (the model showed little sensitivity to K_v of the transitional beds).

Field observations revealed that bed materials of drainage ditches and Davis Slough were relatively silty and thick (one could sink several feet into silty materials while attempting to stand in a ditch). All drainage ditches were assigned a bed thickness of 3 feet, and due to the loose, silty nature of the drainbeds, associated K_{dr} values ranging from 0.01 to 1 ft/d. Higher energy conditions along the Stillaguamish River combined with low sensitivity to associated K_r values led PGG to assign a K_r value of 1 ft/d and a riverbed thickness of 1 foot, and not adjust these values further during calibration. K_r was further reduced to 0.1 ft/d in the "D" versions of both models, a value which is considered to be conservatively low given higher values of K_r will absorb more of the increased groundwater levels associated with Leque Island restoration. Finally, all marine drains were assumed to have a bed thickness of 10 feet, and because the model was most sensitive to marine K_{dr}, values were simply varied during calibration to achieve a good model "fit". Calibrated values were about an order-of-magnitude lower than terrestrial K_{dr} values. Given that Aquifer D groundwater levels observed along the northern coast of the modeled portion of Camano Island are slightly lower than along the southern coast, PGG found that a better calibration fit was achieved by reducing the conductance of the marine drains in Skagit Bay relative to Port Susan Bay (**Table C-2**).

Modeled groundwater levels and calibration residuals for model versions GS-C and LA-C are presented on **Figures C-12** and **C-13**. Calibration statistics for both the "C" and "D" versions of both models are presented on **Table C-5**, and show very little difference. Model calibration was considered acceptable based on the following observations:

- Most residuals on the Camano Island Uplands are within ± 1 foot. It is worth noting that the (anticipated) bias of over-predicted groundwater levels was not observed in areas of significant groundwater withdrawal.
- Most residuals on the monitoring site are less than 0.75 feet. This scale is considered acceptable given that the actual distribution of ditch stage elevations is unknown, but a range of at least 1.7 feet is observed. Predicted values tend to be low on the south side of the site and mixed (high/low) on the north side. PGG elected not to add undocumented complexity to the model in order to attempt removal of this apparent bias on the south side of the site.
- The model predicts upward gradients beneath the monitoring site. Comparison of modeled heads across the uppermost 30 feet of the shallow aquifer (between layers 1 and 4) shows upward head differences ranging from hundredths of a foot to about a foot, with significant variation with respect to distance from the upland escarpment. These values are consistent with the order of magnitude of the upward gradient observed in the two on-site monitoring well pairs. Additional monitoring well pairs would be needed to ascertain the actual range of upward gradient variation across the monitoring site.
- The model predicts relatively low discharge to the drainage ditches on the monitoring site.
- Calibration statistics are considered acceptable with very low values of residual mean (< 0.1 foot), low-to-moderate values of absolute residual mean (~0.6 feet), and ARM values of 12%. The ARM is slightly higher than the 10% goal; however, this slight offset can reasonably be attributed to uncertainty in model target accuracy.

It should be noted that the model predicts a small area of slightly elevated groundwater level just off the southeast corner of the Camano Island Upland. This minor groundwater mound is associated with USGS-estimated distribution of recharge. Whereas most model cells in this vicinity have USGS recharge estimates less than 8 in/yr, cells coincident with the mound have estimated values of about 18 in/yr.

PREDICTIVE SIMULATIONS

PGG used all four versions of the model to predict the impacts of Leque Island restoration on groundwater conditions beneath Camano Island. Restoration was simulated by replacing the modeled drains in layer 1 within Leque Island with a large area of constant head cells covering most of the island. The constant head cells had a specified head of 6.9 feet NAVD88, consistent with PGG's estimation of post-restoration average groundwater levels on Leque Island (Section 4.2.3). **Figures C-14** thru **C-15** present the predicted model results, each showing predicted drawdowns associated with increased heads on Leque Island (negative drawdowns indicate groundwater rise) and arrows showing the directions of groundwater flow. All results are shown for the shallowest portion of the groundwater flow system (Layer 1), but are very similar in underlying layers. The model simulations predict that:

- Increased groundwater levels beneath Leque Island do not cause a reversal of groundwater flow directions on the eastern edge of Camano Island. The model predicts that post-restoration groundwater flow remains from Camano Island towards the Leque Lowland,

- Groundwater changes on Camano Island due to Leque Island restoration are less than 0.1 feet.

Both of those predictions suggest no increased potential for saltwater intrusion beneath eastern Camano Island. Continued groundwater flow from Camano Island to the Leque Lowland means that brackish groundwater beneath the lowland would not migrate to aquifers beneath Camano Island. Although the predicted rise in groundwater elevation beneath Camano Island is very small, increased groundwater heads generally result in reduced potential for saltwater intrusion because higher freshwater hydraulic heads cause the saltwater interface to deepen, thereby thickening the freshwater lens.

Table C-1
Modeled Pumping Withdrawals

Well	Irrigated Acres / Hookups	x	y	Q (gpm)
Irrigation-1	67	1250477	460572	43.3
Irrigation-2	31	1247061	458428	20.1
Irrigation-3	80	1252515	457615	51.5
Irrigation-4	39	1248645	461023	25.3
Irrigation-5	40	1251188	458301	25.7
Irrigation-6	20	1252574	459254	13.0
Irrigation-7	53	1250218	458964	34.0
Juniper Beach	123	1255300	454865	9.0

NOTES:
All irrigation withdrawals assume an application rate of 1.04 ft/yr.
Juniper Beach Water District has a delivery rate of 109 gpd/hookup based on reported 2009-2011 water use.

Table C-2
Boundary Condition and Aquifer Property Parameters for Calibrated Model Realizations

Model Simulation	ET	Pt. Susan Marine Drains	Skagit Marine Drains	"Middle" Ditch Drains	"North" Ditch Drains	"South" Ditch Drains	Davis Slough Drain	Leque Island Drains	Stilliguamish River
	fpd/depth	Kdr/B (3)	Kdr/B (4)	Kdr/B (10)	Kdr/B (12)	Kdr/B (11)	Kdr/B (15)	Kdr/B (14)	Kr/B (1,2)
15c	.0036/3.5	0.0082/10	0.004/10	0.1/3	0.5/3	0.1/3	0.1/3	2.0/3	1.0/1
15d	.0036/3.5	0.0082/10	0.004/10	0.01/3	0.05/3	0.01/3	0.01/3	0.2/3	0.1/1
16c	.0036/3.5	0.0055/10	0.001/10	0.1/3	0.5/3	0.05/3	0.1/3	0.5/3	1.0/1
16d	.0036/3.5	0.0055/10	0.001/10	0.01/3	0.05/3	0.01/3	0.01/3	0.05/3	0.1/1
Water Level Stage	*n/a*	*4.4 - 4.6*	*4.4 - 8.8*	*4.6*	*6.1*	*5.3*	*6.1*	*6.0*	*4.4 - 9.8*

Model Simulation	Aquifer D	Aquifer D	Aquitard D	Aquifer C	Aquitard C	Aquifer B	Finer Bay Sediments	Coarser Bay Sediments	Sandy Alluvium	Silty Alluvium	Gravelly Alluvium	Mainland Outwash	Mainland Trans Bed	Mainland Qu
	Kh/Kv (11)	Kh/Kv (14)	Kv (15)	Kh/Kv (13)	Kv (16)	Kh/Kv (17)	Kh/Kv (5)	Kh/Kv (6)	Kh/Kv (1)	Kh/Kv (2)	Kh/Kv (3)	Kh/Kv (8)	Kv (9)	Kh/Kv (10)
15c	545	8	9.E-05	250	9.E-04	4	10/0.1	150/15	40/4	10/0.01	n/a	50/5	n/a	n/a
15d	545	8	9.E-05	250	9.E-04	4	10/0.1	150/15	40/4	10/0.01	n/a	50/5	n/a	n/a
16c	150	8	9.E-05	150	9.E-04	4	10/0.1	150/15	50/5	10/0.01	150/15	50/5	0.005	30/3
16d	150	8	9.E-05	150	9.E-04	4	10/0.1	150/15	50/5	10/0.01	150/15	50/5	0.005	30/3

NOTES
Model zone or reach number in parenthesis
Water level stage elevations reported in NAVD88.
Abbreviations: fpd = feet per day, B = thickness of streambed or drainbed, Kdr = hydraulic conductivity of drainbed, Kr = hydraulic conductivity of riverbed

Table C-3
Hydrostratigraphic Units and Model Layering

"Glacially Stratified" Model (v15)

Layer	Top Elev	Bot Elev	Upland - Camano	Lowland - Monit Site	Lowland - Leque Is.	Lowland - Mainland	Upland - Mainland	Bays	Marine Drains
1		-3	Aquifer D (11/14)	Alluvium Silty (2)	Alluvium Silty (2)	Alluvium Sandy (1)	Mainland Outwash (8)	Bay - Finer Grained (5)	extensive, mudflat
2	-3	-13	Aquifer D (11/14)	Alluvium Silty (2)	Alluvium Sandy (1)	Alluvium Sandy (1)	Mainland Outwash (8)	Bay - Finer Grained (5)	extensive, mudflat
3	-13	-23	Aquifer D (11/14)	Alluvium Silty (2)	Alluvium Sandy (1)	Alluvium Sandy (1)	Mainland Outwash (8)	Bay - Coarser Grained (6)	few, scattered, just Pt Susan
4	-23	-33	Aquifer D (11/14)	Alluvium Silty (2)	Alluvium Silty (2)	Alluvium Silty (2)	Mainland Outwash (8)	Bay - Coarser Grained (6)	few, scattered, just Pt Susan
5	-33	-43	Aquifer D (11/14)	Alluvium Silty (2)	Alluvium Silty (2)	Alluvium Silty (2)	Mainland Outwash (8)	Bay - Coarser Grained (6)	few, scattered, just Pt Susan
6	-43	-53	Aquifer D (11/14)	Alluvium Silty (2)	Alluvium Silty (2)	Alluvium Silty (2)	Mainland Outwash (8)	Bay - Coarser Grained (6)	few, scattered, just Pt Susan
7	-53	-63	Aquifer D (11/14)	Alluvium Silty (2)	Alluvium Silty (2)	Alluvium Silty (2)	Mainland Outwash (8)	Bay - Coarser Grained (6)	few, scattered, just Pt Susan
8	-63	-73	Aquitard D (15)	Aquitard D (15)	Aquitard D (15)	Aquitard D (15)	Aquitard D (15)	Aquitard D (15)	few, scattered, just Pt Susan
9	-73	-83	Aquitard D (15)	Aquitard D (15)	Aquitard D (15)	Aquitard D (15)	Aquitard D (15)	Aquitard D (15)	few, scattered, just Pt Susan
10	-83	-93	Aquifer C (13)	Aquifer C (13)	Aquifer C (13)	Aquifer C (13)	Aquifer C (13)	Aquifer C (13)	few, scattered, just Pt Susan
11	-93	-103	Aquifer C (13)	Aquifer C (13)	Aquifer C (13)	Aquifer C (13)	Aquifer C (13)	Aquifer C (13)	few, scattered, just Pt Susan
12	-103	-123	Aquifer C (13)	Aquifer C (13)	Aquifer C (13)	Aquifer C (13)	Aquifer C (13)	Aquifer C (13)	few, scattered, just Pt Susan
13	-123	-143	Aquitard C (16)	Aquitard C (16)	Aquitard C (16)	Aquitard C (16)	Aquitard C (16)	Aquitard C (16)	few, scattered, just Pt Susan
14	-143	-163	Aquitard C (16)	Aquitard C (16)	Aquitard C (16)	Aquitard C (16)	Aquitard C (16)	Aquitard C (16)	few, scattered, just Pt Susan
15	-163	-183	Aquitard C (16)	Aquitard C (16)	Aquitard C (16)	Aquitard C (16)	Aquitard C (16)	Aquitard C (16)	few, scattered, just Pt Susan
16	-183	-203	Aquifer B (17)	Aquifer B (17)	Aquifer B (17)	Aquifer B (17)	Aquifer B (17)	Aquifer B (17)	few, scattered, just Pt Susan

