Aspect consulting

IN-DEPTH PERSPECTIVE

NORTHERN LUMMI ISLAND HYDROGEOLOGIC INVESTIGATION

Prepared for: Whatcom County Planning & Development Services

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Executive Summary

Whatcom County contracted with Aspect Consulting to perform a groundwater study of northern Lummi Island (*Figure 1.1*), in response to State Environmental Policy Act (SEPA) review comments on the Lummi Island Subarea Plan (LISP). The study has two principal components:

1. A technical investigation of the northern Lummi Island aquifers and groundwater quality, and

2. Development of a methodology to protect the groundwater resources of northern Lummi Island.

The results of the technical study will be used to establish standards and policies that are protective of the groundwater resource, natural environment, and human health. This report presents results of the technical groundwater study and discusses the technical findings that are the basis for the methodology development. The groundwater protection methodology is the subject of a separate report.

Principal Aquifers

The principal groundwater aquifers on northern Lummi Island include: 1) unconsolidated glacial and nonglacial deposits, and 2) bedrock. Island wells are nearly evenly divided between these two main aquifer types. The bedrock aquifer is further subdivided into a sandstone aquifer that occupies most of the northern part of the study area, and a Greenstone aquifer, located in the south part of the study area.

The unconsolidated aquifer is subdivided into shallower and deeper aquifers, separated by an intervening layer of relatively low permeability, fine-grained material. The unconsolidated aquifer occupies a large portion of the central and southern study area, but also occurs as discrete pockets, typically bounded by sandstone, in the northern part of the study area. Aquifer productivity is generally low in the bedrock aquifers, while the unconsolidated aquifers have modest productivities relative to other parts of Puget Sound.

Safe Yield

Safe yield of an aquifer is the amount of water that can be withdrawn on a sustained basis without inducing adverse water quality effects such as seawater intrusion, or other environmental impacts such as drying up of aquifers, streams, or wetlands. Only a fraction of the groundwater recharge can be withdrawn without incurring these types of impacts.

This investigation found the aquifers of northern Lummi Island to be highly variable from place-to-place, and safe yield could not be reliably quantified. On the nearby Lummi Peninsula, detailed study found the theoretical maximum aquifer safe yield to be about one-third of the total recharge, where safe yield was defined as the maximum pumping rate from a representative array of wells that could be sustained without inducing chloride concentrations in excess of the secondary drinking water regulation of 250 milligrams per liter (mg/L).

Total annual average groundwater recharge on northern Lummi Island was estimated at about 2 inches, or about 360 acre-feet. This equates to about 6 percent of the mean annual precipitation of 33 inches. Current annual groundwater withdrawals were estimated at about 110 to 120 acre-feet. Of this, approximately 45 acre-feet probably returns to the aquifer through drainfields, leaving a net withdrawal of 66 acre-feet annually, or about 20 percent of the available recharge.

Recharge was found to be significantly less in the bedrock areas than in the unconsolidated aquifers. Because water within the bedrock aquifers is transmitted through fractures of limited and highly variable permeability, there is strong potential for withdrawals to exceed aquifer safe yield on a very localized basis.

Groundwater Quality

Seawater intrusion and naturally occurring arsenic were identified as the principal water quality concerns on northern Lummi Island. Most wells on Lummi Island have chloride concentrations within background levels (less than 40 mg/L); however several areas show elevated chloride levels indicative of seawater intrusion. For the most part, high chloride wells are not distinctly clustered geographically.

No relationships were identified between chloride levels and well depths or completion elevations, indicating that the freshwater/seawater relationship is more complex than elevations, indicating that the freshwater/seawater relationship is more complex than models developed for uniform aquifer systems such as the Ghyben-Herzberg or transition zone models. The data suggest a complex groundwater flow system where the location of the freshwater/saltwater transition zone is strongly influenced by local variations in aquifer permeability and pumping.

Arsenic in exceedance of the drinking water standard was identified over much of the study area. The maximum contaminant level (MCL) for arsenic was lowered to 10 micrograms/liter (µg/L) effective January 23, 2006 from the previous MCL of 50 µg/L. About 70 percent of bedrock wells exceed the MCL, compared to 27 percent in the unconsolidated aquifer.

The highest prevalence of arsenic and the highest concentrations occur within the sandstone wells. Wells completed in the Greenstone aquifer are typically low in arsenic concentration. Geochemical and hydraulic data suggest that groundwater migrates laterally outward from the sandstone aquifer into the unconsolidated deposits. Pumping arsenic-bearing groundwater from unconsolidated aquifers may induce increased arsenic migration and contamination.

Considerations for Developing Protective Methodology

Findings from the hydrogeologic investigation provide a technical basis for development of a methodology to evaluate and regulate groundwater withdrawals, as summarized below. The preferred approach to develop the methodology is use of an antidegradation policy that would limit further declines in groundwater quality.

- **Safe Yield** – Safe yield of groundwater on northern Lummi Island is typically limited by water quality impacts of pumping and cannot be known with certainty without detailed field investigations and numerical groundwater modeling. Even with such efforts, considerable uncertainty on aquifer safe yield would likely remain, given the variability of the aquifers. For practical purposes, this precludes development of a methodology based on prescribing allowable withdrawal amounts.
- **Seawater Intrusion** – Relationships between chloride levels, well completion elevations and groundwater elevations are highly variable and unpredictable on northern Lummi Island. Policies such as those in Island County that are based on relationship of groundwater elevation and salinity are not applicable to northern Lummi Island. Similarly, methods limiting development based on a prescribed radius from a well exhibiting seawater intrusion, such as in Jefferson County are not applicable to northern Lummi Island. Methodologies for limiting seawater intrusion on northern Lummi Island must be adaptive to area-specific circumstances.
- **Arsenic** – Arsenic appears to be naturally occurring, sourced in the sandstone aquifer, and has the potential to migrate laterally from the sandstone aquifer into the unconsolidated aquifer. The methodology should consider potential arsenic migration in response to pumping.

Protective measures should be based on an antidegradation standard that would limit groundwater development in areas where impacts are observed. The methodology is the subject of separate report being prepared as part of this study.

The contributions of the well owners and Island residents who participated in the northern Lummi Island hydrogeologic investigation are gratefully acknowledged.

1 Introduction

Whatcom County is in the process of evaluating impacts from proposed groundwater withdrawals and developing a methodology to protect the groundwater resource on northern Lummi Island (Island) (Figure 1.1). The results of the study will be used to establish standards and policies for Island development that are protective of the groundwater resource, natural environment, and human health. Development of standards and policies to protect the groundwater resource stems from the Lummi Island Subarea Plan (LISP) (Revised Final Draft, 2/26/04). The proposed, updated LISP was reviewed under State Environmental Policy Act (SEPA). SEPA review by Whatcom County required a groundwater study be performed prior to issuing final SEPA threshold determination. The groundwater study is being performed under contract to Aspect Consulting.

This report summarizes significant aquifer characteristics, estimates and discusses aquifer recharge and withdrawals, and identifies potential water quality concerns as follows:

- **Section 2** – Hydrogeologic Framework – provides a summary of the geologic conditions on the Island and introduces the principal aquifers.
- **Section 3** – Groundwater System – discusses the lateral and vertical distribution of the principal aquifers, the aquifer hydraulic properties, groundwater recharge and use

the principal aquifers, the aquifer hydraulic properties, groundwater recharge and use, and groundwater quality.

- **Section 4** – Technical Considerations for Development of Methodology – summarizes technical considerations for development of a methodology to evaluate proposed withdrawals.
- **Appendix A** – Well Database – presents an overview of the project well database.
- **Appendix B** – Field Methods – describes field methods used during sampling and surveying of study participant wells.

A public workshop was held on January 28, 2006 on Lummi Island to present an overview of the study and solicit well information and participation in this study, approximately 40 Island residents participated in the study by allowing access to their wells for sampling and/or water level measurements in April and August, 2006. Another outcome of the public workshop was connecting with Island residents who participated in the 1994 Lummi Island Groundwater Study. On February 16, 2006, with the assistance of Island residents, a follow-up global positioning system (GPS) survey was made of many of the 1994 study wells.

2 Hydrogeologic Framework

The hydrogeologic framework for northern Lummi Island was developed based on the project well database, and on published maps, theses, and consulting reports. The project well database is summarized in Appendix A with a tabulated summary of well construction details. Appendix A describes the process of correlating wells from various studies. A geologic map of the project area is presented on Figure 2.1. Figure 2.2 presents the locations of surveyed/located wells used to define the geologic and groundwater conditions on Lummi Island. Wells located only to the nearest ¼, ¼ section are not included.

2.1 Published Reports

The most extensive source of hydrogeologic information related to Lummi Island was completed by William Sullivan (2005) for his Master's Thesis at Western Washington University. Sullivan's The *Hydrogeology of North Lummi Island, Washington* presents a comprehensive investigation of the physical hydrogeology of the island. His work was primarily based on the hydrogeologic interpretation of 130 domestic well logs mostly obtained from the Washington State Department of Ecology (Ecology) and the Whatcom County Heath Department (WCHD).

Two other key reports on the hydrogeology of Lummi Island were published in 1978 and 1994. Schmidt (1978) completed the first comprehensive study of the island, and identified the bedrock and Pleistocene (glacial) deposits as the two primary aquifer systems on the island. Detailed water quality analyses from two wells, along with specific conductivity, hardness and chloride values from 36 additional wells were included in the study. Schmidt (1978) also calculated a water budget for the island.

In the early 1990s, a groundwater study of the Island (Whatcom County, 1994) was completed in cooperation with Island residents, the Whatcom County Health and Planning Departments, the Washington State Department of Ecology (Ecology) and the Washington State Department of Health (DOH). The purpose of the study was to evaluate concerns about elevated arsenic and potential seawater intrusion. Arsenic and chloride samples were taken bi-monthly from selected wells. In addition, a 1-day tidal study was conducted to determine the relationship between tidal stage chloride and arsenic concentrations.

2.2 Geologic History and Principal Geologic Units

Lummi Island is underlain by regions of unconsolidated sediment and bedrock. The principal geologic units on Lummi Island and their characterization as aquifers or aquitards (units that retard groundwater flow) are listed below from youngest to oldest:

- Sand and Gravel overlying Glaciomarine Marine Drift – typically unsaturated
- Glacial Marine Drift – aquitard

- Glacial Till – aquitard
- Glacial Advance Outwash – aquifer
- Cherry Point Silt – aquitard
- PreVashon-Sand and Gravel Deposits – aquifer
- Chuckanut Sandstone – aquifer
- Greenstone (Fidalgo Ophiolite) – aquifer

The origin, composition and distribution of each of these units are described below. Section 2.2 discusses the role of each of these units in storing and transmitting groundwater.

2.2.1 *Bedrock Units*

Exposed bedrock on Lummi Island is comprised predominantly of Chuckanut formation sandstone and Greenstone. Bedrock geology of Lummi Island is described by Sullivan (2005), Easterbrook (1976), Lapen (2000) and Carroll (1980). Greenstone is a common name used to refer to rocks of the Decatur Terrane. Bedrock geology of San Juan Islands and Lummi Island consists of a sequence of fault bounded rock packages, each distinct in lithology (rock type) and age. These packages, referred to as terranes, traveled significant distances from their point of origin prior to accreting together and onto the North American continent.

The Decatur Terrane is about 160 million years old (middle to upper Jurassic), and within

The Decatur Terrane is about 160 million years old (middle to upper Jurassic), and within the study area consists of Fidalgo Ophiolite complex. An ophiolite is an assemblage of rocks rich in iron and manganese of igneous origin (formed from molten or partially molten rock). These rocks often contain minerals (serpentine, chlorite, and epidote) which contribute to the rock's characteristic green color. Within the study area, Greenstone consists of igneous intrusive rocks (rocks cooled beneath the earth's surface), gabbro and diorite at the south end of the study area, north of Sunrise Road.

The Lummi Formation is a distinct terrane from the Decatur Terrane (Lapen, 2000) and consists of metamorphic basalts and sedimentary rocks (rocks subjected to heat and pressure within the earth) of oceanic origin between Point Migley and Lummi Point (Figure 2.1). Although from a distinctly different origin than the ophiolite, these rocks are considered collectively with the Fidalgo Ophiolite and are considered collectively in this study as "Greenstone". Greenstone is inferred to underlie all of Lummi Island (Carroll, 1980). Two wells in the north part of the study area were identified which encountered Greenstone-beneath Chuckanut Sandstone. Well 14, located northwest of Richards Mountain, encountered Greenstone at a depth of 144 feet (about elevation 112 feet) and well 260 located north of Legoe Bay, encountered Greenstone at a depth of 340 feet (about elevation -255 feet). Well 262 located near Village Point was reported by Sullivan (2005) to be completed at a similar depth. Greenstone has no primary porosity and water movement is through fractures.

The Chuckanut Sandstone was deposited on the erosional surface of the Greenstone. The Chuckanut Formation on Lummi Island is comprised of the youngest member of the formation (Padden Member) and is about 65 million years old (late Cretaceous-Paleocene). The Chuckanut formation was deposited in a river (alluvial) floodplain environment and is described by Carroll (1980) as a coal-bearing, arkosic sandstone with interbedded conglomerate and thin mudstone lenses. Chuckanut Sandstone is exposed throughout the north end of Lummi Island. Exposures are typically comprised of the more resistant conglomerate units. Chuckanut Sandstone has also been mapped upslope from Legoe Bay and near the ferry terminal (Figure 2.1). The rock has little or no primary porosity and water movement is through fractures within the sandstone. Maximum thickness of the Chuckanut Sandstone is estimated at 330 feet (Carroll, 1980).

An east-west trending fault zone separates south Lummi Island from the study area. This area is indicated as "tectonic zone" in Figure 2.1 and represents a strike-slip fault juxtaposing igneous Fidalgo Ophiolite rocks against metasediments of south Lummi Island (Carroll, 1980). The Chuckanut Formation on Lummi Island was folded about 45 million years before present (middle Eocene) into a broad synclinal structure (Carroll, 1980). Subsidiary folding lead to development of anticlines on either limb of the syncline. The locations of these structures are shown on Figure 2.1. The underlying Greenstone is believed to have been folded with the Chuckanut Formation. The axis of the more southerly syncline was extrapolated into the region of bedrock low by Sullivan (2005). Sullivan (2005) hypothesized that these structures may influence groundwater flow.