"Lumped Anisotropy" Model (v16)

Layer	Top Elev	Bot Elev	Upland - Camano	Lowland - Monit Site	Lowland - Leque	Lowland - Mainland	Upland - Mainland	Bays	Marine Drains
1		-3	Aquifer D (11/14)	Alluvium Silty (2)	Alluvium Silty (2)	Alluvium Sandy (1)	Outwash (8)	Bay - Finer Grained (5)	extensive, mudflat
2	-3	-13	Aquifer D (11/14)	Alluvium Silty (2)	Alluvium Sandy (1)	Alluvium Sandy (1)	Outwash (8)	Bay - Finer Grained (5)	extensive, mudflat
3	-13	-23	Aquifer D (11/14)	Alluvium Silty (2)	Alluvium Sandy (1)	Alluvium Sandy (1)	Outwash (8)	Bay - Coarser Grained (6)	few, scattered, just Pt Susan
4	-23	-33	Aquifer D (11/14)	Alluvium Silty (2)	Alluvium Silty (2)	Alluvium Silty (2)	Outwash (8)	Bay - Coarser Grained (6)	few, scattered, just Pt Susan
5	-33	-43	Aquifer D (11/14)	Alluvium Silty (2)	Alluvium Silty (2)	Alluvium Silty (2)	Outwash (8)	Bay - Coarser Grained (6)	few, scattered, just Pt Susan
6	-43	-53	Aquifer D (11/14)	Alluvium Silty (2)	Alluvium Silty (2)	Alluvium Silty (2)	Outwash (8)	Bay - Coarser Grained (6)	few, scattered, just Pt Susan
7	-53	-63	Aquifer D (11/14)	Alluvium Silty (2)	Alluvium Silty (2)	Alluvium Silty (2)	Transitional Bed (9)	Bay - Coarser Grained (6)	few, scattered, just Pt Susan
8	-63	-73	Aquitard D (15)	Alluvium Silty (2)	Alluvium Silty (2)	Alluvium Silty (2)	Transitional Bed (9)	Bay - Coarser Grained (6)	few, scattered, just Pt Susan
9	-73	-83	Aquitard D (15)	Alluvium Silty (2)	Alluvium Silty (2)	Alluvium Silty (2)	Transitional Bed (9)	Bay - Coarser Grained (6)	few, scattered, just Pt Susan
10	-83	-93	Aquifer C (13)	Alluvium Silty (2)	Alluvium Silty (2)	Alluvium Silty (2)	Transitional Bed (9)	Bay - Coarser Grained (6)	few, scattered, just Pt Susan
11	-93	-103	Aquifer C (13)	Alluvium Silty (2)	Alluvium Silty (2)	Alluvium Silty (2)	Transitional Bed (9)	Bay - Coarser Grained (6)	few, scattered, just Pt Susan
12	-103	-123	Aquifer C (13)	Alluvium Gravelly (3)	Alluvium Gravelly (3)	Alluvium Gravelly (3)	Transitional Bed (9)	Bay - Coarser Grained (6)	few, scattered, just Pt Susan
13	-123	-143	Aquitard C (16)	Alluvium Gravelly (3)	Alluvium Gravelly (3)	Alluvium Gravelly (3)	Transitional Bed (9)	Bay - Coarser Grained (6)	few, scattered, just Pt Susan
14	-143	-163	Aquitard C (16)	Alluvium Gravelly (3)	Alluvium Gravelly (3)	Alluvium Gravelly (3)	Qu (10)	Bay - Coarser Grained (6)	few, scattered, just Pt Susan
15	-163	-183	Aquitard C (16)	Alluvium Gravelly (3)	Alluvium Gravelly (3)	Alluvium Gravelly (3)	Qu (10)	Bay - Coarser Grained (6)	few, scattered, just Pt Susan
16	-183	-203	Aquifer B (17)	Alluvium Gravelly (3)	Alluvium Gravelly (3)	Alluvium Gravelly (3)	Qu (10)	Bay - Coarser Grained (6)	few, scattered, just Pt Susan

NOTES:
Hydraulic conductivity zone number in parenthesis

Type of HSU:

- (cyan) - highly permeable aquifer
- (light blue) - moderately permeable aquifer
- (light green) - relatively low permeability aquifer
- (pink) - aquitard

Table C-4
Sensitivity Analysis Results

Lumped Anisotropy Model (V16C) Hydraulic Conductivity Values

	Aquifer D	Aquifer D	Aquitard D	Aquifer C	Aquitard C	Aquifer B	Finer Bay Seds	Finer Bay Seds	Coarser Bay Seds	Sandy Alluvium	Silty Alluvium	Silty Alluvium	Gravelly Alluvium	Mainland Outwash	Mainland Transit. Beds	Mainland Qu	Marine Drains	Monitor Site Drains	Leque Is Drains	Stilliguamish River
Orig Value (ft/d) →	150 ft/d	8 ft/d	0.00009	150	0.0009	4	10	0.1	150	50	10	0.01	150	50	0.005	30	.001-.005	0.5	0.5	1
Multiplier ↓	Kh (11)	Kh (14)	Kv (15)	Kh (13)	Kv (16)	Kh (17)	Kh (5)	Kv (5)	Kh (6)	Kh (1)	Kh (2)	Kv (2)	Kh (3)	Kh (8)	Kv (9)	Kh (10)	Kdr	Kdr	Kdr	Kr
0.1	850%	777%	96%	99%	100%	100%	100%	100%	270%	93%	95%	106%	103%	99%	102%	101%	230%	97%	100%	99%
0.3	186%	203%	96%	100%	100%	100%	100%	99%	128%	94%	97%	102%	101%	99%	101%	100%	129%	98%	100%	100%
1	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
3	120%	167%	117%	100%	100%	100%	100%	101%	111%	115%	105%	103%	99%	101%	99%	100%	127%	104%	100%	100%
10	140%	232%	164%	101%	100%	100%	101%	102%	123%	135%	114%	111%	99%	101%	99%	100%	168%	110%	100%	100%

Glacial Stratified Model (V15C) Hydraulic Conductivity Values

	Aquifer D	Aquifer D	Aquitard D	Aquifer C	Aquitard C	Aquifer B	Finer Bay	Finer Bay	Coarser Bay	Sandy Alluvium	Silty Alluvium	Silty Alluvium	Gravelly Alluvium	Mainland Outwash	Transit. Beds	Mainland Qu	Marine Drains	Monit. Site Drains	Leque Is Drains	Stilliguamish River
Orig Value (ft/d) →	545	8	0.00009	250	0.0009	4	10	0.1	150	40	10	0.01	n/a	50	n/a	n/a	.004-.008	0.1 - 0.5	2	1
Multiplier ↓	Kh (11)	Kh (14)	Kv (15)	Kh (13)	Kv (16)	Kh (17)	Kh (5)	Kv (5)	Kh (6)	Kh (1)	Kh (2)	Kv (2)	Kh (3)	Kh (8)	Kv (9)	Kh (10)	Kdr	Kdr	Kdr	Kr
0.01	5072%	4839%	103%	105%	100%	100%	101%	517%	946%	118%	123%	126%	n/a	193%	n/a	n/a	9479%	99%	100%	102%
0.1	308%	1043%	101%	105%	100%	100%	101%	125%	384%	109%	98%	114%	n/a	126%	n/a	n/a	1586%	99%	100%	100%
0.3	125%	252%	97%	100%	100%	100%	101%	105%	184%	103%	99%	105%	n/a	107%	n/a	n/a	345%	100%	100%	100%
1	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	n/a	100%	n/a	n/a	100%	100%	100%	100%
3	100%	167%	115%	103%	100%	100%	99%	99%	104%	104%	100%	99%	n/a	99%	n/a	n/a	130%	101%	100%	100%
10	102%	236%	172%	105%	100%	100%	97%	99%	119%	114%	101%	99%	n/a	99%	n/a	n/a	199%	103%	100%	100%
100	103%	286%	272%	105%	100%	100%	106%	99%	123%	114%	112%	99%	n/a	100%	n/a	n/a	280%	107%	100%	100%

Evapotranspiration (ET) Rates

Orig Value (in/yr) ↘	V16C	V15C
Multiplier ↓	16	16
0.5	145%	141%
0.7	102%	101%
1	100%	79%
1.5	147%	100%

NOTES:

Zone and reach numbers shown in parentheses.

Results of ET sensitivity shown seperately due to different range of multipliers

Unrealistic values shown in gray.

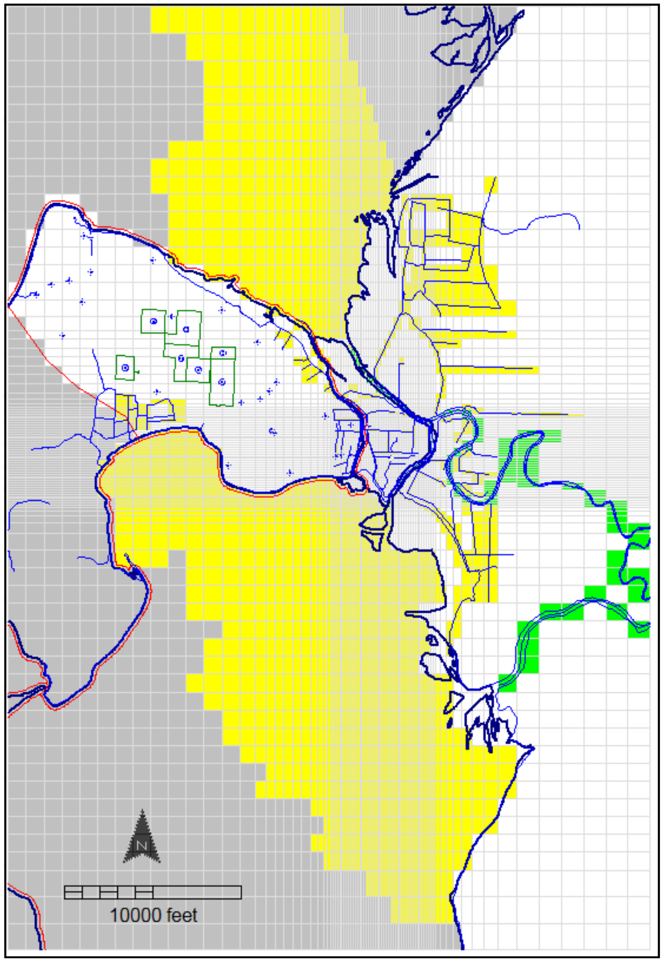
Relative Sensitivity:

- low
- medium
- high

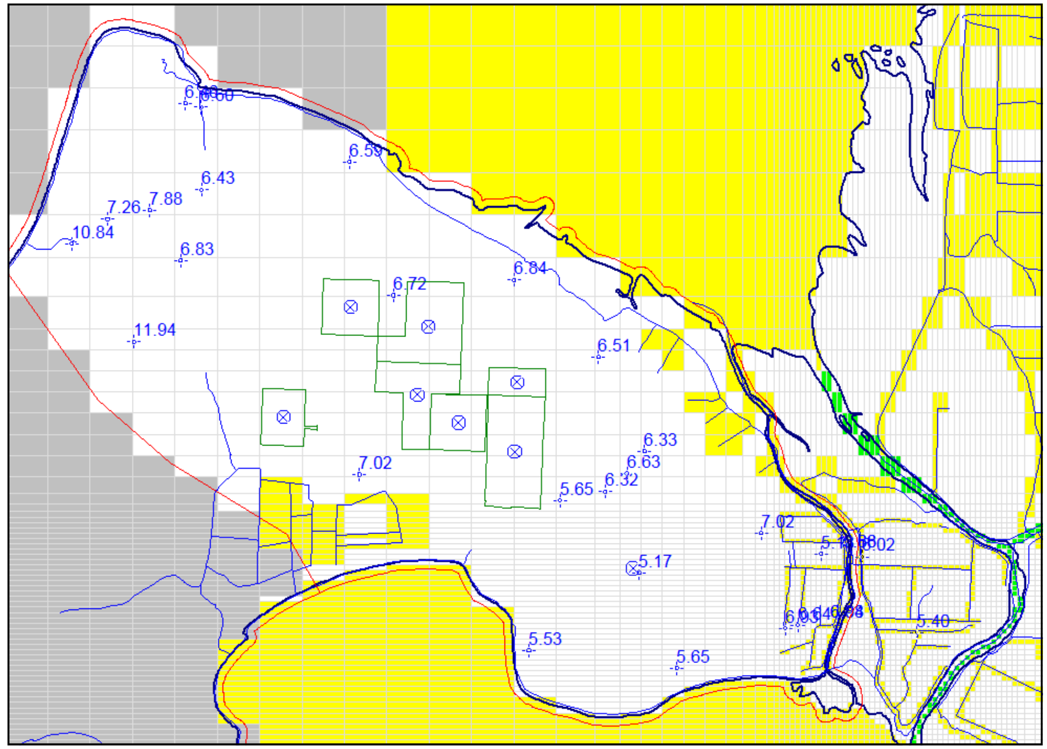
Table C-5
Model Calibration Results

Target Name	Observed Head (ft)	Residual GS 15-C	Residual GS 15-D	Residual LA 16-C	Residual LA 16-D
Well 6.8a	6.8	0.35	0.32	0.65	0.64
Well 6.7	6.7	0.15	0.13	0.43	0.42
Well 6.5a	6.5	0.04	0.01	0.37	0.36
Well 6.6a	6.6	-0.02	-0.03	0.23	0.23
Well 7	7.0	0.49	0.47	0.82	0.81
Well 5.6	5.6	-0.93	-0.96	-0.72	-0.73
Well 6.3	6.3	-0.24	-0.27	-0.07	-0.08
Well 6.6b	6.6	0.04	0.01	0.17	0.16
Well 6.3	6.3	-0.27	-0.30	-0.14	-0.16
Well 6.4	6.4	-0.34	-0.35	-0.45	-0.45
Well 6.8b	6.8	-0.51	-0.53	-0.65	-0.66
Well 6.6c	6.6	-0.06	-0.07	0.05	0.05
Well 7.9	7.9	-0.18	-0.19	-0.15	-0.16
Well 6.5b	6.5	-0.47	-0.49	-0.35	-0.36
Well 11.9	11.9	2.41	2.39	2.49	2.49
Well 5.2	5.2	-1.42	-1.45	-1.28	-1.30
Well 7.3	7.3	-2.21	-2.23	-2.01	-2.01
Well 5.5	5.5	-0.78	-0.80	-0.26	-0.27
Well 10.8	10.8	0.53	0.52	0.76	0.76
Well 5.7	5.7	-0.82	-0.85	-0.40	-0.41
Oksendahl	7.3	0.40	0.36	0.74	0.71
N1S	6.0	0.28	0.17	0.53	0.46
N2D	5.9	-0.36	-0.45	0.21	0.16
N2S	5.7	-0.13	-0.27	0.09	-0.01
N3S	5.2	-0.64	-0.75	-0.48	-0.56
S1D	7.0	0.90	0.80	1.16	1.11
S1S	6.8	0.84	0.70	0.98	0.91
S2S	6.6	0.35	0.28	0.52	0.47
S3S	6.9	0.47	0.40	0.58	0.53
Leque	5.4	0.02	-0.05	0.18	0.14
Residual Mean	- - -	-0.07	-0.12	0.13	0.11
Absoluate Residual Mean	- - -	0.55	0.55	0.60	0.59
Residual Std. Deviation	- - -	0.79	0.79	0.80	0.79
Sum of Squares	- - -	18.95	18.90	19.60	19.22
RMS Error	- - -	0.79	0.79	0.81	0.80
Min. Residual	- - -	-2.21	-2.23	-2.01	-2.01
Max. Residual	- - -	2.41	2.39	2.49	2.49
Number of Observations	- - -	30.00	30.00	30.00	30.00
Range in Observations	- - -	6.77	6.77	6.77	6.77
Scaled Residual Std. Deviation	- - -	12%	12%	12%	12%
Scaled Absolute Residual Mean	- - -	8%	8%	9%	9%
Scaled RMS Error	- - -	12%	12%	12%	12%
Scaled Residual Mean	- - -	-1%	-2%	2%	2%
Drain Flux on Monitoring Site (cfs)		0.019	0.002	0.013	0.002

NOTES:
All values in feet unless otherwise specified.
Residual = observed minus modeled value.



Detailed View of Camano Island Upland and Leque Lowland



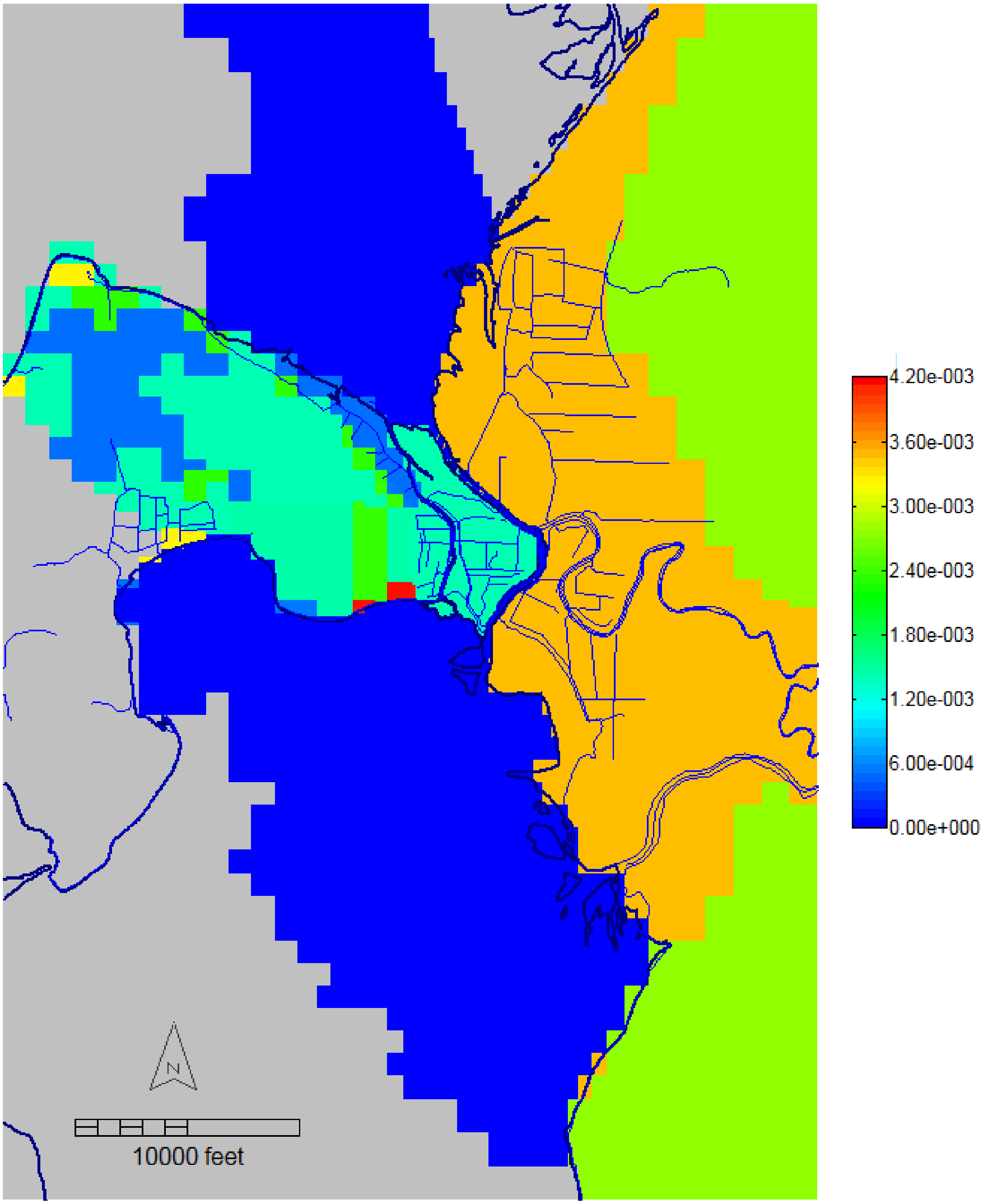
NOTES:

Inactive Model Cell	6.51 Calibration Target (and Target Value)
Drain Cell	Irrigated Field
River Cell	Groundwater Sub-Basin Boundary
Well	Terrestrial inactive cells occur in all model layers. Marine only in layers 1 & 2.

Figure C-1
Model Grid, Calibration Targets and Layer-1 Boundary Conditions

Ducks Unlimited
Leque Island Restoration

PgG



NOTES:

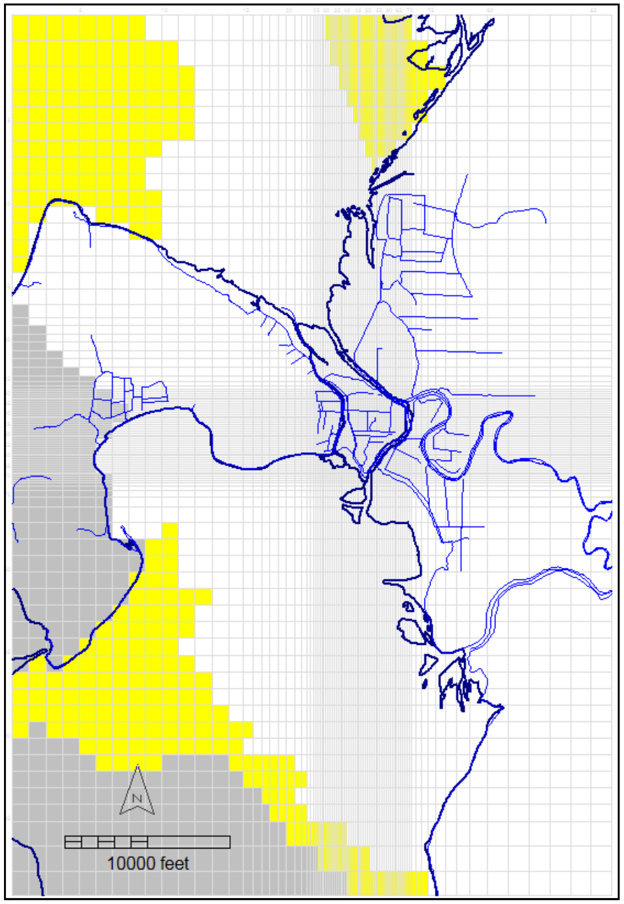
All values in feet per day.
From Sumioka & Bauer, 2004.