2.3 Glacial Deposits

The unconsolidated sediment in the northern Puget Sound area was deposited primarily by a series of Pleistocene age (about 2 million to 10,000 years before present [ypbl]) continental glacial advances that extended from British Columbia into the Puget Lowland. Stream sediment (alluvium) was deposited between glaciations. The oldest of these glacial and interglacial deposits have been identified in the southern Puget Lowland and do not crop out in the project area. The thickness of the unconsolidated deposits in the study area range from 0 to over 250 feet.

Figure 2.3 presents an elevation contour map of top of bedrock, which represents the base of the glacial deposits. Depressions in the bedrock surface to elevations at least 175 feet below sea level occur along Legoe Bay Road and beneath Lane Spit, where several deep wells completed in older glacial deposits are present. Unconsolidated deposits also occur adjacent to the tectonic zone at the south end of the study area.

Two older glacial and interglacial deposits, known regionally, are not exposed on Lummi Island but are likely present in the subsurface. Deposits of the Double Bluff drift (glacial) and the Whidbey Formation (interglacial) have been identified to the south on Whidbey Island. These sediments have been dated from between 250,000 ybp and 100,000 ypb. Sediment of the Possession Drift, deposited by the continental glaciation preceding the most recent (Fraser) glaciation, is also exposed on Whidbey Island. Deposits from the Possession Glaciation are dated at about 80,000 ybp (Easterbrook, 1994). These older deposits were likely encountered during drilling of several deep wells beneath and south of Legoe Bay Road.

Prior to the most recent (Fraser) glaciation, floodplain and fluvial sediments ranging from silt and clay to sand gravel were deposited in the Lummi Island area during the interglacial Olympia Stade (about 60,000 ypb to 15,000 ypb) (Troost, 1999). Olympia age deposits are the oldest sediments exposed on the Lummi Peninsula, across Hale Passage from Lummi Island, and are exposed at the base of the bluffs along the west shore of the Lummi Peninsula and Portage Point, where they occur predominantly as fine-grained silts.

At the onset of the Vashon Stade of the Fraser Glaciation, the Puget Lobe, an arm of the continental glacier, advanced southward, blocking the Strait of Juan de Fuca and forming a large, proglacial lake (lake in front of a glacier generally in contact with the ice). Coarser-grained sediment transported by rivers and streams was deposited in deltas near the lowland margin, and finer-grained sediment settled out in the quiet lake water to form the fine sand and silt deposits recognized at the base of the fine-grained exposures along portions of the Lummi Peninsula. This unit is thought to be correlative with the Cherry Point Silt, exposed north of Lummi Island at Cherry Point. The Cherry Point Silt has been identified (tentatively) only in the subsurface through driller's logs on Lummi Island. Age dating of sediments on the Lummi Peninsula indicates that deposition of fine-grained silts extended from Olympia interglacial period to the onset of the Fraser Glaciation.

The most recent glacial period, the Fraser Glaciation, has been broken into two advances of the ice sheet. The first advance (Vashon Stade) extended into the southern Puget Lowland. During the second advance (Sumas Stade), the ice advanced just into northern Washington. The Vashon Stade was the last major advance of the ice sheet and probably reached the Bellingham area about 18,000 ybp (Easterbrook, 1976). During this glaciation, which lasted until about 13,000 ybp, up to several hundred feet of glacially derived soils were deposited in the Puget Lowland. In the Lummi Island area, these soils include advance outwash and glacial till.

As the Vashon continental glacier advanced farther southward, sediments were deposited by glacial meltwater, creating an outwash plain in front of the advancing ice. The Vashon advance outwash is known as the Esperance sand and is locally referred to as the Mountain View Sand and Gravel (Easterbrook, 1963). This unit is the most significant unconsolidated aquifer on Lummi Island. Eventually the glacier overrode the outwash plains, consolidating the Esperance Sand and underlying sediments.

Vashon till was deposited beneath as much as 6,000 feet of ice as the continental glaciers advanced. Glacial lodgement till is an unsorted to poorly sorted soil mixture composed of clay to boulder-size particles that were deposited at the base of a glacier. Compaction by the weight of the overlying ice resulted in a concrete-like texture and appearance. The weight of ice also depressed the land surface by several hundred feet.

As the climate changed and the glacier retreated, isostatic rebound of the land surface occurred, leaving much of the Puget Lowland south of Everett above sea level. Rebound to the north was slower than rising sea level and this area, including Lummi Island, was inundated by marine waters entering through the Strait of Juan de Fuca. Lummi Island was submerged beneath about 400 feet of seawater at this time (Dethier and others, 1995). By about 11,000 ypb, isostatic rebound in the northern Puget Lowland outstripped sea level rise, and the submerged lands emerged.

The period from about 13,600 to 11,000 ybp is referred to as the Everson Interstade and is typified by deposition of glaciomarine drift (GMD) from abundant floating ice in the northern Puget Lowland. Bellingham and Kulshan Glaciomarine drifts were deposited during this time. GMD mantles much of Lummi Island and is exposed along some areas of the coast. The unit typically consists of pebble to boulder "dropstones" in a silt matrix although in places the unit is fine-grained silts and clays without dropstones.

The record of emergence of the northern Puget Lowland during the Everson Interstade is complicated by deposition of the Deming Sand. The Deming Sand is sandwiched between the Bellingham and Kulshan Drifts at its type locality, Deming, Washington (east of Bellingham). The Deming Sand is a fluvial (stream-deposited) sand and is interpreted as being subareally deposited when sea level was about 40 to 70 feet above current sea level (Easterbrook, 1976). Carbon14 dating of basal organic sediments in conjunction with age dates of the under- and over-lying Kulshan and Bellingham Drifts suggest that the area emerged and resubmerged over a period of less than a 1,000 years (Dethier and others, 1995, Easterbrook, 1963), although competing hypotheses have been developed (see Sullivan, 2005 for further discussion).

The Everson Interstade ended with emergence of the land after deposition of Bellingham Drift and readvance of the continental ice sheet termed the Sumas Stade about 11000 ybp. During the emergence of the land, wave reworked sand and gravel beach deposits were deposited on the GMD on Lummi Peninsula, and on Lummi Island. This unit forms a surficial soil layer and is typically above the groundwater table (unsaturated). The advancing and later retreating ice lobes of the Sumas Stade deposited outwash over a wide area between Bellingham and the Canadian border; however, these deposits have not been identified on Lummi Island. By about 10,000 ybp, the Sumas Stade had ended.

2.4 Hydrostratigraphic Units

An aquifer is a water-bearing unit comprised of some combination or part of geologic formations that can yield significant quantities of water to wells and springs. On Lummi Island, the principal aquifers include both:

- Pleistocene Unconsolidated Deposits; and
- Bedrock Aquifers.

The general distribution of these aquifers is presented in Figure 2.4, which differentiates the unconsolidated aquifers and bedrock aquifers based on well completions. Of the wells with completion zones identified in the well database, 50 percent are completed in unconsolidated deposits and 50 percent are completed in bedrock.

A hydrostratigraphic unit is a geologic formation, part of a formation, or a group of formations with similar hydrogeologic characteristics such as porosity and permeability that can be characterized as an aquifer or a non-water-bearing confining layer. Hydrostratigraphic units within the unconsolidated aquifers were designated with a "Q" to indicate Quaternary (the geologic time period during which the units were deposited), followed by a suffix of "c" for coarse-grained units or "f" for fine-grained units.

Youngest (shallowest) units were assigned a "1" and older (deeper) units a "2". For example, Qc1 indicates the uppermost coarse-grained unit in the unconsolidated deposits. The hydrostratigraphic units of importance on Lummi Island include:

- Qf1 – An aquitard comprised collectively of GMD and Vashon Till.
- Qc1 – An aquifer comprised predominantly of advance glacial outwash.
- Qf2 – An aquitard comprised predominantly of fine-grained silt and clay, likely correlative with the Cherry Point silt.
- Qc2 – Deep coarse-grained sand and gravel deposits of the deepest of the identified unconsolidated aquifers on Lummi Island and are comprised of undifferentiated pre-Vashon deposits.
- Chuckanut Sandstone – Predominantly an aquifer, but in places where unfractured may also act as an aquitard.
- Greenstone – a low yielding aquifer where fractured, otherwise acts as an aquitard.

Five hydrostratigraphic cross sections were developed through the study area to further depict the distribution of the hydrostratigraphic units. The locations of the cross sections are shown on Figure 2.5 and the cross sections are presented in Figures 2.6 through 2.10. The geologic interpretation of the soils descriptions as shown on the well logs is combined with surficial geology and assumes a relatively continuous stratigraphic sequence. As additional age dating and descriptions of geologic materials are developed on Lummi Island, these geologic assignments may change.

The major hydrostratigraphic units are depicted with similar color to assist in differentiating aquifers and aquitards. The Qc1 aquifer (indicated in yellow on the cross sections) is typically overlain by GMD of the Qf1 aquitard (shown in green on the cross sections). The Qf1 mantles most of the project area with thicknesses ranging from 0 to over 100 feet with thin areas predominating on the upland Chuckanut Sandstone areas.

The Qc1 aquifer is present near sea level. Based on the cross sections, elevations of the Qc1 aquifer range from about mean sea level down to elevation of about -70 feet. Silt and clay of the Qf2 unit underlie the Qc1 and separate it from the Qc2 aquifer. The Qc2 aquifer is present in the synclinal (down-folded) bedrock depression in the area of Legoe Bay Road (Figures 2.3 and 2.4). The deep aquifer identified beneath Lane Spit is also interpreted to be part of the Qc2 aquifer.

3 Groundwater System

This section describes lateral and vertical limits (boundaries) of the principal aquifers, discusses aquifer hydraulic properties (i.e., relative permeability and storage), presents estimates of groundwater recharge and compares these estimates to north Lummi Island water use.

3.1 Aquifer Boundaries

3.1.1 Unconsolidated Aquifers

The Qc1 aquifer occurs in a relatively large portion of the south part of the study area on either side of South Nugent Road, extending west to Village Point and as small, discontinuous pockets, predominantly along the shoreline (Figure 2.4). Groundwater in the Qc1 aquifer is typically present under confined conditions, with water levels in wells tapping the Qc1 aquifer rising into the level of the overlying GMD (see *Section 3.2.2* for additional explanation and discussion of confining conditions). The Qc1 aquifer in the vicinity of South Nugent Road is typically overlain by 100 feet or more of Pleistocene fine-grained deposits that serve as the confining unit for the aquifer. It is bounded by the Greenstone aquifer to the east and Rosario Strait to the west. This portion of the aquifer has an average saturated thickness of 39 feet and overlies the fine-grained Qf2 aquitard and Greenstone (Figures 2.6 and 2.7) (Sullivan, 2005).

To the west, in the area of Legoe Bay Road, the Qc1 aquifer is widespread, bound by Rosario Strait on the east and west sides of the Island. The lateral and vertical extent of this part of the aquifer can be seen in cross section C-C' (Figure 2.8). This portion of the aquifer is thinner than the southern portion, with an average thickness of only 15 feet (Sullivan, 2005). The relatively thin aquifer is sandwiched between 50 and 100 feet of overlying fine-grained material of the Qf1 aquitard and underlying Qf2 deposits or sandstone (Figures 2.8 and 2.9). The northern boundary of the aquifer is sandstone, while the southern boundary is typically Pleistocene fine-grained units or Greenstone.

There is some uncertainty about the degree of connectivity between the portion of the Qc1 aquifer around Nugent Road, and the unconsolidated units around Legoe Bay Road. The driller's log from well 102 indicates only minor lenses of water-bearing materials were encountered prior to a deeper aquifer at depth of 250 feet (Figure 2.5). This deeper aquifer (Qc2) may be present throughout an east-west trending bedrock trough. Wells completed in the Qc2 aquifer are indicated on Figure 2.4. The Qc2 aquifer has variable thickness ranging between 4 and 55 feet thick (Sullivan, 2005). It is bounded to the north and south by sandstone and on the east and west by salt water bodies.

The Qc1 aquifer is present in discrete pockets, typically bound by sandstone, in the northern half of the study area. Around Centerview Road, coarse-grained materials were likely deposited in a closed depression of the sandstone bedrock. The aquifer is bound on all sides by sandstone and confined under Pleistocene fine-grained material (Qf1). The Qc1 aquifer in this area reaches a thickness of about 45 feet (Sullivan, 2005).

Both shallow and deep coarse-grained unconsolidated deposits are present at Lane Spit. The aquifers are separated by 40 to 100 feet of Pleistocene fine-grained deposits, and each supports multiple wells (Figure 2.10). The shallow aquifer is interpreted as a series of thin, coarse-grained seams of the Qc1 unit. The water-bearing unit typically is logged as fine sand or sand and gravel with clay. In many areas on Lane Spit, the upper unit is not productive enough to provide adequate water, so wells are drilled into the deeper aquifer. The deep aquifer was correlated to the Pleistocene coarse-grained unit Qc2 based on its elevation. The aquifer is bound to the west by sandstone and the east by Hale Passage. The thickness of the aquifer is unknown (Figure 2.10).

Two additional pockets of coarse-grained deposits (Qc1) occupy depressions in the sandstone bedrock surface along the western shoreline of the Island (Figure 2.4). Both aquifers are bound by sandstone to the east and Rosario Strait to the west, and are confined under 80 to 100 feet of fine-grained sediments (Qf1). The lower bounds of the aquifers are likely additional fine-grained deposits (Qf2) or sandstone. The thickness of each aquifer is around 20 feet (Sullivan, 2005).

3.1.2 Bedrock Aquifers

Two bedrock aquifers also provide a significant amount of water to Island residents. The largest aquifer on the Island is the Sandstone aquifer which occupies a majority of the northern half of the study area (Figure 2.4). The aquifer is made up of folded sandstone, shale and conglomerate of the Chuckanut Formation. The sandstone aquifer is bound on the north, east and west sides by Georgia Strait, Hale Passage, and Rosario Strait, respectively. Pleistocene sediments deposited in a deep bedrock trough border the aquifer to the south. The aquifer may be present beneath the unconsolidated deposits, but because of the presence of the unconsolidated aquifers, no wells have been drilled to explore the Sandstone aquifer in that area.

The Chuckanut Formation is estimated to be around 330 feet thick (Carroll, 1980) and overlies Greenstone. A layer of fine-grained unconsolidated Pleistocene deposits (GMD) overlie the sandstone aquifer, except in areas where the sandstone crops out at the land surface. The GMD deposits are typically thickest along the shoreline and in bedrock depressions, creating confining conditions within the sandstone in most areas below about 150 feet in elevation (land surface) (Sullivan, 2005).

The second bedrock aquifer is located in the southeast portion of the study area and is composed of Greenstone. The Greenstone aquifer is bound to the east by Puget Sound and by Pleistocene sediments to the north, south and west (Figure 2.6). Like the sandstone aquifer, at lower elevations, the upper bound of the Greenstone is defined by a mantle of Pleistocene sediments that typically thickens toward the east shore. It appears that most of the aquifer is under confined conditions (Sullivan, 2005). The lower bound of the aquifer is unknown and information on the thickness of the Greenstone in this area is unavailable.

Two wells in the north part of the study area, wells 14 and 260, identified Greenstone on the well log indicating that this aquifer is present beneath the Chuckanut sandstone. Geochemical data discussed in Section 3.4 also suggests shallow Greenstone in the well 14 area.

3.2 Hydraulic Properties

3.2.1 Aquifer Yields

Relative aquifer yields on Lummi Island were evaluated primarily through specific capacity data. Specific capacity is a simple empirical measure of well productivity that is computed by dividing pumping rate in gallons per minute (gpm) by the water level drawdown below static level in feet (ft). Specific capacities are a function of both the aquifer and the well construction. Because drawdown commonly continues to increase slowly over time, specific capacity is most meaningful if the duration of pumping is specified.

For wells of similar construction, specific capacity provides a surrogate measure of aquifer transmissivity. Transmissivity is a measure of the capacity of an aquifer to transmit water horizontally. Transmissivity is most accurately defined by long-term pumping tests, but can also be estimated from specific capacity data. Three long-term pump tests were identified on Lummi Island – Hilltop wells 2 and 3, and one at Isle Aire. Because of the limited number of long-term pump tests, aquifer productivity was largely estimated through specific capacity based on driller's pump tests.

Figure 3.1 is a map depiction of specific capacity data from the well database for the unconsolidated and bedrock aquifers. The size of the symbol is proportional to the specific capacity. Wells which were bailed dry during testing are indicated with a red color.

In general, aquifer productivity is low in the bedrock aquifers on Lummi Island, while the unconsolidated aquifers have modest productivities relative to other parts of the Puget Sound region. Put another way, on northern Lummi Island specific capacities of wells completed in bedrock aquifer are considerably lower than the specific capacities of the wells completed in the unconsolidated aquifer. Average specific capacity in the sandstone aquifer is 0.2 gpm/ft and average reported yields from driller's logs are 10 gpm. Studies of sedimentary bedrock in the Gulf Islands indicates that the fine-grained mudstone interbeds typically have higher permeability than the sandstone layers due to more brittle behavior and increased fracturing (Allen and others, 2003).

Specific capacities in the Greenstone are significantly less than the sandstone. Apparently, the more massive igneous intrusions of the Greenstone formation were structurally deformed as large blocks, with generally less fracturing than the sandstone. Average specific capacity in the Greenstone is 0.03 gpm/ft or about an order of magnitude less than that of the sandstone aquifer. Well yields reported on driller's logs from the Greenstone aquifer average about 3 gpm.

The highest specific capacities are found in the unconsolidated aquifers. Average specific capacity in the unconsolidated aquifer was 1.8 gpm/ft, and average yield reported on driller's logs was 12 gpm. Transmissivity of well 240 was estimated at 106 gallons per day/foot (gpd/ft) based on a 24 hour pump test. This well is completed in the Qc2 aquifer and has a reported specific capacity of 0.21 gpm/ft. Tidal monitoring conducted at the end of the test predicted a weak tidal influence on water levels (Northwest HydroGeo Consultants, 2004a and 2004b).

3.2.2 *Water Levels/Storage/Flow Directions*

Static water level is measured as the depth to water in a well before pumping. Static water elevations, or heads, define the potentiometric surface of the aquifer. If the level to which water rises in the well is above the top of the aquifer, the aquifer is "confined" or "artesian". If the water level is free to fluctuate within the aquifer zone and is not constrained by the stratigraphic top of the aquifer, it is an "unconfined" aquifer.

The sandstone aquifer exists under both confined and unconfined conditions. At higher elevations, the sandstone aquifer tends to behave in an unconfined manner. For wells completed at lower elevations (generally below sea level), the fractured sandstone aquifer is contained by impermeable portions of the sandstone itself, or by the overlying GMD of the Qf1 unit, and the aquifer behaves in a confined manner.

The Qc1 aquifer generally exists under both confined and unconfined conditions, with wells completed at higher elevations exhibiting unconfined conditions. The Qc2 aquifer is typically confined.

Water level data were collected by Whatcom County (1994) over a 2-year period from 1991 to 1993 on a monthly basis. Water level fluctuations in the unconsolidated aquifers ranged from 1.2 to 3.4 feet, with low water conditions typically occurring in late summer or fall (Figure 3.2a).

Groundwater fluctuations were much larger in the bedrock aquifers, ranging from 4.75 (well 52) to 24.3 (well 251) feet (Figure 3.2b). Low groundwater levels in bedrock wells usually occur in the late summer and early fall; however, the data show some variability in the seasonality of the water levels. The well measured in the Greenstone aquifer exhibited over a 28-foot difference between its low (occurring in the winter and spring) and high (occurring in the summer and fall) groundwater levels, consistent with relatively low storage and a time lag for recharge.

Fall 2002 and Spring 2003 water level data collected by Sullivan (2005) exhibited similar groundwater level fluctuations as those observed in the early 1990s. Water level changes from Fall 2002 to Spring 2003 in the unconsolidated aquifers showed little variation and ranged from 0.1 to -2.4 feet with a median value of -0.2 feet. Water level changes for this time period were more pronounced in the bedrock aquifers and ranged from 0.2 to 26.6 feet in the Sandstone Aquifer with a median value of 1.5 feet. Water levels in the Greenstone Aquifer were lower in the spring than in the fall ranging from -0.4 feet to -15.2 feet with a median value of -1.9 feet (Sullivan, 2005).

Groundwater storage volumes for the aquifers on Lummi Island were calculated by Sullivan (2005) and are only summarized here. The aquifer with the largest calculated storage capacity was the sandstone aquifer, with 8.17×10^4 acre-feet of water. The Greenstone aquifer had a calculated storage capacity of 1.63×10^4 acre-feet of water, and the calculated volume of water in the Pleistocene aquifers was 0.73×10^4 acre-feet of water. Stored water cannot be pumped sustainably at rates greater than the recharge rate, so these volumes should not be considered recoverable.

A groundwater elevation contour map (Figure 3.3) was developed for typical late fall conditions by combining study water level measurements made in August 2006 with measurements by Sullivan in August 2002. In general, groundwater in the sandstone aquifer flows outward from the topographically higher inland region toward the shore in a radial pattern. However, it is likely that actual groundwater flow patterns in the sandstone aquifer are controlled by fractures and high permeability zones within the Chuckanut Formation that are difficult to map or predict in detail. Hydraulic gradients (change in groundwater level/distance between wells) are relatively steep, consistent with the relatively low permeability of the sandstone. Gradients varied from about 0.1 (528 feet/mile) in the north to less than 0.035 (183 feet/mile) in the southeast, with higher gradients corresponding to the steeper bedrock surface in the north relative to the southeast.

In the Greenstone aquifer, a northwest-southeast trending groundwater divide separates easterly flow into Hale Passage from westerly flow beneath the Pleistocene sediments and into Rosario Strait on the west side of the Island. The hydraulic gradient in the Greenstone aquifer was estimated at about 0.08 (431 feet/mile).

Groundwater in the Pleistocene aquifers typically flow seaward nearly perpendicularly to the shoreline. However, in some instances, Sullivan (2005) interpreted groundwater flow parallel to the shoreline before turning and flowing toward the sea, particularly in the aquifer near Nugent Road in the southwestern portion of the study area. The estimated gradient of 0.004 feet/day (21 feet/mile) in the glacial aquifers is considerably less than in the bedrock aquifers, reflecting higher transmissivity.

3.3 Safe Yield

Safe yield of an aquifer is the amount of water that can be withdrawn on a sustained basis without inducing adverse water quality effects such as seawater intrusion or other environmental damage such as drying up of aquifers, streams and wetlands. Only a fraction of groundwater recharge can be safely withdrawn without incurring these kinds of adverse impacts. This section presents estimates of annual average groundwater recharge and current rates of withdrawals by wells on northern Lummi Island.

The Lummi Peninsula Groundwater Investigation estimated that the theoretical maximum aquifer safe yield was about one- third of the total recharge, where safe yield was defined as the maximum pumping rate from a representative array of wells that could be sustained without inducing chloride concentrations in excess of 250 milligrams per liter (mg/L). The actual safe yield was believed to be somewhat less than this due practical limitations on well locations.

3.3.1 Method Used to Evaluate Recharge

Annual recharge to an aquifer system is typically computed by applying a water mass balance of the hydrologic cycle, where:

Recharge = Precipitation – Runoff – Evapotranspiration-Increase in Soil Moisture

Application of this method typically relies on direct measurement of precipitation and runoff, local monitoring of climate parameters necessary to estimate evapotranspiration (typically wind, relative humidity, solar radiation and temperature, or alternatively use of evaporation pan data), and measurement of soil moisture changes. At the onset of the wet season, soil moisture is at a seasonal low and must be filled to its available soil moisture holding capacity before recharge will begin. Water balances are ideally calculated using a daily time step.

Spot measurements of runoff have been performed on Lummi Island (Nielsen and Armfield, 2005) but no continuous runoff monitoring data are available. Likewise, no soil moisture data are available. An alternative methodology to estimate groundwater recharge was developed based on detailed studies performed on San Juan Islands (USGS, 2002) and Lummi Peninsula (Aspect Consulting, 2003). Using these studies, annual recharge was estimated for three surficial/near surface geologic conditions (glaciomarine drift, glacial outwash and bedrock) based on correlations between recharge and precipitation.

The USGS conducted an analysis of the relationship between groundwater recharge and precipitation for both glacial-deposited and bedrock aquifers for six basins on Lopez, San Juan, Orcas, and Shaw Islands for water years 1997 and 1998 (USGS, 2002). Three basins were monitored on Lopez Island, including two located in areas of glacial deposits and the third in a bedrock aquifer area. The other three watersheds monitored in the study were in areas of bedrock aquifers on San Juan, Orcas, and Shaw Islands. Recharge was computed using the Deep Percolation Method (DPM), using site measured values of precipitation, canopy through-fall, solar radiation, temperature and runoff. Other parameters required by DPM are clear sky radiation, soil limiting transpiration, and snow melt/sublimation which were complied from previous studies in Western Washington.

As part of the Lummi Peninsula Groundwater Investigation, detailed water balances were evaluated for 12 basins for a four year period extending from October 1997 through September 2001. All water balance components were field measured including continuous runoff, precipitation, evapotranspiration, and soil moisture. A spreadsheet water balance model utilizing field measured parameters was developed to compute recharge on a daily time-step. The predominant soil type in the gaged basins on the Lummi Peninsula was either glaciomarine drift or glacial outwash.

Precipitation and corresponding estimated recharge from each of the above-referenced studies were tabulated and categorized based on surficial/near surface soil type into one of three categories: glaciomarine drift, glacial outwash and bedrock. *Figure 3.4 presents* the correlations between mean annual precipitation and mean annual recharge for glaciomarine drift, glacial outwash, and bedrock. For a given mean annual precipitation amount, recharge was greatest in the outwash soils, lowest in the bedrock, and intermediate in the glaciomarine drift, consistent with the expected permeability variations for these soil types. With the exception of the bedrock aquifer, recharge increases with increasing mean annual precipitation.

Annual recharge in areas of undifferentiated glacial-deposits in the USGS (2002) study averaged 11 percent of annual precipitation. Annual recharge in areas of glaciomarine drift on the Lummi Peninsula (Aspect Consulting, 2003) averaged 13 percent of annual precipitation, and recharge to coarse-grained glacial (e.g., outwash) aquifers averaged 24 percent of annual precipitation. Second order polynomial regression equations were found to give a reasonable correlation function between mean annual precipitation and recharge for glacial outwash soil type (r^2=0.94), and for the glaciomarine drift (r^2=0.88).

Annual recharge to bedrock aquifers in the USGS (2002) study was approximately 0.5 inches per year, irrespective of precipitation, and, as such, showed no apparent correlation to precipitation. The data suggest that recharge to bedrock is limited by fracture permeability and, for a given precipitation event, the permeability is quickly exceeded and precipitation, rejected as recharge, is diverted to runoff. The recharge study on Lummi Peninsula did not include any bedrock aquifers.

3.3.2 Recharge Estimate Results

Recharge estimates calculated for Lummi Island are presented in acre-feet per year in Table 3.1. These estimates were developed by relating mean annual precipitation on Lummi Island to recharge. To develop these estimates, mean annual precipitation was synthesized based on correlation with Bellingham Airport. Monthly precipitation data on the Island has been collected intermittently at four locations by volunteers since the early 1980s. These four stations were used to calculate an average monthly precipitation record for the island. This record was correlated to precipitation data collected at the Bellingham International Airport to develop a synthetic precipitation record extending back to 1950 for Lummi Island.

The synthesized precipitation record was used to calculate 10-, 50-, and 90-percent exceedance precipitation percentiles for the island. Exceedance values are the statistical calculation of the annual precipitation that would be exceeded during the specified percentage of years in a given period. In general, the 10 percent exceedance precipitation value provides a representation of wet conditions (only 10 percent of the years exceed this precipitation), the 50 percent exceedance value represents the median annual precipitation, and the 90 percent exceedance value provides a representation of drought conditions. The 10-, 50-, and 90-percent exceedance precipitation values for Lummi Island were 38, 33, and 25 inches, respectively.

The correlations between recharge and precipitation for different soil types were used to estimate the 10-, 50-, and 90-percent exceedance values for annual recharge on Lummi Island (Table 3.1). Recharge was calculated for the entire northern Lummi Island study area (about 2,500 acres). About 63 percent of the island was assigned to the bedrock category, 35 percent to GMD and the remaining 2 percent to outwash, predominantly in the spit areas. Areas of bedrock mantled by GMD were considered as a bedrock soil type in estimating recharge. Recharge discharging from the GMD at rates exceeding bedrock permeability would be expected to migrate along the bedrock/GMD interface daylighting as seeps, effectively limiting recharge rates to that of the bedrock permeability.