Figure C-2
Distribution of Model Recharge

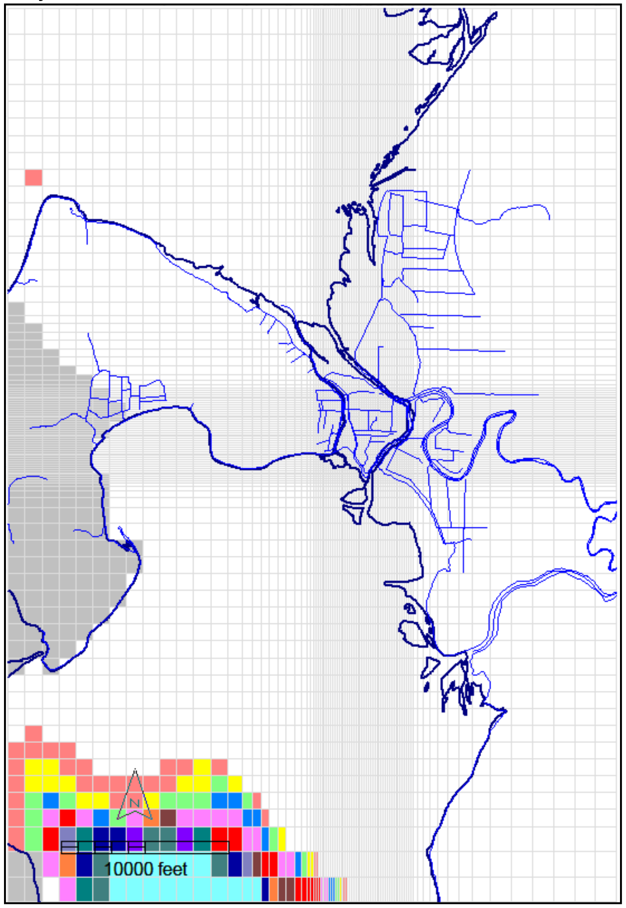
Ducks Unlimited
Leque Island Restoration

PGG

Layer 2



Layers 3-16



NOTES:
Drains in layers 3 thru 16 are grouped by colors, with northernmost drains positioned in layer 3 and southernmost drains positioned in layer 16. Drain layer assignments based on intersection of bathymetry and model layering.

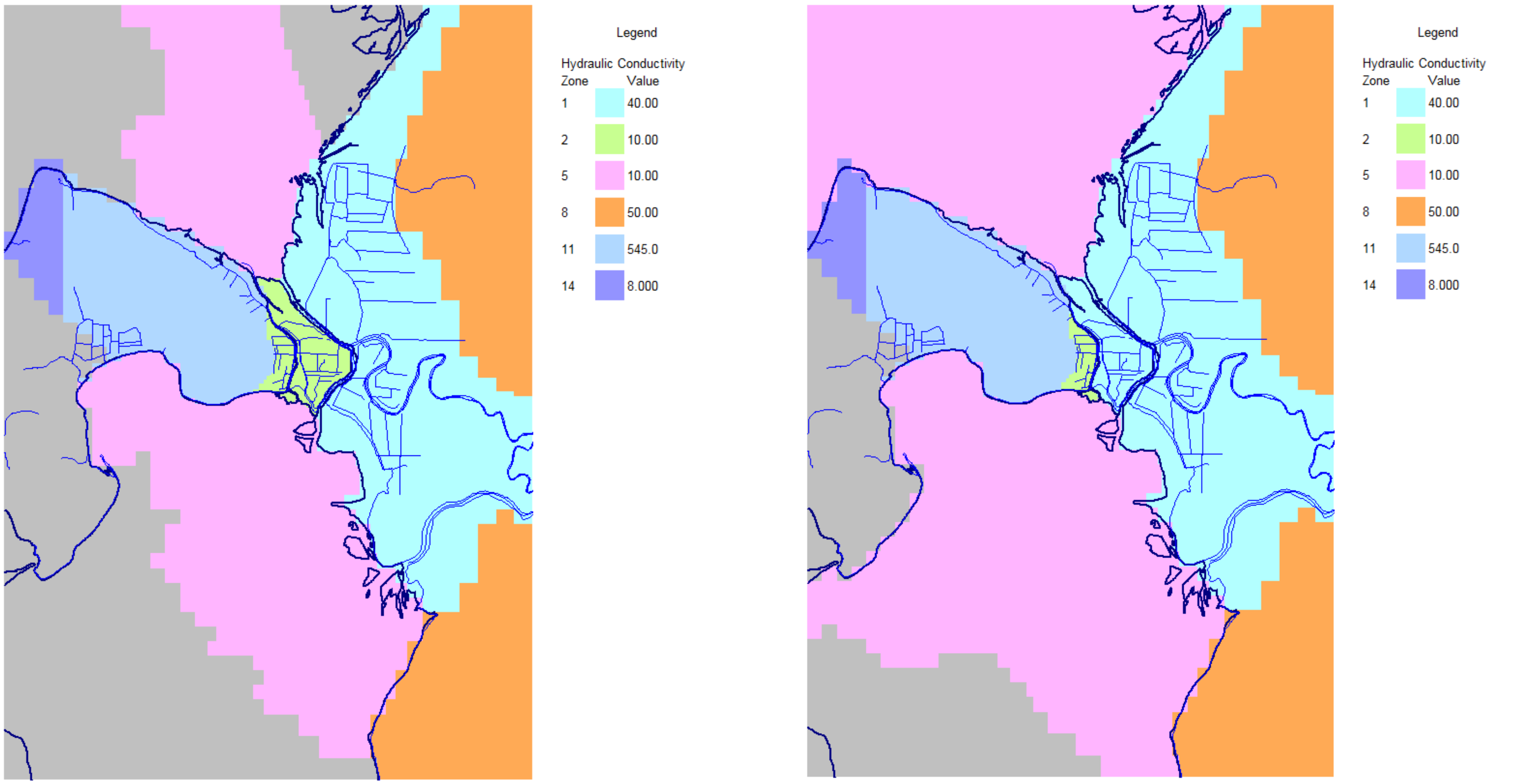
Figure C-3
Distribution of Drain Cells in Model Layers 2 thru 16

Ducks Unlimited
Leque Island Restoration

PgG

Layer 1

Layer 2



NOTES:

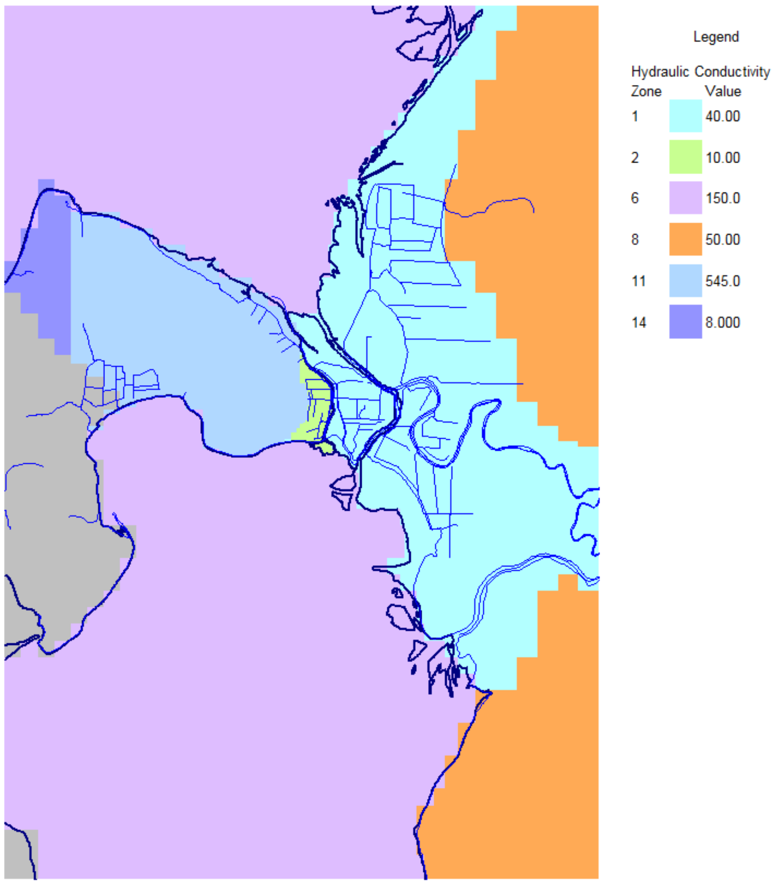
Hydraulic conductivity values listed are horizontal. For vertical hydraulic conductivity values see Table C-2.

Figure C-4
GS Model Hydraulic Conductivity Distribution

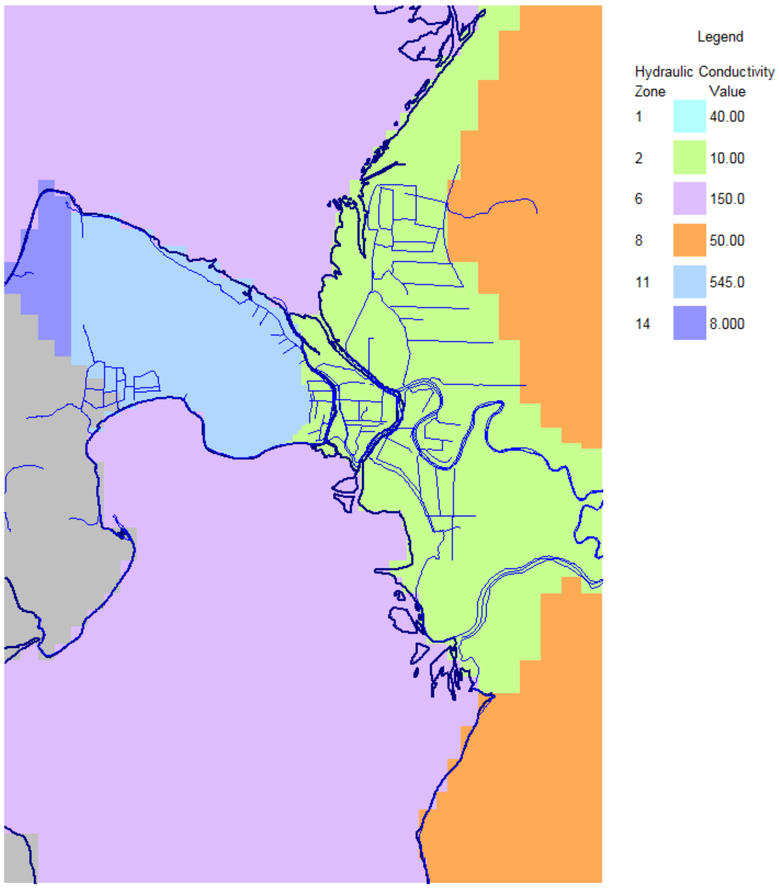
Ducks Unlimited
Leque Island Restoration

PgG

Layer 3



Layers 4-7



NOTES:

Hydraulic conductivity (K) distribution values for layers 8 thru 16 are uniform per layer in the GS Model. See Table C-2 for summary of K values per GS model layer.