Mean annual recharge for northern Lummi Island area is estimated at about 2 inches or about 360 acre-feet (6 percent of precipitation), with the majority of the recharge occurring in the GMD areas. For 10 percent and 90 percent, exceedances, recharge is estimated at about 3 inches and 1 inch, respectively.

Previous investigations estimated greater recharge, but their estimates were based on less detailed information analysis. Schmidt (1978) calculated a water budget for Lummi Island based on a simplified water balance equation using precipitation, runoff, recharge and evapotranspiration. Aquifer recharge was calculated to range between 5 and 9 inches (16 percent and 28 percent of precipitation). Sullivan (2005) estimated annual recharge to range from 0 to 20 inches and average 8 inches (24 percent of precipitation) based on the a simple mass balance approach apparently utilizing monthly time step and data from water years 2001 to 2004. The Sullivan mass balance approach did not account for changes in soil moisture, and runoff was based on spot measurements, rather than a continuous record. Sullivan (2005) also used a chloride-mass balance approach to estimate an average recharge of 4.3 inches (11 percent of precipitation) for water year 2004.

3.3.2.1 North Lummi Island Water Usage

Water use on Lummi Island was computed based on well data, and a second, independent check of the calculation was made using island population data. Details of the methodology are presented below. Total groundwater withdrawal of 111 acre-feet annually was estimated from well data. Of this approximately 45 acre-feet (40 percent) is expected to return via on-site drainfields, for a total net estimated water use of 66 acre-feet. The distribution of the withdrawals is presented on Figure 3.5. The population based estimate of groundwater withdrawals for northern Lummi Island was 122 acre-feet annually, the difference likely being caused by withdrawals from unrecorded wells. Thus, withdrawals represent about one-third of the estimated average study area recharge, while net water use is estimated at about 20 percent of estimated mean annual recharge.

Water usage was estimated from well data by totaling the number of wells in each individual quarter-quarter section. Well locations were obtained from the Aspect well database, and all wells were assumed to be currently in use. Water usage for Group A and B wells was calculated based on the number of system connections obtained from Whatcom County. Water usage for each of the domestic and municipal wells was

Whatcom County. Water usage for each of the domestic and municipal wells was calculated based on a per capita water use of 111 gpd for privately supplied residences in Whatcom County for year 2000 (Lane, 2004), and assuming that each residence has an average population of 2.1 people, based on the LISP. Total per capita water usage was summed for each quarter-quarter section (40 acres) of North Lummi Island. In order to accommodate seasonal water usage, it was assumed that 45 percent of the per capita water usage for each quarter-quarter section was used on a seasonal basis of 120 days. The remaining 55 percent of the per capita water usage was assumed to be used on a yearly basis of 365 days. It is important to note that no allowances were made for commercial/industrial use and this water usage was assumed to be minimal on northern Lummi Island.

Total annual groundwater withdrawals computed in this manner totaled 111 acre-feet. Figure 3.5 presents water usage for the various quarter-quarter sections of North Lummi Island. The majority of the quarter-quarter sections for North Lummi Island have a total yearly water usage of less than 2 acre-feet. Total yearly water usages greater than 5 acre-feet typically correspond to Group A water systems. Examples include T37R01E-09A and T37R01E-09B - Hilltop Water Owners Association, T38R01E-32B - Owners Association of Beach Club Condos, and T38R01E-32K - Isle Aire Beach Association and Sunset Beach Association (Figure 3.5).

A portion of the withdrawals are returned to the aquifer via drainfields. Ecology (1997) estimates approximately 45 gpd per capita is returned to the subsurface, or 95 gpd per household in the study area (about 40 percent of total estimated withdrawals). Recharge via drainfields is then estimated at 45 acre-feet annually and net withdrawals are estimated at 66 acre-feet.

Lummi Island population estimates for the year 2000 from the LISP were utilized in order to determine an overall population-based water usage. The LISP provided estimates of both permanent and seasonal populations for Lummi Island. Seasonal populations were assumed to be resident on Lummi Island for a period of 120 days. These estimates were used in conjunction with a per capita water usage of 111 gpd in the year 2000 for privately supplied residences in Whatcom County (Lane, 2004). Using these data, yearly water usage of 129.4 acre-feet was calculated for Lummi Island (Table 1). This calculation assumed that withdrawals by Lummi Island Estates Community Club (LISECC) contributed the majority of water usage for south Lummi Island. A population of 90 residences was used for the LISECC, based on Group A water system data obtained from Whatcom County. A total yearly water usage of 121.5 acre-feet was therefore calculated for North Lummi Island. The difference in the estimate based on wells (111 acre-feet) and population (122 acre-feet) likely results from wells without recorded logs.

3.4 Groundwater Quality

Water quality has been previously investigated in several studies on Lummi Island, including Sullivan (2005) and Whatcom County (1994). The Whatcom County (1994) study identified arsenic and seawater intrusion as the principal water quality concerns on Lummi Island, and those were the primary focus of this investigation. Each of these water quality concerns are relevant to island-wide groundwater management. Other site-specific quality concerns are relevant to island-wide groundwater management. Other site specific water quality issues such as naturally occurring iron and manganese, leaking fuel tanks, or drainfield-related impacts may be present, but were not investigated in this study. Seawater intrusion and arsenic occurrence on Northern Lummi Island are described in the sections below.

3.4.1 Seawater Intrusion

Marine salt water surrounds the study area on three sides. The occurrence of salt water at depth constrains the recovery of groundwater from wells. Pumping from wells that penetrate too deep, are located too close to the coast, or are pumped at excessive rates may induce movement of freshwater into saltwater.

Several wells within the study area have been affected by seawater intrusion, as discussed below. Prudent management of existing wells in the study area and any new development of groundwater supplies require characterization and appropriate consideration of conditions leading to salinity impacts.

3.4.1.1 Significance of Seawater Intrusion on Water Supply

Total dissolved solids are present in seawater of normal salinity at about 35,000 mg/L. Chloride is present in normal seawater salinity at concentrations of about 19,000 mg/L. Chloride, because of its conservative or non-reactive behavior, provides a convenient constituent by which to measure seawater intrusion.

Federal and state drinking water standards include secondary (recommended) drinking water regulations (SDWR) for chlorides (250 mg/L), and total dissolved solids (500 mg/L) or specific conductance of 700 micromhos per centimeter (µmhos/cm). Addition of about 1 to 1.5 percent seawater would cause typical, non-impacted groundwater to exceed one or both of the secondary MCL's, with chloride controlling. According to the Washington Administrative Code (WAC) 246-290-320, the Washington State Department of Health (WDOH) may require follow-up action of community water systems under its jurisdiction that report exceedances of SDWR.

As described below, pumping from wells may induce intrusion of salt water into the fresh water aquifer. Intrusion is generally reversible by curtailing pumping, but return to acceptable conditions may require a lengthy period of time. Similarly, salt water intrusion induced by pumping may take a long time to be manifested in degradation of water supply. By the time the problem is recognized, a community may have become dependent on the water supply, making control and correction of the problem economically difficult. For this reason, early warning of developing salt water intrusion is necessary.

WDOH (2001) considers 100 mg/L chloride to be a threshold of salt water intrusion risk, and at least one Washington county (Jefferson) has adopted a policy that uses 100 mg/L chloride as a criterion for management of salt water intrusion. This is consistent with the Department of Ecology's (WDOE) draft seawater intrusion policy (Washington Department of Ecology, 1991), which would have prohibited new water rights and discouraged new building permits where chloride levels exceeded 100 mg/L. A review of seawater intrusion ordinances including Ecology's draft seawater intrusion policy is presented in draft *Technical Memorandum 1* (Aspect Consulting, 2006a).

3.4.1.2 Mechanics of Seawater Intrusion

Seawater in the Lummi Peninsula vicinity has been found to contain from about 20,000 to 34,000 mg/L of dissolved solids (Aspect Consulting, 2003). These measurements likely represent lower salinities found at shallow depths and close to shoreline inflows of fresh water. Deeper salinities probably correspond to normal marine salinity of about 35,000 mg/L dissolved solids (including about 19,000 mg/L chloride ion). Lummi Island, further from the influences of Nooksack and Lummi River discharge, would be expected to have salinities closer to normal seawater. Water of this typical marine salinity is about 2.5 percent denser than fresh water.

Seawater and fresh water are fully miscible; however, where they are in contact with minimal turbulence at the interface, fresh water tends to form a layer that floats above the denser seawater. Salt water extends laterally beneath coastal groundwater aquifers.

The basic behavior of the fresh water-salt water interface is described in texts on ground-water hydrology such as Todd (1980) or Bear (1979). Without mixing, a lens of fresh groundwater theoretically would "float" above salt water, with its base at a depth below sea level about 40 times as great as its height above sea level (Figure 3.6). This theoretical configuration is known as the Ghyben-Herzberg lens. The influx of fresh ground water recharge moves the toe of the lens slightly offshore.

This idealized Ghyben-Herzberg lens geometry is modified in the real world by several factors. Most importantly, a sharp interface between fresh and salt water does not exist but is replaced by a "transition zone" that grades over some vertical distance from fresh

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water above the zone to salt water below. The transition zone results mainly from mixing induced by constant tidal motion. Tidal activity results in a back-and-forth particle motion which, combined with geologic discontinuities, smears the interface over a zone spanning tens to hundreds of feet vertically (Figure 3.6). The sharp-interface formulas can be used to characterize the midplane (50 percent seawater) of the transition zone.

Pumping from wells can induce upward intrusion of saline water from the transition zone, termed "upconing" (Figure 3.6). The amount of degradation in water quality associated with upconing depends on the salinity of the upconed water, the height of the well bottom above the transition zone, the presence or absence of geologic barriers to vertical flow (vertical hydraulic conductivity), and the rate and frequency of pumping.

3.4.1.3 Seawater Impacts on Lummi Island Groundwater

The distribution of chloride in the study area is presented in Figure 3.7 based on median chloride values for located/surveyed wells. Also indicated on Figure 3.7 are the elevations of the completion intervals and the well yields reported on the driller's logs. Chloride concentrations are indicated by color according to the following categories: less than background (0 to 40 mg/L), between background and the early warning value of 100 mg/L (40-100 mg/L), between the early warning value and SDWR (100-250 mg/L) and greater than the SDWR (>250mg/L).

Inspection of Figure 3.8 indicates that most wells completed above sea level have chloride concentrations less than 40 mg/L. These data suggest that background chloride on the Lummi Peninsula are less than about 40 to 50 mg/L. A value of 40 mg/L was conservatively selected as indicative of background conditions. This value is consistent with findings on the Lummi Peninsula (Aspect Consulting, 2003) and with Sullivan (2005).

Approximately 40 wells on northern Lummi Island were sampled in April and August, 2006 for chloride. Results are summarized in Table 3.2, and field methodology is presented in Appendix B. In addition, selected wells were also sampled for bromide to assist in evaluation of the chloride source.

Median chloride concentrations in excess of background levels are found in the following five areas:

Point Migley – Two wells exhibit chloride of 100 mg/L or greater. One of the wells has an associated well log and indicates the base of completion elevation of about -72 feet in bedrock. No well log is available for the other well. Both wells are located within about 300 feet of the shoreline. The bedrock well had a reported yield of 5 gpm but was bailed dry during testing.

Northwest Coast – Two wells were identified which exceeded background levels along the northwest coast. One well (242), north of the Willows, had a median chloride concentration of 24 mg/L; however, review of historic data for this well indicates chloride levels increased between 1993 sampling (22 mg/L) and sampling in October 2002 (128 mg/L). Chloride levels decreased to 49 mg/L in May 2003. Completion elevation for this well is -70 feet. The other well, located south of the Willows, is completed at about 111 feet below sea level, and the median chloride value (45 mg/L) is close to the background level.

Village Point – Two wells east of Village Point have median chloride concentrations in excess of 250 mg/L. Well completion depths for both wells are greater than 70 feet below sea level. One well is completed in the Qc1 unconsolidated aquifer and the other is completed in the sandstone aquifer. The median chloride in the sandstone well is in excess of 3,000 mg/L. Both wells are located within about 700 feet of Legoe Bay. The bedrock well had a reported yield of 15 gpm, but was bailed dry during testing.

Southwest Shoreline Single Well (west of South Nugent Drive) – one well completed in the Qc1 aquifer at an elevation of about -79 feet was identified with chloride in excess of 100 mg/L. The well had a reported yield of 19 gpm and a specific capacity of 2.5 gpm/ft drawdown.

Central East Shoreline Area – Five wells exceed background chloride concentrations along the central east shoreline area between Centerview Road and Legoe Bay Road, with four of these in exceedance of 100 mg/L. Well completion elevations range from -36 to -183 feet. All five of these wells are likely completed in bedrock. Two of the bedrock wells are very low yielding. Distances from the shoreline ranges from 300 to about 1,000 feet.

Lane Spit – One shallow well on Lane Spit, completed near sea level and located adjacent to the shoreline, exceeded the SDWR for chloride.

Anomalously high chloride concentrations in inland wells were investigated in the April and August sampling events. Wells 76 and 188 had elevated chloride levels measured in 2003, although chloride levels were within background for samples collected in 2006.

Median chloride for well 232 is at the background threshold and well 247 median chloride value slightly exceeds background levels. The base of well 76 screen is near sea level, and wells 188, 232, and 247 have well screens well below sea level.

Inland wells with historically elevated chloride concentrations (76, 247, 232, and 188) were analyzed for bromide and sodium to evaluate if seawater was the source of chlorides for these wells. Seawater typically has a Cl/Br ratio of 297 and a Na to Cl ratio of about 0.6. Chloride and bromide are typically nonreactive with the aquifer matrix (referred to as conservative behavior), except where high amounts of organic matter are present (Bear and others, 1999). Cation exchange and other processes may modify sodium concentrations during transport of seawater within the aquifer (Hem, 1970).

Bromide data are equivocal with respect to identification of seawater in the inland wells. Bromide was typically below detection limits, which limited the data evaluation. Assuming bromide was present at the detection limits, C1/Br ratios ranged from about 128 to 300. Bromide present at levels less than the detection limit would increase these values. Thus, for the wells where bromide concentrations were less than the detection limit, seawater intrusion cannot be ruled out, nor can it be confirmed based on Cl/BR ratios. Bromide was detected in one well in the August sample round at a concentration higher than would be expected for seawater. Well 247 had a chloride to bromide ratio of 24 suggesting bromide concentrations were supplemented by a source other than seawater.