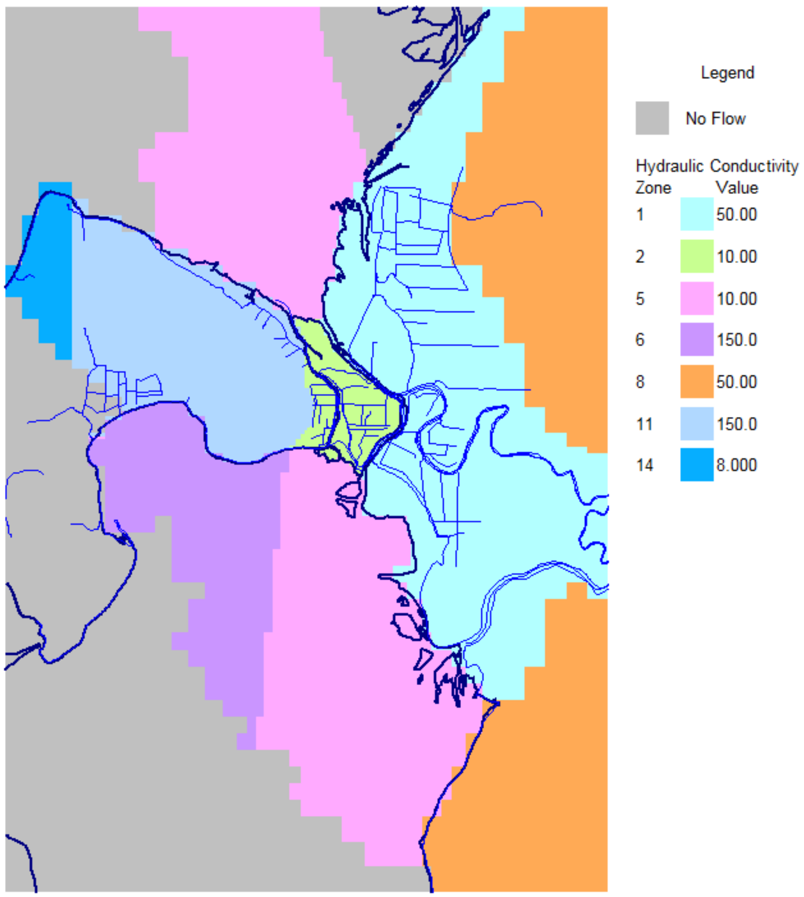
Hydraulic conductivity values listed are horizontal. For vertical hydraulic conductivity values see Table C-2.

Figure C-5
GS Model Hydraulic Conductivity Distribution (cont)

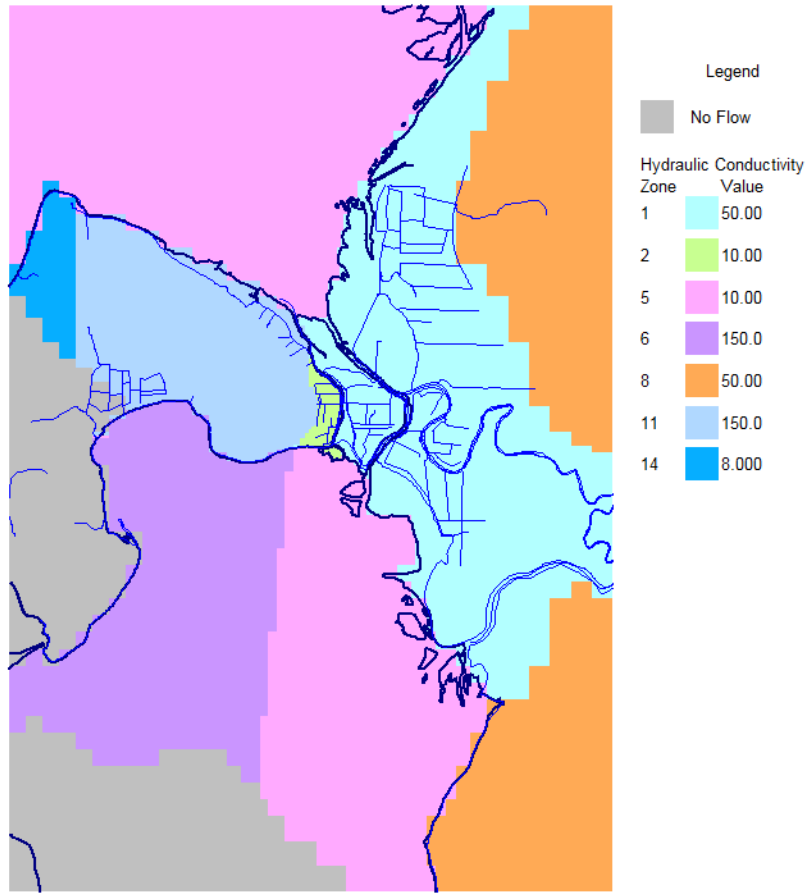
Ducks Unlimited
Leque Island Restoration

PGG

Layer 1



Layer 2



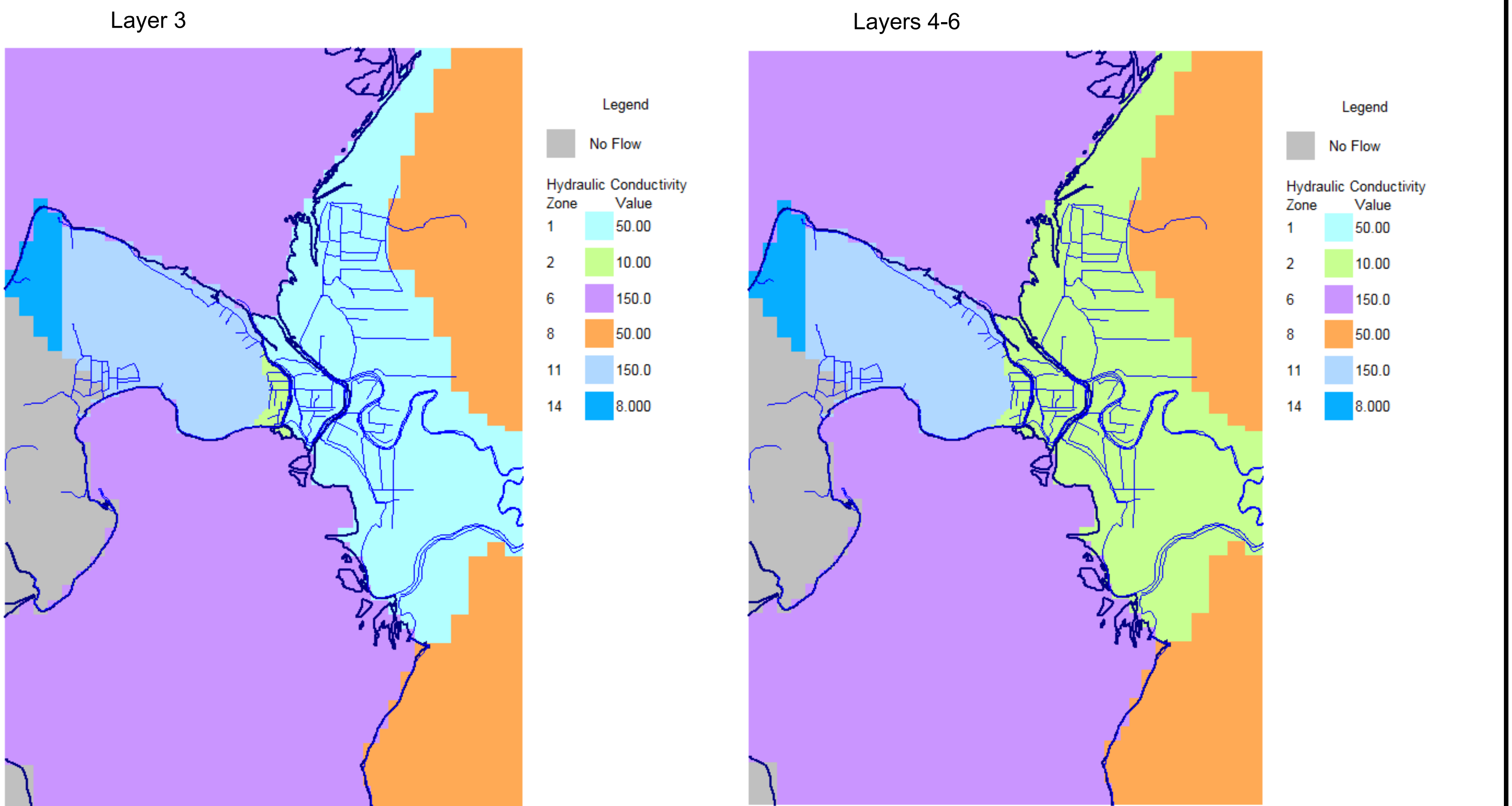
NOTES:

Hydraulic conductivity values listed are horizontal. For vertical hydraulic conductivity values see Table C-2.

Figure C-6
LA Model Hydraulic Conductivity Distribution

Ducks Unlimited
Leque Island Restoration

PgG



NOTES:

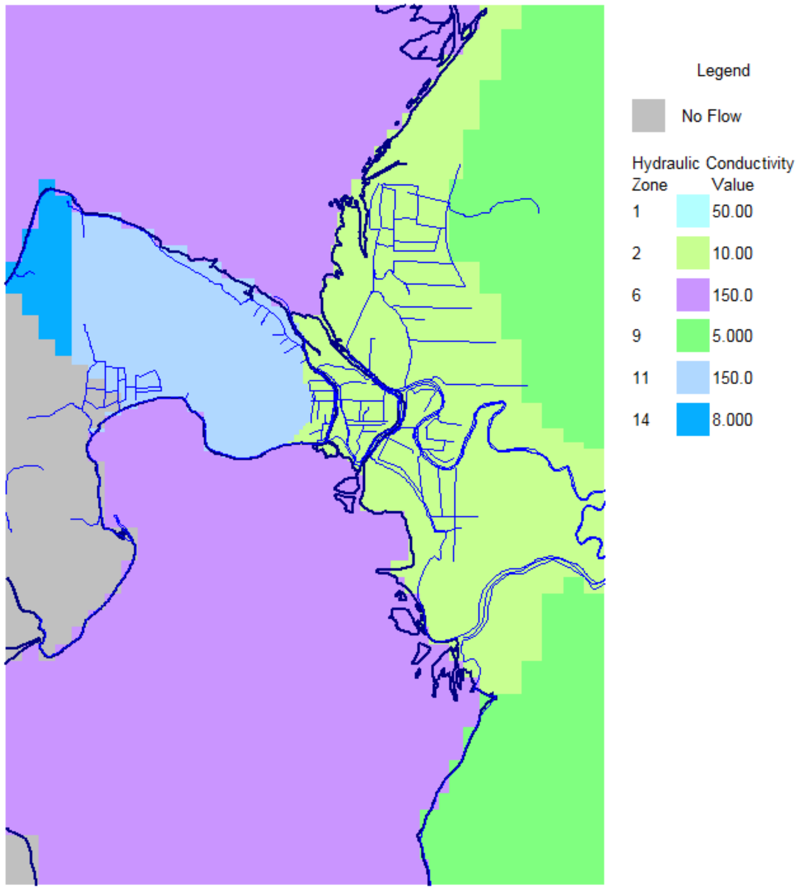
Hydraulic conductivity values listed are horizontal. For vertical hydraulic conductivity values see Table C-2.

Figure C-7
LA Model Hydraulic Conductivity Distribution (cont)

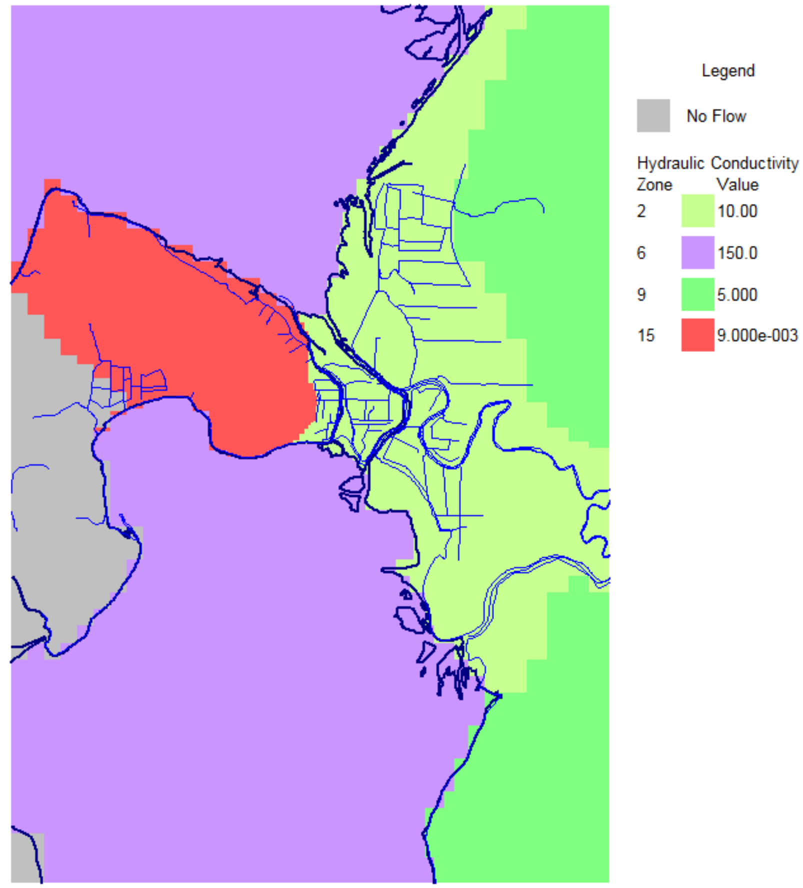
Ducks Unlimited
Leque Island Restoration

PGG

Layer 7



Layers 8-9



NOTES:

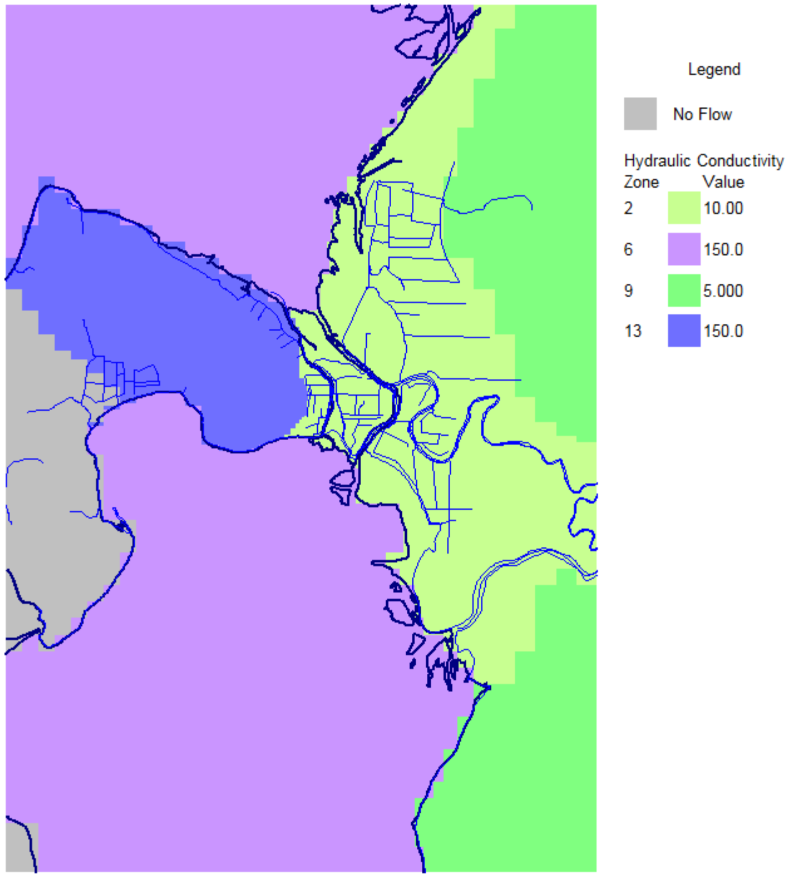
Hydraulic conductivity values listed are horizontal. For vertical hydraulic conductivity values see Table C-2.

Figure C-8
LA Model Hydraulic Conductivity Distribution (cont)

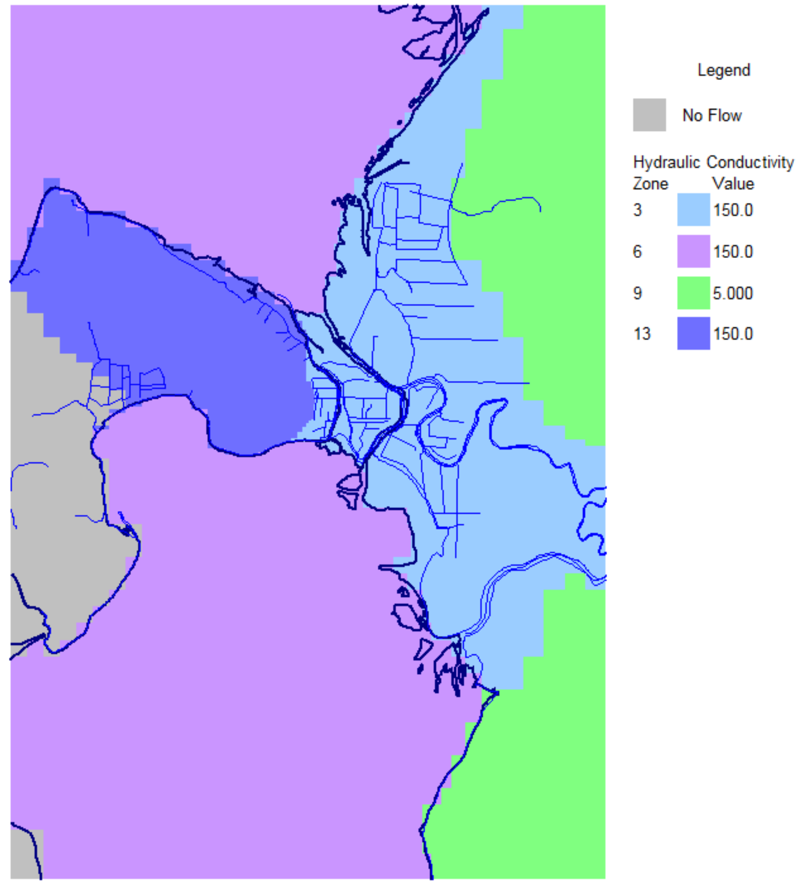
Ducks Unlimited
Leque Island Restoration

PGG

Layers 10-11



Layer 12



NOTES:

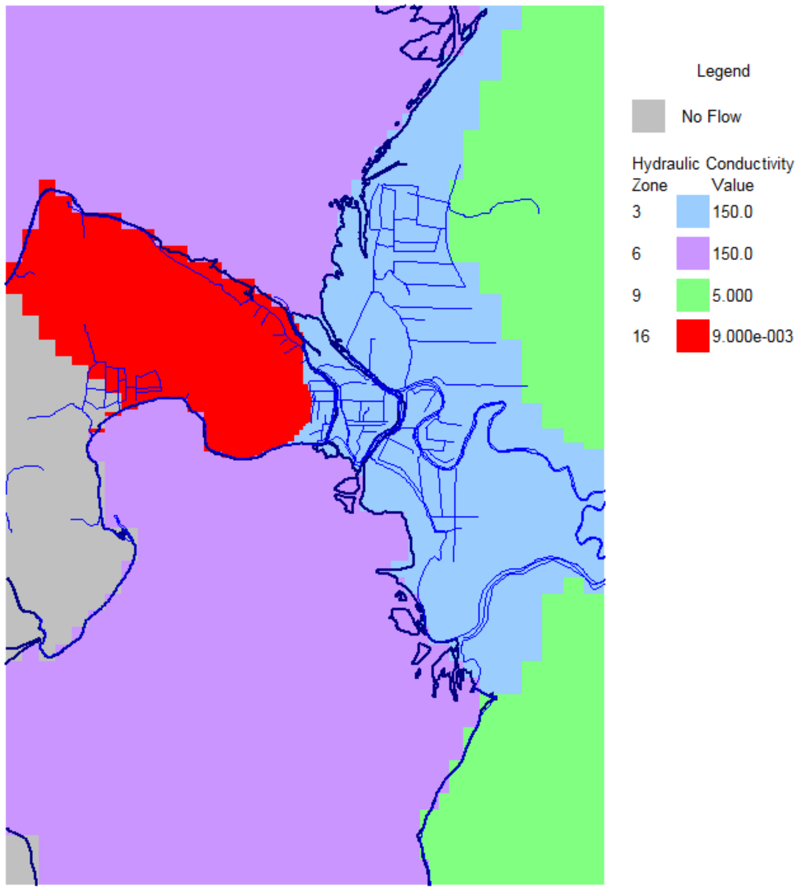
Hydraulic conductivity values listed are horizontal. For vertical hydraulic conductivity values see Table C-2.