Well 188 had a sodium to chloride concentration of about 0.5 in both the spring and fall sample rounds, generally consistent with a seawater source for this well, while Na to Cl ratios of about 1 for wells 76 and 247 do not support seawater intrusion. Sullivan (2005) categorized well 247 as "probably intruded" based on analysis of head and ion data. Of the other inland wells with elevated chloride, Sullivan classified wells 188 and 232 as "possibly intruded".

The relationship between chloride concentration and well depth was examined by plotting well completion depth against median chloride concentration for wells with surveyed well elevations (Figure 3.8). In an island setting with a homogenous aquifer, chloride levels would be expected to increase with well completion depths that extend into the transition zone. At Lummi Island, there are several wells (both unconsolidated and bedrock completions) with completion depths well below sea level and chloride levels within background concentrations that indicate a more complex flow system is present. As a corollary, wells were also identified with relatively shallow completion depths and elevated chloride levels. For the most part, high chloride wells are not distinctly clustered geographically. These data suggest a heterogeneous groundwater flow system where the location of the transition zone is strongly influenced by local variations in aquifer permeability and pumping.

The relationship between groundwater elevation (head) and median chloride concentration was also examined (Figure 3.9). In Island County, Kelly (2005) noted a relationship between head and chloride levels. By maintaining a groundwater elevation of 8.4 feet (NAVD 88) or higher between the well and the coast, sufficient head is present to maintain the shoreward position of the seawater/fresh water interface on Whidbey Island (see Technical Memorandum 1 for additional description of the Island County Seawater intrusion ordinance). This relationship was not found to hold true on Lummi Island. Several wells were identified with chloride levels elevated above background and groundwater elevations of 8 feet (NGVD 88) or more.

Allen and others (2003) studied seawater intrusion in the bedrock aquifers of the Gulf Islands of Canada. Based on downhole flowmeter (spinner) surveys and geophysical borehole logging, they identified single, discrete fractures and more highly fractured zones as entry points for seawater into wells. Seawater may occur as wedges within these individual high permeability, fracture zones. These high permeability zones act as discharge points for freshwater under unstressed aquifer conditions and, because of the high flux of water through them, will maintain the saltwater/freshwater interface a greater distance off-shore than a lower permeability zone. If the flow direction is reversed, as may occur in the case of a pumping well, they may become a conduit for seawater into an aquifer. Vertical and subvertical fractures were also identified by Allen and others (2003) as playing a major role in transmitting water, with the potential of allowing seawater to move upward through these conduits.

The poor correlations between: 1) chloride concentration and well completion elevation, and 2) chloride concentration and head indicate that the conceptual model of the saltwater/freshwater interface on northern Lummi Island is far more complex than the classic Ghyben-Herzberg or transition zone models. The data are consistent with a conceptual model of groundwater flow controlled in many areas by fracture permeability. That many of the seawater intruded wells are low yielding wells is consistent with limited pumping inducing movement of the saltwater wedge into a well. The numerous deep wells with low chloride concentrations indicate that some water-bearing fractures are isolated by low permeability intact portions of the aquifer, preventing seawater intrusion. Unconsolidated wells with high chloride concentrations and high head may be similarly affected by seawater transmitted through bedrock or by heterogeneities within the unconsolidated material.

3.4.2 Arsenic

Arsenic in exceedance of drinking water standards was identified over much of the study area. The MCL for arsenic was lowered to 10 micrograms/liter (µg/L) effective January 23, 2006 from the previous MCL of 50 µg/L. An MCL is the highest level of a contaminant that is allowed in drinking water. Under the County drinking water statute (Chapter 24.11), if arsenic exceeding the MCL of 10 µg/L is identified in a water supply well serving as a one- or two-party drinking water source to be approved by the health department, then treatment of the water source is required, with the exception of wells in short and long plats. In the case of short or long plats, for the purpose of oversight, the County drinking water regulation does not allow for treatment. The expectation is that where new lots were being created and an MCL exceedance occurred, a public water system under state DOH review would be created and sources with MCL exceedances would be overseen by state WDOH. At *this time, the arsenic* standard for Group B (3 to 14 connections) systems in Washington is 50 µg/L. The arsenic standard in Whatcom County at this time is 10 µg/L for systems with 1 or 2 connections or for 15 or more connections (Group A). (Lee Phipps, personal communication, March 2006).

Median arsenic distribution based on available data is presented in Figure 3.10 for the study area. Wells with arsenic concentrations exceeding the MCL of 10 μg/L are colored red, and wells with arsenic concentration less than the MCL are shown in blue. The well yield and completion elevation are shown along with the arsenic concentration. The source of arsenic appears to be within the sandstone aquifer, where highest concentrations are typically found. Wells completed in the Greenstone Aquifer are typically low in arsenic.

The highest prevalence of median arsenic exceeding the MCL of 10 μg/L occurs in the sandstone wells – about 70 percent of wells recorded in the database as completed in the bedrock aquifer exceed the MCL, compared to about 27 percent in the unconsolidated aquifer. Based on the existing data, the occurrence of arsenic above the MCL may be subdivided into the following three areas.

Point Migley/Loganita Area – Median arsenic distribution in this area appears spatially variable. Three wells were identified with median arsenic concentrations more than an order of magnitude greater than MCL (i.e., greater than 100 μg/L), with several wells in the area exceeding the arsenic MCL but less than 100 μg/L. No well logs are available for wells with the highest median arsenic concentrations in this area, and completion depths are unknown. Median arsenic concentrations exceed the MCL in two wells completed in unconsolidated deposits south of Point Migley along the west shore.

Central Area – This area extends approximately from south of the Richards Mountain/Willows area to Lovers Bluff and the ferry terminal. A northeast trending band of wells with median arsenic concentrations less than the MCL separate this area from

Point Migley/Loganita area. Highest median arsenic concentrations are found in sandstone wells along the east shoreline, south of Lummi Point and north of the ferry terminal. A large data gap is present in the area south of Richards Mountain, where no arsenic data are available. Most wells in the central arsenic area are completed in sandstone bedrock. At the south end of this area, two wells completed in unconsolidated aquifer (Qc) with arsenic levels in exceedance of the MCL were identified north of Legoe Bay Road. The occurrence of arsenic in the Qc wells is discussed further below.

South Area – This area is defined predominantly by wells along the southwest coast. A broad band of unconsolidated wells and Greenstone wells with arsenic concentrations less than MCL separates the central and south areas. To the south, a band of wells along Sunrise Road, mostly completed in unconsolidated material, have arsenic levels less than the MCL. One well completed in a sandstone and Greenstone on the east shore exhibited high arsenic, although the location of the well could not be verified. Wells may show considerable seasonal variability in arsenic concentrations. Two wells were identified from the 1994 study that exhibited order of magnitude changes in arsenic concentration, and several wells had arsenic concentrations which fluctuated over a half order of magnitude annually. Between the April and August 2006 sample rounds, fluctuations in arsenic concentrations ranged from none to as much as four-fold increase (Table 3.2).

Median arsenic concentrations were plotted as a function of well elevation to investigate the relationship between arsenic occurrence and well intake elevation (Figure 3.12). No apparent relationship is present between median arsenic concentrations and well intake elevation, and the data indicate that median arsenic concentrations above the MCL are not a function of intake elevation. Plot of well depth and median arsenic concentrations indicated a similar lack of correlation. Low and high arsenic concentrations occur in both shallow and deep wells.

The wide spread distribution of arsenic and lack of correlation of arsenic levels with depths are consistent with a natural arsenic source. Arsenic may have been used on Lummi Island as a pesticide for orchards, poultry and other livestock during the 1940s and 1950s (Whatcom County, 1994); however, if arsenic were related to anthropogenic surface sources, arsenic would be expected to occur in hot spots related to application areas. In addition, a consistent pattern to concentration and depth would be expected as surface sources migrated vertically. This conclusion is consistent with findings of the 1994 report. Additional sampling to establish trends in arsenic concentrations since the early 1990s could provide additional evidence of natural occurrence of arsenic (i.e., arsenic concentrations would be expected to decline with the end of surface applications).

The distribution of unconsolidated wells with elevated arsenic suggests that arsenic-impacted groundwater migrates laterally outward from the sandstone aquifer into the unconsolidated deposits. This hypothesis is based on the distribution of unconsolidated wells with elevated arsenic levels around the fringes of bedrock areas, as contrasted with low arsenic in the unconsolidated wells located in areas more distant from the bedrock (Figure 3.10). An arsenic concentration gradient is broadly defined along the southern sandstone limit in the Central area, by median arsenic concentrations decreasing from a high of 305 μg/L at bedrock well 226 to a low of 5 μg/L at downgradient Qc1 well 225, suggesting lateral migration of groundwater with elevated arsenic (Figure 3.10).

Further evidence for migration of elevated arsenic water to unconsolidated aquifers is provided in the examination of water types characteristic of the sandstone and unconsolidated aquifers. Figure 3.11 presents Stiff diagrams showing the "signatures" of the major water types for selected wells. Stiff diagrams permit quick evaluation of water types based on geometric shapes. Bedrock wells with high arsenic have a distinctive water type typified by high sodium and very low calcium and magnesium (wells 226, 247, 227, Figure 3.11). In contrast, wells completed in the unconsolidated material with low arsenic (for example wells 053 and 225) exhibit nearly equal parts of sodium, calcium, and magnesium, with calcium being the slightly dominant cation. Unconsolidated wells on the south fringe of the sandstone (wells 268, 88 and 240) with arsenic levels intermediate between these end members suggest a mixing of these two water types. These wells exhibit a higher proportion of sodium relative to Qc wells with low arsenic (indicative of bedrock) and higher calcium and magnesium relative to bedrock wells, indicating migration of groundwater with elevated arsenic from the bedrock and mixing within the Qc1 aquifer.

Wells completed in the Qc1 aquifer in the South Area with elevated arsenic also exhibit elevated sodium, suggesting that sandstone may underlie the Qc aquifer in this area and influence the water quality. The Stiff plots for these wells show greater similarity to the sandstone than to the adjacent Greenstone. The log for at least one well in the south Greenstone area indicated sandstone overlying the Greenstone. The 1994 study reports elevated arsenic for this well; however, the location of the well could not be verified in the present study.

Water types for wells in the low arsenic band that separates the Point Migley and Central arsenic areas exhibit relatively low sodium and relatively greater calcium (wells 257 and 14) (Table 3.2). The water type signature for these wells appears more closely related to Greenstone water type identified at well 232 at the south end of the study area. The well log for well 14, located in the northerly low arsenic band indicates that the bottom 8 feet of the well is completed in Greenstone, suggesting that the band of low arsenic wells could be related to shallow Greenstone. This band of low arsenic wells is also coincident with the top of a recharge area (Figures 3.3 and 3.10).

Median arsenic concentrations in sandstone (32 µg/L) are significantly greater the median concentrations in unconsolidated aquifer (4 µg/L), also suggesting sandstone as a source for arsenic (values obtained from database by taking the median of all individual well median arsenic concentrations).

Arsenic concentrations were also examined as a function of specific capacity (Figure 3.13). Groundwater in lower permeability units with longer residence may be expected to develop higher arsenic concentrations. The data indicate that at specific capacities above about 1.5 gpm/ft, arsenic concentrations are less than the MCL. At lower specific capacities, there was no apparent relationship between specific capacity and arsenic.

0240

4 Summary of Technical Considerations for Development of Methodology

Findings from the hydrogeologic investigation provide a technical basis for development of a methodology to evaluate groundwater withdrawals. Key findings are discussed below in terms of seawater intrusion, arsenic, and safe yield. In summary, the lack of predictability for chloride precludes use of methods currently in use in Jefferson, Island and other western Washington Counties. Rather, the methodology should focus on development of an antidegradation policy that limits any further declines in groundwater quality.

Safe Yield

Safe yield of the aquifer cannot be known with certainty without detailed field investigations to estimate recharge and numerical modeling to identify the percent of recharge available for development. Pending these studies, a prescriptive approach to evaluating groundwater withdrawals on Lummi Island cannot be implemented. Even if performed, considerable uncertainty in safe yield could remain, particularly in the highly variable bedrock aquifer.

Seawater Intrusion

No apparent relationship was identified between well depth and salinity or between groundwater head and salinity. This finding coupled with heterogeneity of the bedrock aquifers indicates that a seawater intrusion policy based on relationship to head and salinity (similar to Island County) is not appropriate for Lummi Island. In addition, methods limiting groundwater development within a prescribed radius of wells with elevated chloride levels, such as in Jefferson County, are not recommended, as the chloride distribution cannot be predicted with any certainty, particularly in the bedrock aquifer.

Arsenic

Arsenic appears to be naturally occurring and sourced in the sandstone aquifer. Arsenic appears to migrate laterally outward from the sandstone regions affecting arsenic levels in the unconsolidated aquifer in the downgradient fringe areas. Within the sandstone arsenic concentrations are highly variable and cannot be predicted with any certainty. In addition, arsenic concentrations vary considerably on a seasonal basis in some wells. Methods for evaluating proposed groundwater withdrawals should account for the potential for arsenic-impacted groundwater to migrate laterally into unaffected portions of the aquifer as a result of pumping.

0241

Methodology

To achieve the objective of developing standards and policies that are protective of the groundwater resource, natural environment and human health, an antidegradation standard is recommended. Development of an antidegradation standard will be adaptive to the many area-specific circumstances present in the northern Lummi Island aquifers. Protective measures could be developed based on limiting further degradation of water quality in areas where impacts are observed. The antidegradation standard should include criteria for both seawater intrusion and arsenic.

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Limitations

Work for this project was performed and this report prepared in accordance with generally accepted professional practices for the nature and conditions of work completed in the same or similar localities, at the time the work was performed. It is intended for the exclusive use of Whatcom County Planning & Development Services for specific application to the referenced property. This report does not represent a legal opinion. No other warranty, expressed or implied, is made.