Figure C-9
LA Model Hydraulic Conductivity Distribution (cont)

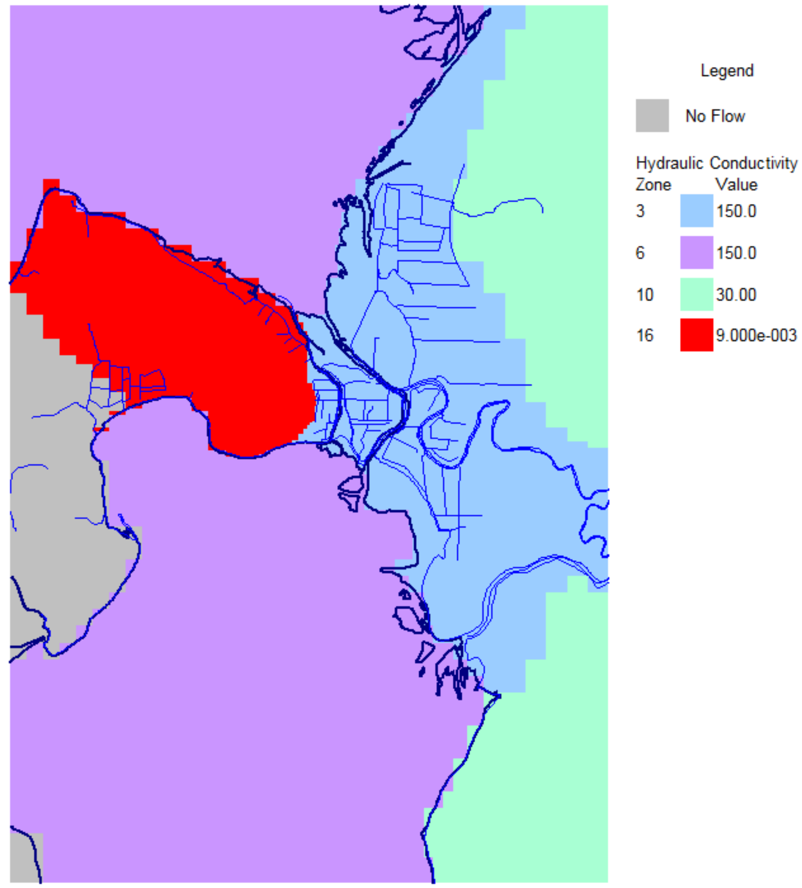
Ducks Unlimited
Leque Island Restoration

PgG

Layer 13



Layers 14-15



NOTES:

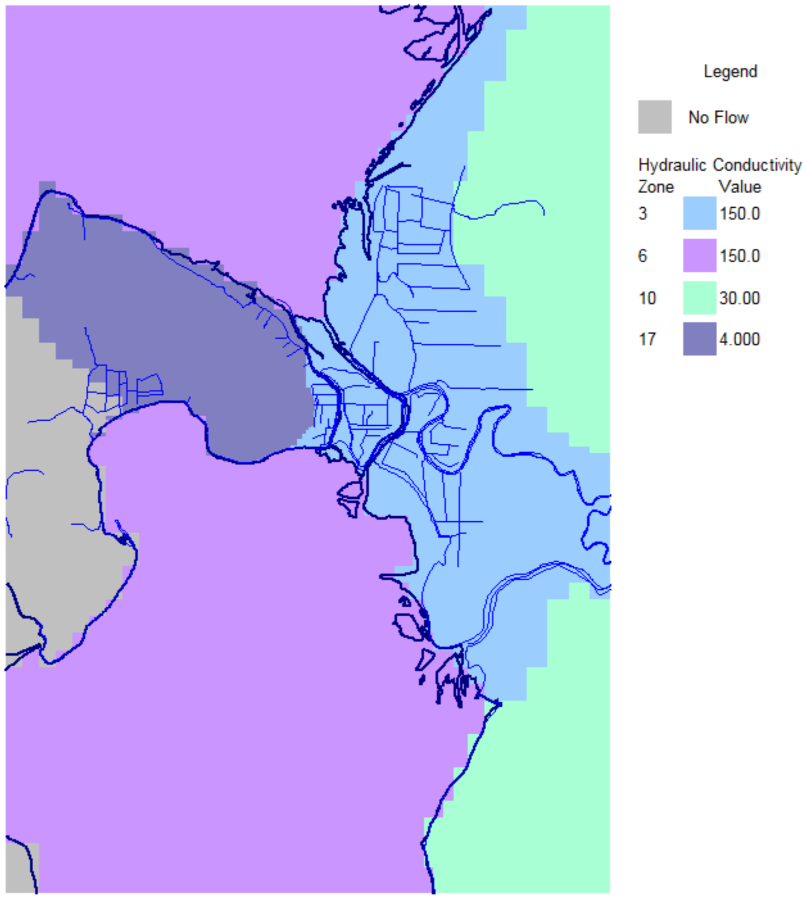
Hydraulic conductivity values listed are horizontal. For vertical hydraulic conductivity values see Table C-2.

Figure C-10
LA Model Hydraulic Conductivity Distribution (cont)

Ducks Unlimited
Leque Island Restoration

PgG

Layer 16



NOTES:

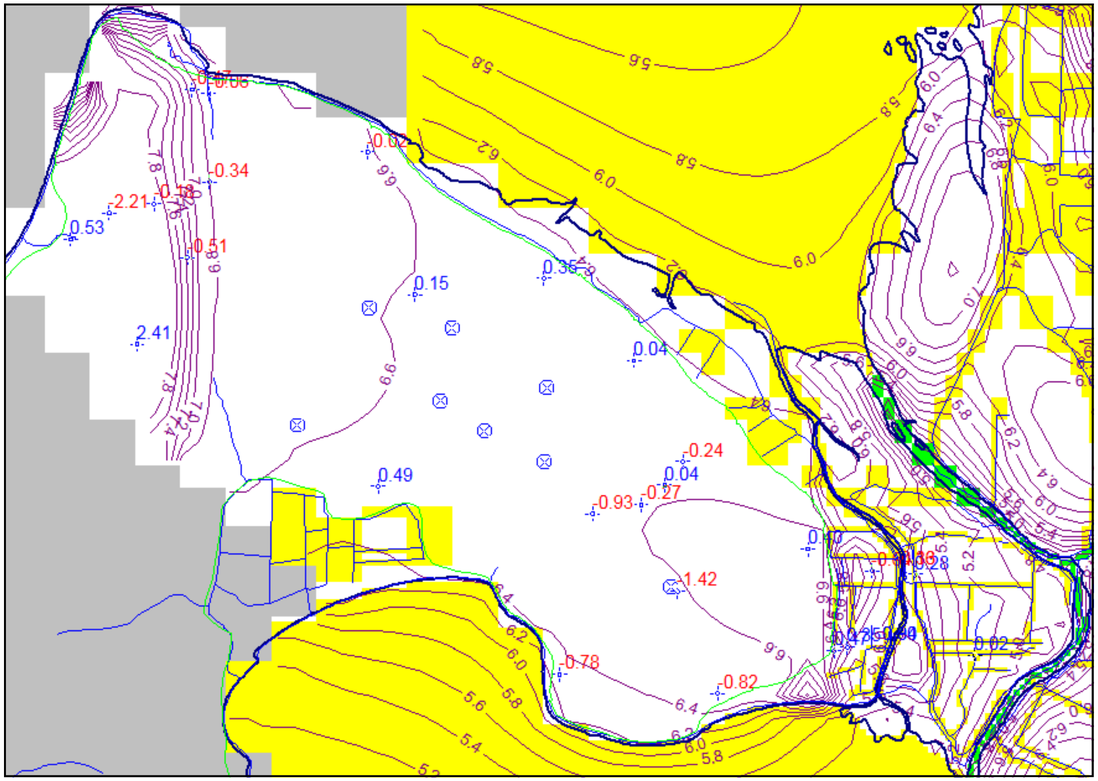
Hydraulic conductivity values listed are horizontal. For vertical hydraulic conductivity values see Table C-2.

Figure C-11
LA Model Hydraulic Conductivity Distribution (cont)

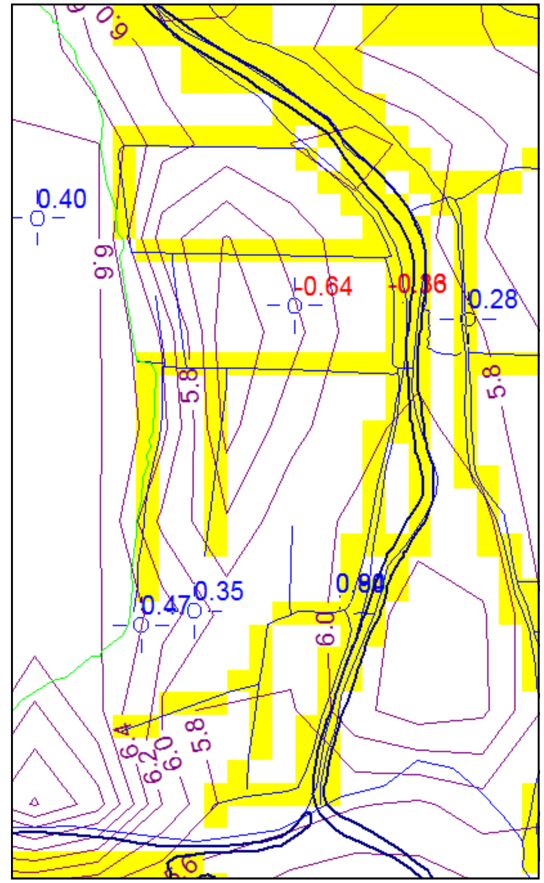
Ducks Unlimited
Leque Island Restoration

PgG

All Calibration Targets



Detailed View of Monitoring Site



NOTES:

- Inactive Model Cell
- Drain Cell
- River Cell
- Well
- 6.51 Calibration Target and Residual
- Groundwater Level Contour (Interval = 0.2 ft)
- Camano Island Upland Escarpment

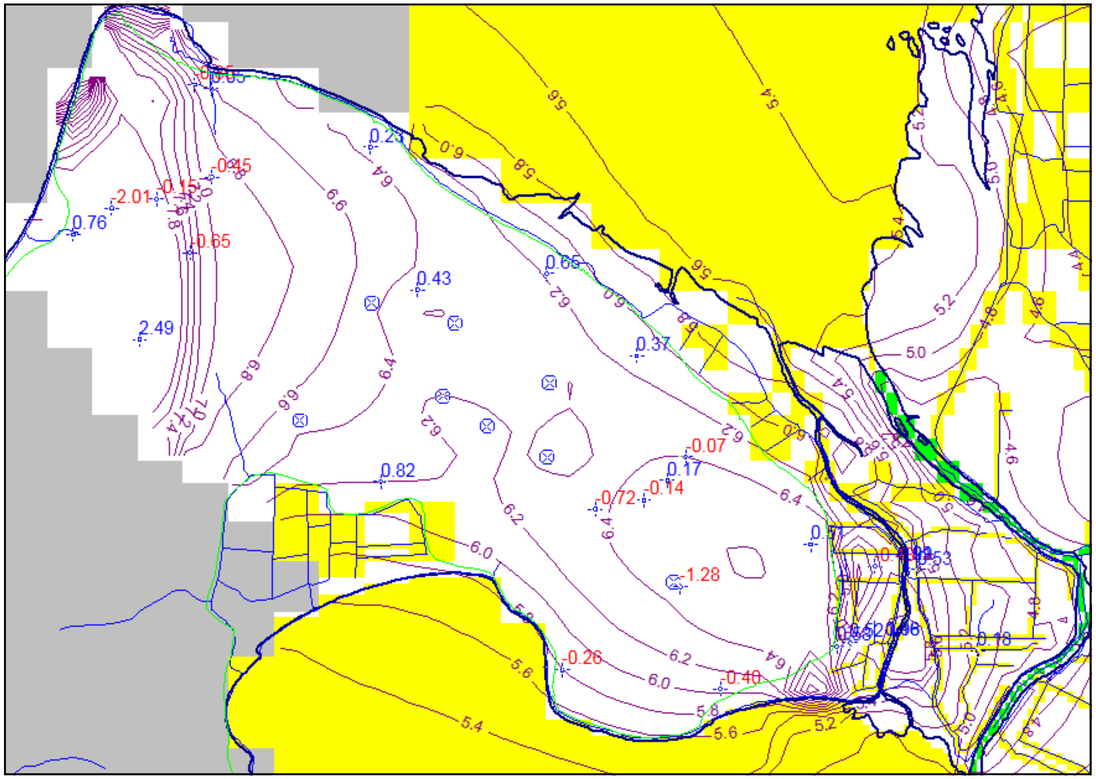
Residual = observed minus predicted (negative values are too high).