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Table 3.1 - Annual Recharge Estimates

Northern Lummi Island Hydrogeologic Investigation

Exceedance Percentile	10	50	90
Annual Precipitation (inches)	38	33	25
Recharge for the entire study area (inches)	2.6	1.7	1.1

Exceedance Percentile	10	50	90
Recharge for the entire study area (acre-ft)	540.6	358.0	233.2
Recharge based on aquifer type (acre-ft)			
Bedrock	66.0	66.0	66.0
GMD	438.9	267.3	154.3
Outwash	35.7	24.8	12.9

0246

Arsenic Research Parameters					Seawater Intrusion Research	Field Parameters				
Mn	P	S	SiO_2	Total Phosphate	Br	Temperature (°C)	Specific Conductivity (uohm/cm)	Dissolved Oxygen (mg/L)	pH	ORP
0.0760	0.01	4.0	26	0.014		10.2	598	2.18	6.87	106.7
0.0365	0.03	3.5	28			10.23	553	1.45	7.54	-24
< 0.0100	< 0.01	3.8	20	< 0.005		16.77	351	2.01	8.05	-6
0.0026	< 0.01	4.3	20			15.84	410	1.08	7.27	51.6
					< 0.42	12.53	593	1.45	6.98	81.8
< 0.0100	0.01	7.1	21			10.33	325	5.86	7.79	158.7
< 0.0005	0.02	7.5	21			12.44	310	5.84	6.51	122.8
						9.6	438	7.35	7.8	18.1
						15.01	411	9.46	8.04	-35.5
0.0620	0.01	5.0	19			9.43	389	2.09	8.18	162
0.1420	0.01	4.3	20			13.89	348	0.97	6.66	158.5
0.0730	0.04	29	31		< 0.05	10.35	711	4.78	7.68	-117.1
0.0877	0.01	29	26			10.28	644	0.59	8.23	-238.1
0.0440	0.18	7.5	26	0.18		11.49	405	1.07	8.01	61.1
0.0823	0.18	8.6	34			11.84	404	0.63	7.77	91.7
0.0930	0.30	14	27			11.01	446	0.47	8.29	10.2
0.0491	0.34	12	30			11.78	416	0.46	7.56	38.8
< 0.0100	0.05	5.8	18	0.049		11.07	352	5.32	8.83	-46.6
0.0021	0.08	4.7	19			14.36	325	5.03	9.13	-68.1
					< 0.05	9.96	308	0.43	7.33	-61
						10.92	292	0.52	7.62	-43.4
						16.00	330	4.1	7.79	40.5
						11.78	262	2.82	8.38	55.1
						15.10	257	4.41	7.82	18.5
						10.66	538	0.64	8.73	2.5
0.0070	1.82	5.5	22			10.70	524	0.14	8.76	-29.7
						10.48	485	0.7	7.74	-50.9
0.0088	0.02	12	23			10.99	485	0.27	7.41	-41.4
						10.55	308	5.00	8.34	17.7
						11.23	288	4.77	7.56	28
0.0456	0.34	7.7	29			10.67	404	0.13	8.33	-35.8
					< 0.42	13.46	1502	2.45	7.47	8.2
					< 0.05	9.62	278	5.2	8.87	-108.7
					< 0.05	18.91	385	2.13	7.12	18.8
						8.89	558	4.22	8.5	184.1
						10.62	553	1.4	7.88	-76.4
						10.14	330	1.86	5.91	119
						10.19	417	1.16	6.46	6.7
0.0460	0.03	7.4	24			10.13	491	0.44	8.01	-27.8
0.0670	0.04	6.5	24			10.77	307	3.77	7.92	335.4
0.131	0.03	8	27			14.98	305	2.47	7.47	24.5
						11.28	383	3.23	7.75	119.5
0.0350	0.09	6.0	20	0.071		13.29	355	3.04	6.5	-93.9
						10.44	736	12.7	8.88	116.3
0.0033	0.05	9.3	12			14.61	661	13.61	7.56	20.1
						9.82	480	7.75	8.6	-114.6
0.0034	0.08	7.9	12			14.23	518	3.74	9.42	-128.6
< 0.0100	< 0.01	15	17		< 0.05	11.17	574	4.36	8.54	-31.4
< 0.0005	0.01	14	17			10.90	538	3.77	8.16	29.5
0.0850	0.01	12	20			10.96	545	1.24	7.19	-27.3
						11.01	502	0.18	7.78	-94.1
0.0240	0.41	12	220	0.41		11.39	475	0.87	8.31	52.7
0.0436	0.43	14	26			11.18	474	0.52	7.83	184.3
< 0.0100	0.01	7.1	18		< 0.05	10.3	411	2.17	7.09	84.8
0.0011	0.02	7.5	14			10.56	444	1.14	6.97	133.7
< 0.0100	0.12	38	14	0.12	< 0.05	11.11	863	0.52	8.67	-26.1
0.0073	0.12	31	14		2.5	11.09	746	0.07	9.8	-138.5
0.160	< 0.01	4.5	21			9.44	436	1.43	7.73	165.7
0.0946	0.02	3.8	22			13.28	408	1.32	657	172.9
0.0180	0.03	8.9	21			10.63	383	3.32	8.48	162.9
0.0115	0.03	7.7	21			11.00	400	2.74	8.95	92.6
						10.30	353	7.22	7.83	22.4
0.0078	0.12	6.7	18			15.62	347	5.64	8.1	-35.7
						10.68	319	6.51	6.98	86.3
						11.01	306	6.65	6.79	81.2
< 0.0100	0.02	35	19	0.017		10.28	588	0.4	7.7	-18.4
0.0042	0.02	22	20			12.00	494	1.42	7.35	50.6
						10.68	451	2.03	8.19	144.9
						11.46	409	2.11	6.95	87.3
						10.28	551	1.26	9.31	29.8
						12.36	545	2.92	8.82	0.2
						9.85	417	5.21	8.37	35.3
						13.50	393	2.96	9.05	-118.4
						11.15	696	0.74	8.14	-140.6
						12.18	662	0.99	7.38	142.7
						10.11	344	3.34	8.16	136.7
						10.34	360	1.04	8.76	155.1

Table 3.2 - Laboratory Data—August 29-31, 2006

Well ID	Date	Time	Arsenic: Total As	Arsenic: As	Major Ions: Ca	Mg	K	Na	Sulfate	Carbonate	Total Alkalinity	Bicarbonate	Cl	Fe
10	4/12/06	12:40	0.065	0.044	73	17	0.52	47	12	< 1	260	260	16	< 0.100
	8/30/06	12:50	0.048	0.043	80	18	0.54	50	11	< 1	260	260	17	< 0.005
14	4/14/06	15:20	0.003	0.003	22	7.3	5.2	23	11	< 1	110	110	9.8	0.239
	8/31/06	14:45	0.006	0.006	44	7.9	7.2	33	13	< 1	180	180	11	< 0.005
23	8/29/06	13:15	0.130	0.120									53	
53	4/13/06	10:38	0.004	< 0.003	26	12	1.4	20	21	< 1	190	190	20	< 0.100
	8/30/06	12:10	0.001	0.001	26	13	1.8	21	23	< 1	90	90	25	< 0.005
54	4/15/06	13:00	0.028	0.026									39	
	8/30/06	15:45	0.021	0.022									34	
62	4/13/06	9:05	0.019	0.016	58	10	1.6	19	15	< 1	190	190	15	< 0.100
	8/30/06	10:49	0.039	0.033	44	7.5	2.0	24	13	< 1	150	150	11	< 0.005
76	4/12/06	14:45	0.016	0.016	65	54	10	18	88	28	190	162	18	0.681
	8/29/06	17:31	0.005	0.003	50	54	9.6	18	66	< 1	250	250	17	< 0.005
79	4/14/06	16:45	0.008	0.008	32	20	8.1	20	22	< 1	160	180	13	< 0.100
	8/31/06	10:57	0.006	0.007	37	20	8.2	20	26	< 1	160	160	12	< 0.005
88	4/13/06	17:05	0.022	0.018	11	19	15	36	42	< 1	180	160	16	< 0.100
	8/30/06	15:35	0.017	0.017	23	20	16	38	37	< 1	160	160	17	< 0.005
109	4/13/06	15:44	0.004	0.004	5.3	1.6	2.5	69	17	24	150	126	7.7	0.117
	8/29/06	16:44	0.004	0.005	4.8	1.6	2.3	71	14	30	140	110	7.4	0.005
113	4/12/06	15:41	< 0.003	< 0.003									9.8	
	8/31/06	12:10	0.002	0.002									9.1	
122	8/29/06	14:30	0.004	0.004									22	
141	4/14/06	15:55	0.006	0.006									11	
	8/30/06	16:40	0.004	0.004									11	
160	4/13/06	15:05	0.019	0.018									15	
	8/31/06	11:15	0.019	0.019	2.1	1.5	5.8	120	18	20	220	200	15	0.094
162	4/14/06	10:50	0.003	< 0.003									17	
	8/31/06	10:30	0.002	0.001	58	25	3.1	14	35	< 1	190	190	17	< 0.005
166	4/13/06	14:50	< 0.003	< 0.003								0	13	
	8/30/06	18:30	0.002	0.002									13	
180	8/31/06	12:15	0.017	0.017	20	12	15	41	23	< 1	150	150	18	0.005
181	8/29/06	16:15	0.198	0.123									100	
188	4/13/06	17:30	< 0.003	< 0.003									12	
	8/30/06	10:38	0.004	0.005									15	
195	4/12/06	13:05	0.224	0.220									19	
	8/29/06	15:10	0.220	0.210									20	
203	4/13/06	11:35	< 0.003	< 0.003									21	
	8/29/06	17:12	0.002	0.001									20	
205	8/30/06	12:05	0.025	0.018	43	13	7.4	41	22	< 1	180	180	35	< 0.005
208	4/14/06	10:17	0.004	< 0.003	18	16	2.1	13	20	< 1	130	130	8.9	0.182
	8/31/06	13:23	0.003	0.002	30	16	2.2	14	18	< 1	120	170	7.5	0.146
225	4/12/06	11:58	0.007	0.005									22	
	8/29/06	12:16	0.005	0.006	31	13	4.9	26	18	< 1	150	150	16	< 0.005
226	4/12/06	10:55	0.060	0.044									180	
	8/28/06	15:08	0.560	0.570	1.3	0.07	0.19	140	28	80	220	140	39	< 0.005
227	4/13/06	11:40	0.115	0.103									20	
	8/29/06	13:46	0.180	0.150	1.6	0.10	0.32	120	24	40	210	170	23	< 0.005
232	4/13/06	13:20	< 0.003	< 0.003	40	24	1.8	17	48	< 1	190	190	37	< 0.100
	8/30/06	16:49	< 0.001	< 0.001	69	25	1.8	18	43	< 1	180	180	36	< 0.005
239	4/12/06	14:01	0.074	0.060	28	7	5.8	81	35	< 1	260	260	22	0.11
	8/30/06	17:35	0.080	0.080									20	
240	4/14/06	17:25	0.022	0.023	18	13	14	61	36	< 1	160	160	18	< 0.100
	8/31/06	10:00	0.018	0.018	16	13	15	81	41	< 1	160	160	18	0.023
245	4/14/06	12:25	0.009	0.009	14	5.6	6.1	44	21	< 1	130	130	20	< 0.100
	8/30/06	13:08	0.042	0.039	27	5.4	6.9	68	23	< 1	170	170	22	< 0.005
247	4/12/06	16:34	0.188	0.187	3.2	0.47	0.39	180	110	< 1	170	170	88	< 0.100
	8/29/06	13:09	0.170	0.170	2.7	0.25	0.33	160	92	40	190	150	59	< 0.005
257	4/13/06	9:55	0.005	0.003	89	12	1.0	18	14	< 1	98	98	14	< 0.100
	8/30/06	10:10	0.004	0.005	57	12	1.0	20	11	< 1	180	180	15	< 0.005
264	4/12/06	13:59	0.006	0.004	33	11	1.7	43	27	< 1	180	180	19	< 0.100
	8/29/06	12:25	0.003	0.003	26	11	1.6	41	23	< 1	150	150	18	< 0.005
268	4/15/06	14:15	0.014	0.014									15	
	8/29/06	11:22	0.014	0.012	28	12	5.5	26	20	< 1	150	150	13	< 0.005
300	4/13/06	13:30	< 0.003	< 0.003									16	
	8/30/06	14:20	0.002	0.002									16	
354	4/13/06	14:00	0.206	0.171	22	3.1	6.9	81	100	< 1	180	180	18	< 0.100
	8/30/06	18:10	0.170	0.170	28	2.8	6.6	86	67	< 1	170	170	19	< 0.005
393	4/12/06	16:00	0.020	< 0.003									18	
	8/30/06	13:45	0.010	0.002									22	
398	4/14/06	13:35	0.234	0.234									22	
	8/29/06	18:30	0.192	0.198									22	
399	4/14/06	11:19	< 0.003	< 0.003									17	
	8/29/06	16:16	0.001	0.003									21	
402	4/12/06	9:35	0.019	0.017									12	
	8/29/06	11:35	0.016	0.016									11	
425	4/12/06	15:18	0.004	0.003									12	
	8/30/06	11:38	0.004	0.005									12	

Notes:

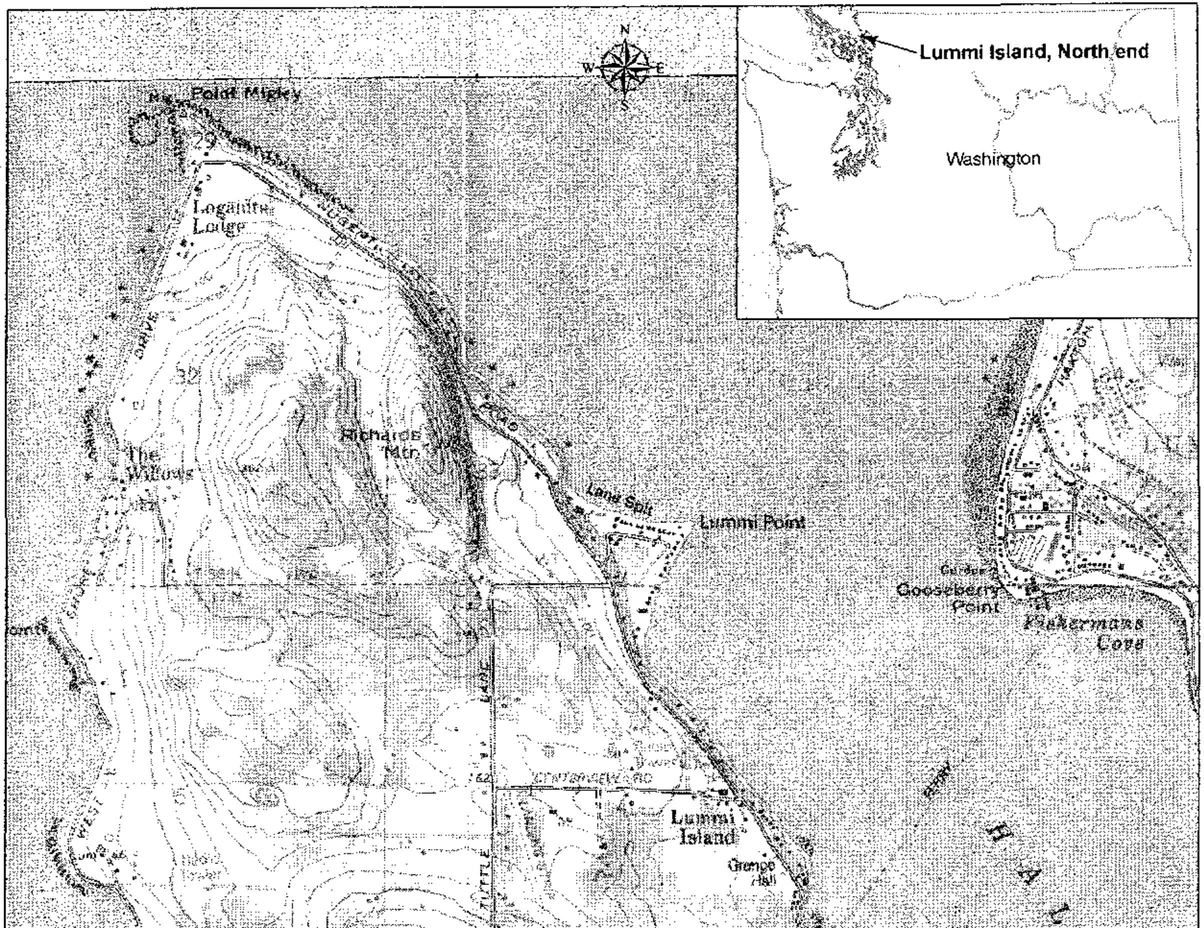
All values in mg/L unless otherwise noted

All values represent dissolved constituents unless otherwise noted

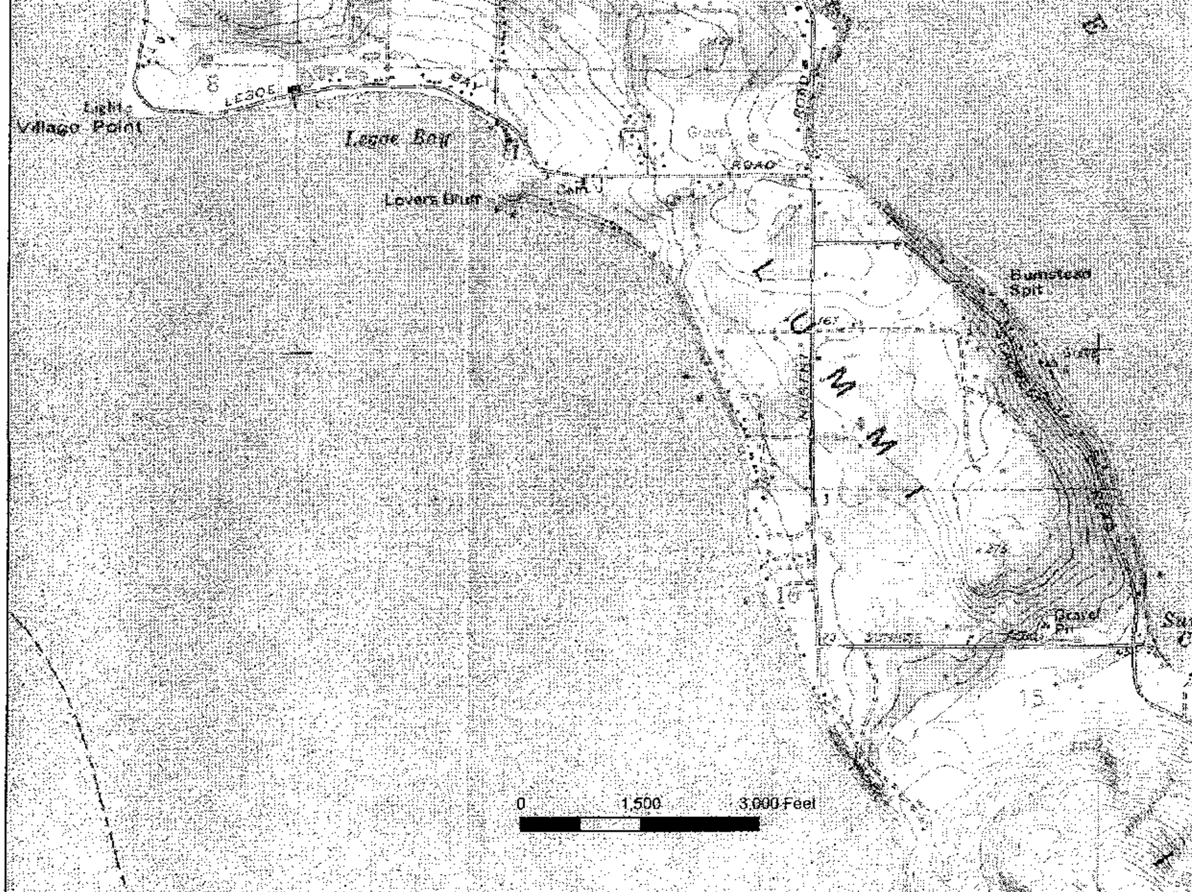
As: Arsenic; Ca: Calcium; Mg: Magnesium; K: Potassium; Na: Sodium; Cl: Chloride; Fe: Iron; Mn: Manganese; P: Phosphorus; S: Sulfur; SiO2: Silicate; Br: Bromide

Aspect Consulting
12/31/2006
W:\050039 Whatcom Co - Lummi Island GW\Hydrogeologic Investigation\Table3.2.xls

0247



Lummi Island, North end
Washington
N
W
E
S
Point Migley
Richards Mtn
The Willows
Lane Spit
Lummi Point
Gooseberry Point
Fishermans Cove
Lummi Island
Grange Hall



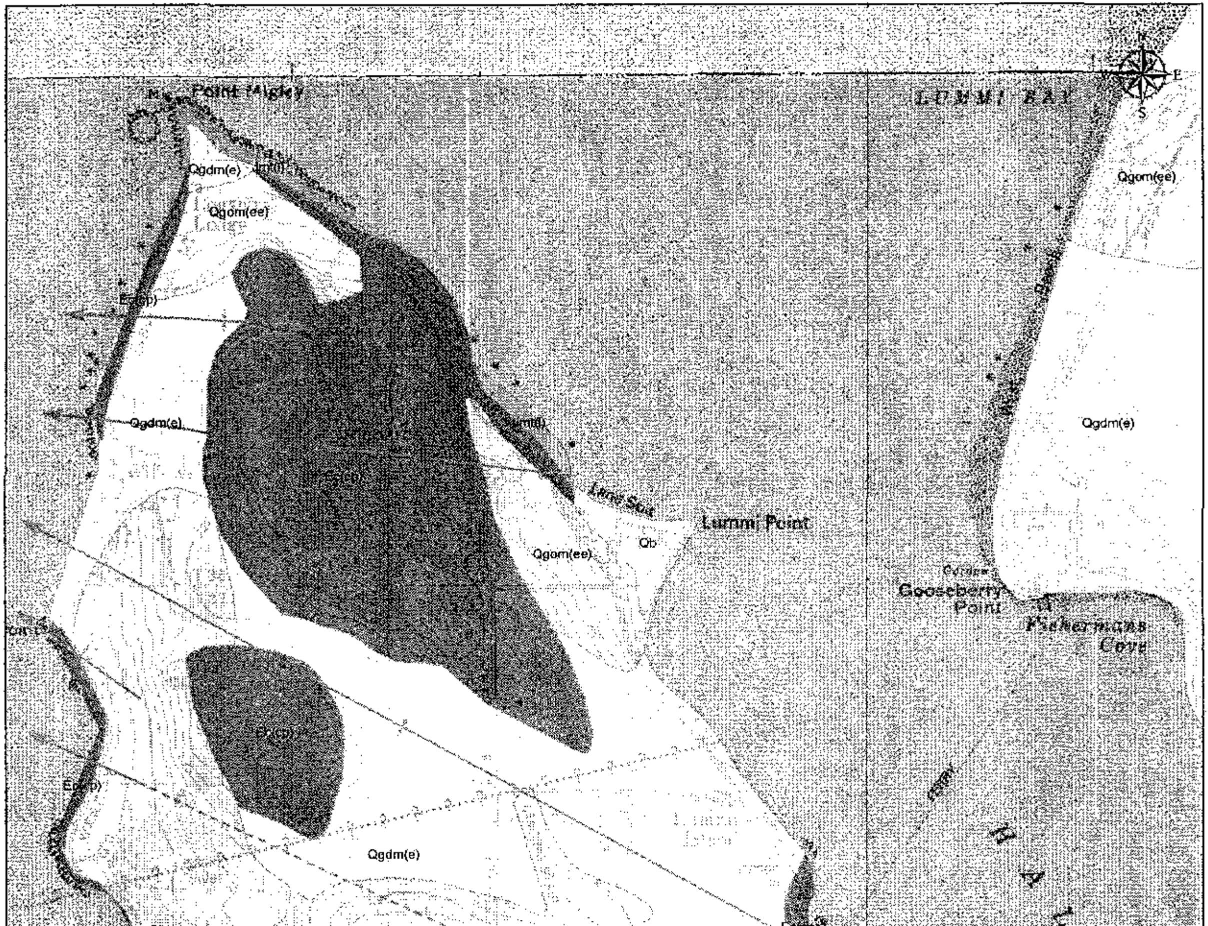
Source: USGS 1:24000 quadrangle map, Lummi Island