Figure C-12
Model GS-C: Water Levels and Calibration Residuals

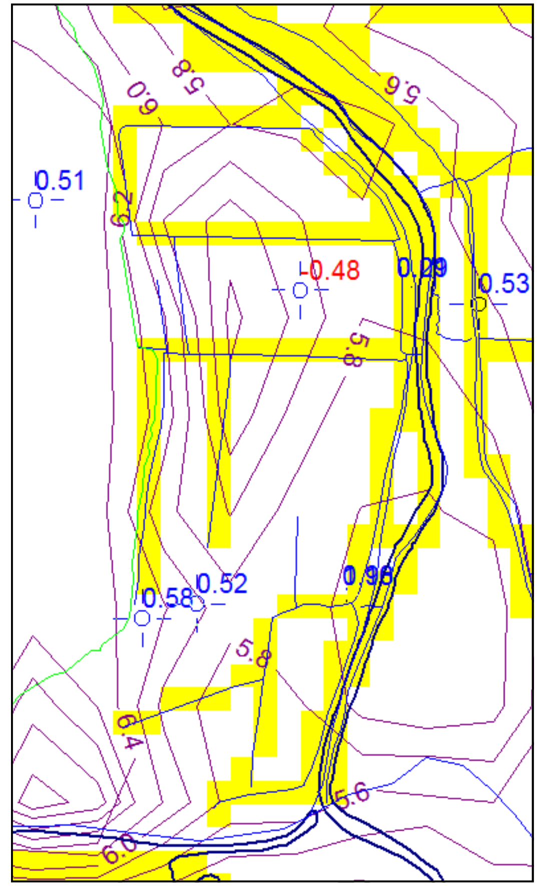
Ducks Unlimited
Leque Island Restoration

PgG

All Calibration Targets



Detailed View of Monitoring Site



NOTES:

- Inactive Model Cell
- Drain Cell
- River Cell
- Well
- 6.51 Calibration Target and Residual
- Groundwater Level Contour (Interval = 0.2 ft)
- Camano Island Upland Escarpment

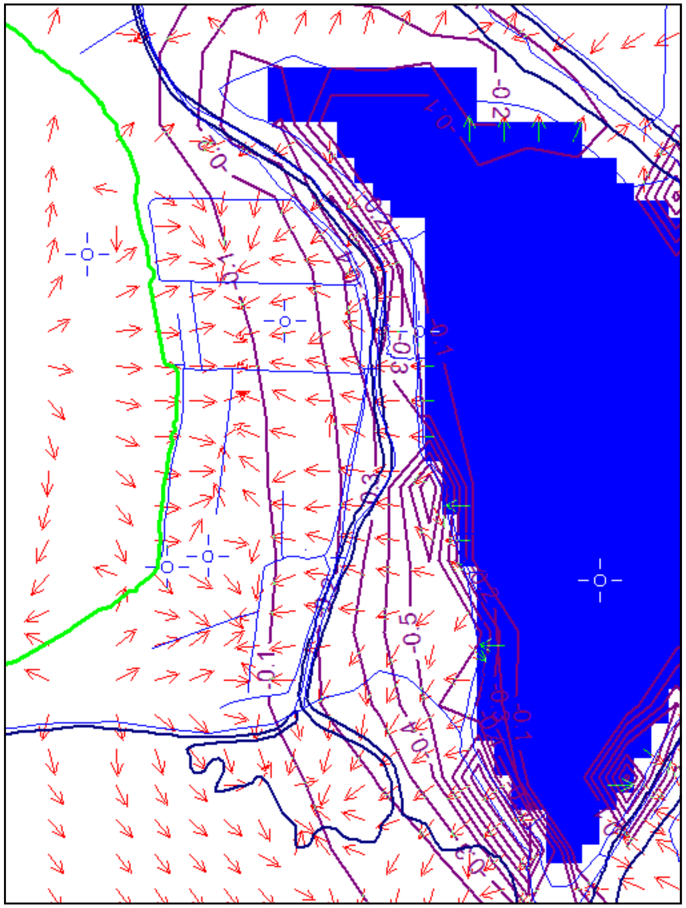
Residual = observed minus predicted (negative values are too high).

Figure C-13
Model LA-C: Water Levels and Calibration Residuals

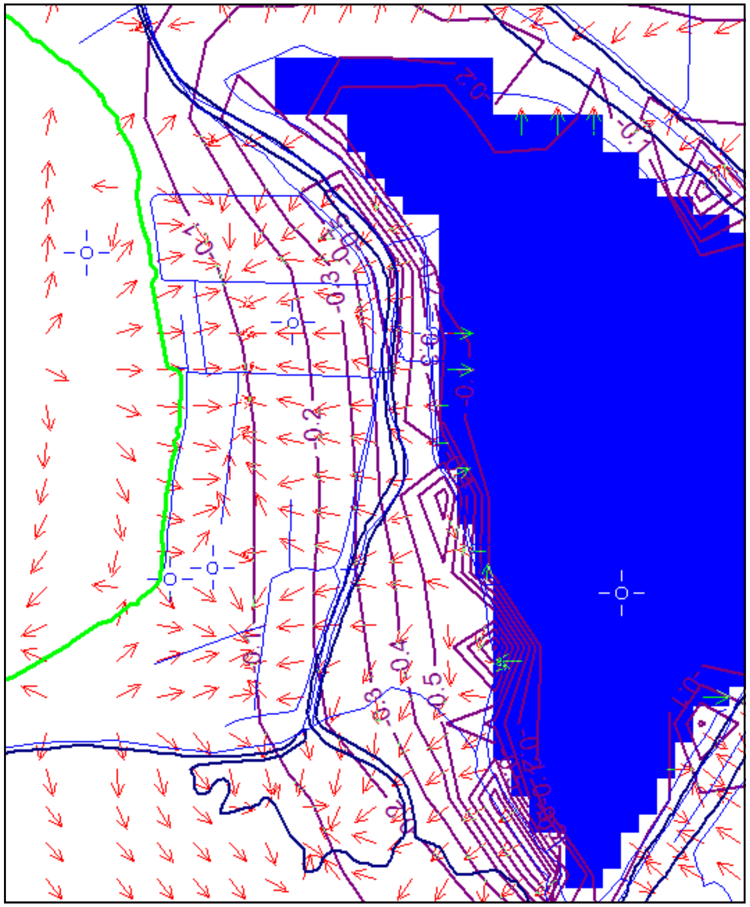
Ducks Unlimited
Leque Island Restoration

PGG

Model Version GS-C



Model Version GS-D



NOTES:

- Constant Head Cell
- Calibration Target
- Layer 1 Modeled Groundwater Flow Direction
- Layer 1 Drawdown (Contour (Interval = 0.1 ft)
- Camano Island Upland Escarpment

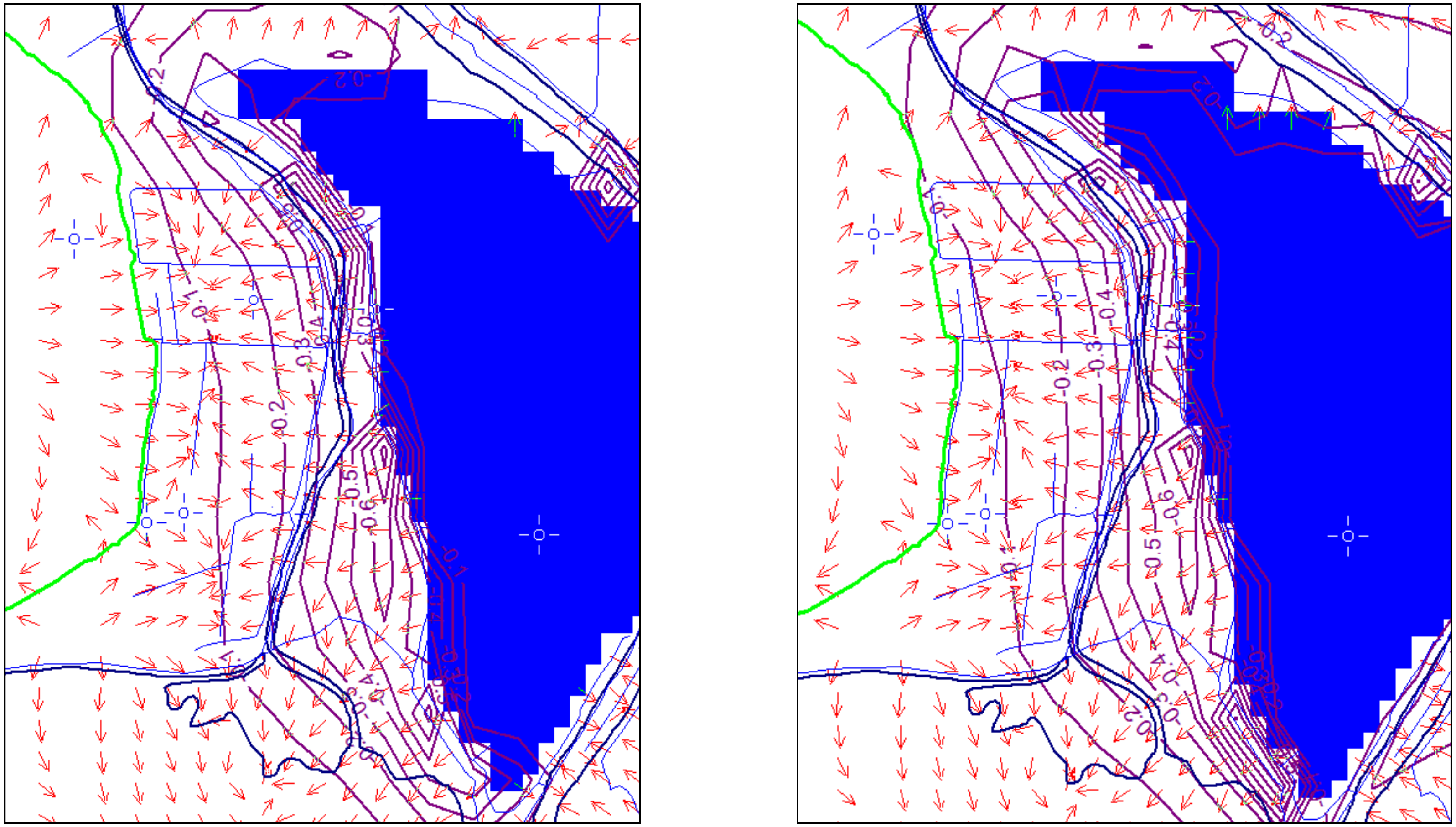
Negative Drawdown Indicates Water Level Rise

Figure C-14
GS Model: Predicted Drawdown & Flow Directions After Restoration

Ducks Unlimited
Leque Island Restoration

Model Version LA-C

Model Version LA-D



NOTES:

- Constant Head Cell
- Layer 1 Drawdown (Contour (Interval = 0.1 ft)
- Calibration Target
- Camano Island Upland Escarpment
- Layer 1 Modeled Groundwater Flow Direction

Negative Drawdown Indicates Water Level Rise

Figure C-15
LA Model: Predicted Drawdown & Flow Directions After Restoration

Ducks Unlimited
Leque Island Restoration

PgG