Aspect Consulting

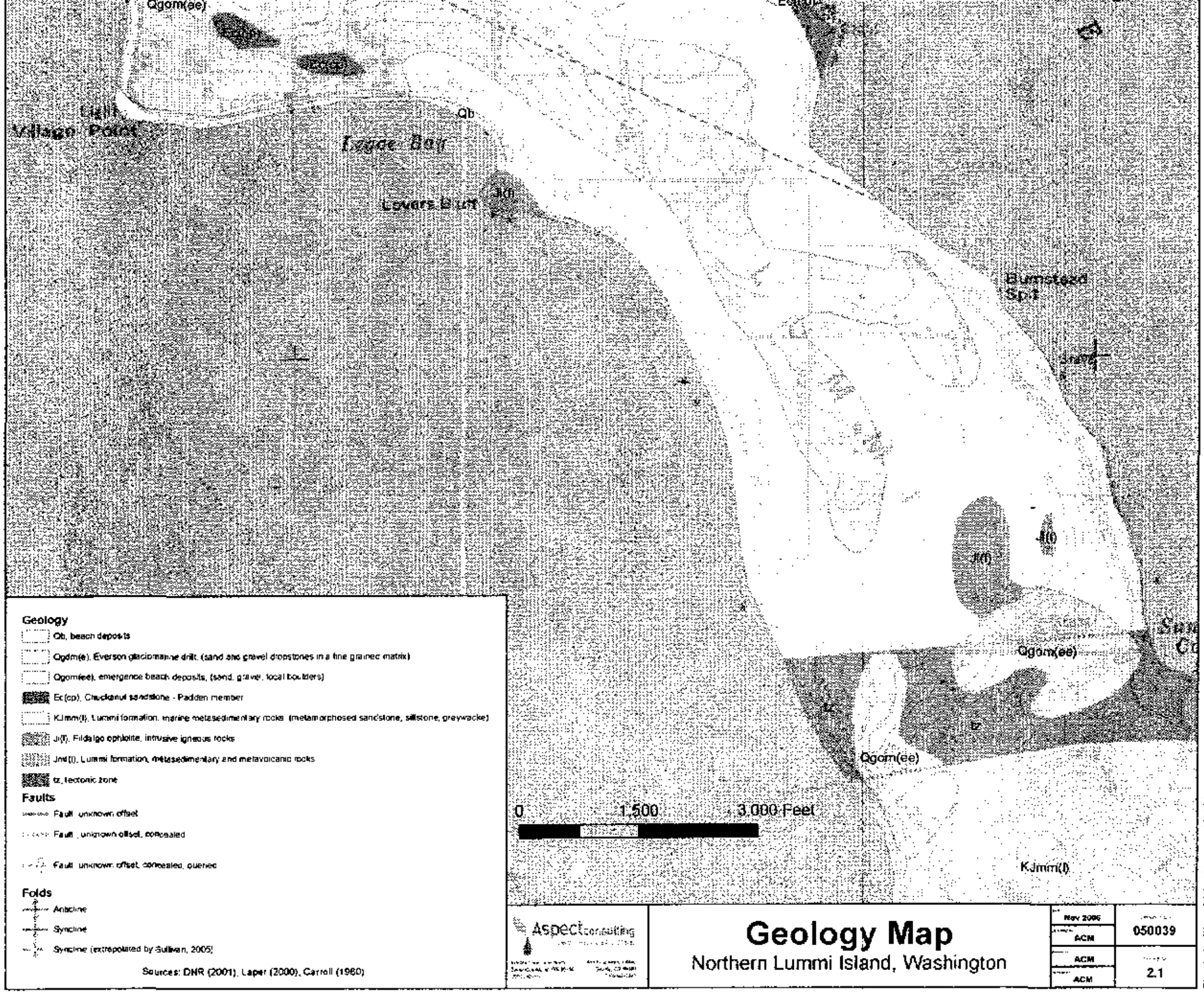
Project Location Map

Northern Lummi Island, Washington

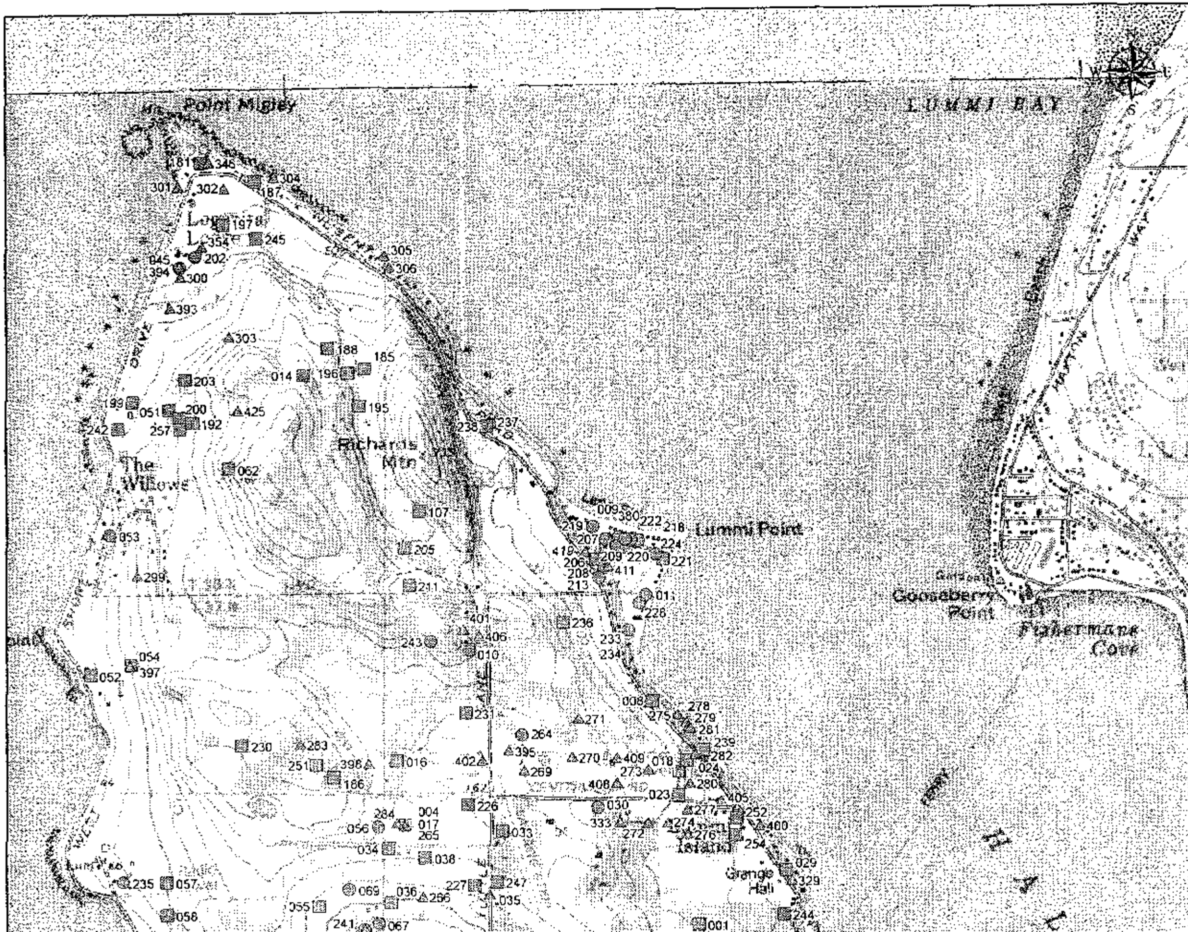
Nov 2006	050039
ACM	
ACM	1.1
ACM	

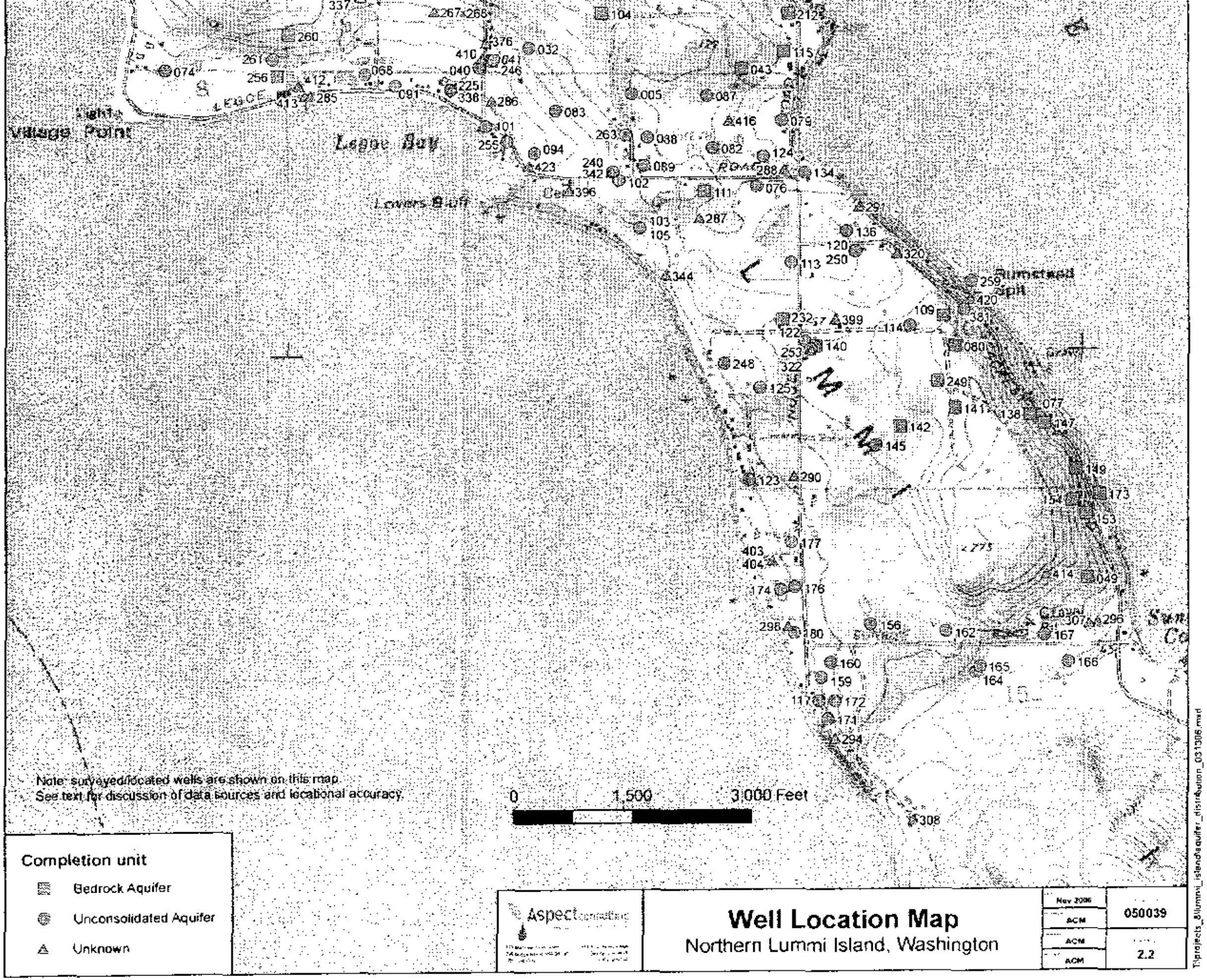


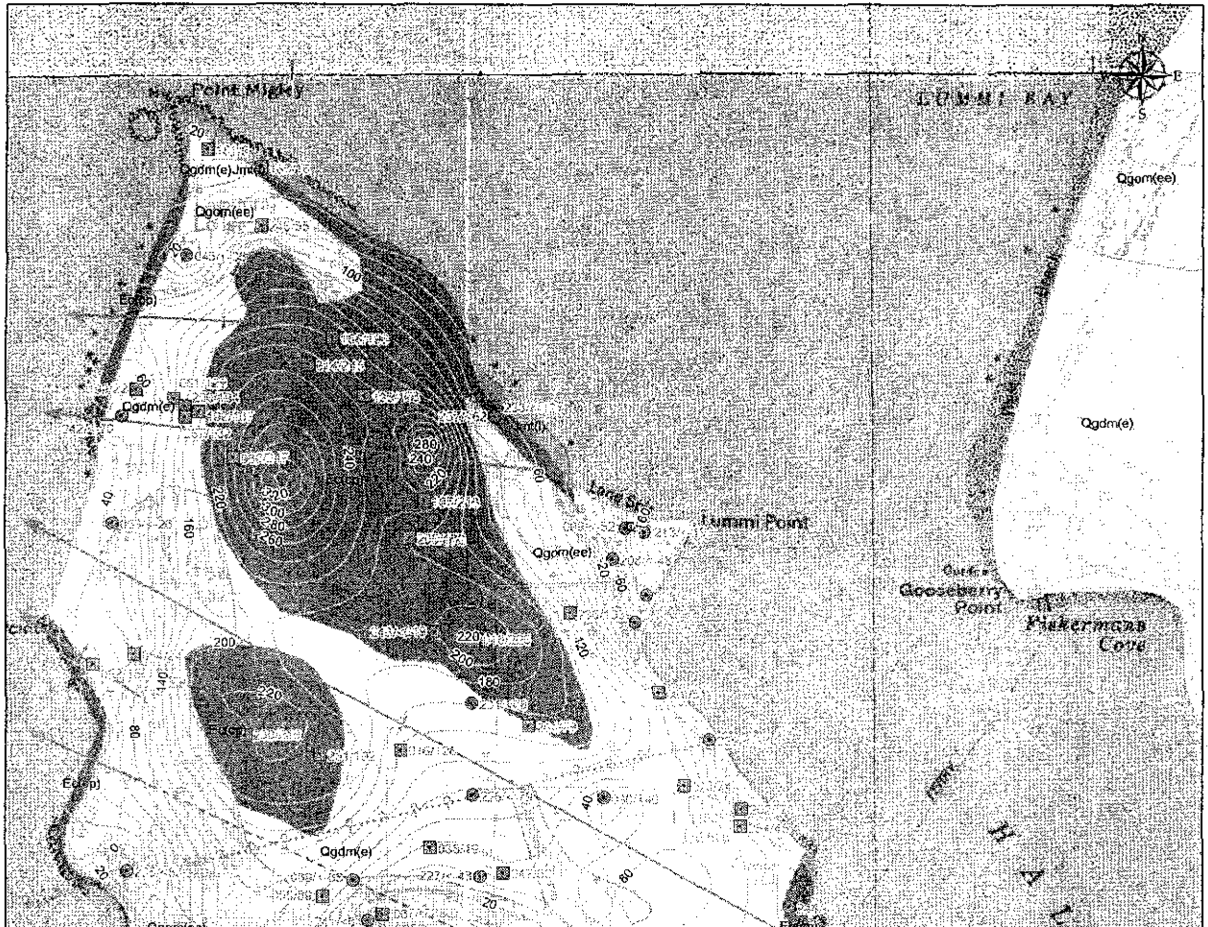
Point Migley
LUMMI BAY
Qgdm(e)
Qgom(ee)
Ec(p)
Lane Spit
Lummi Point
Qb
Gooseberry Point
Fishermans Cove

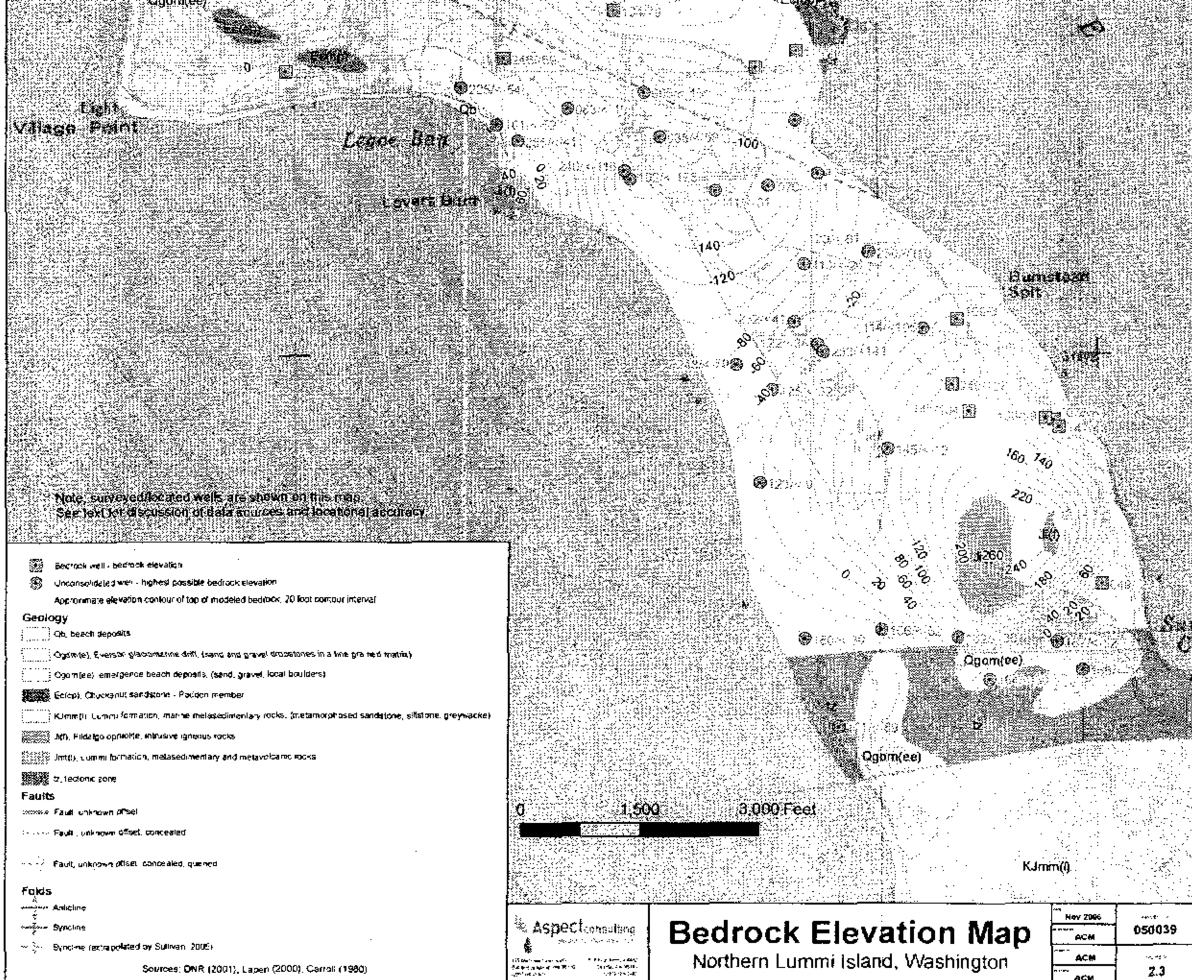

Qgom(ee)
Village Point
Legoe Bay
Qb
Lovers Bluff
Ji(f)
Bumstead Spit
Ji(f)
Ji(f)
Qgom(ee)
tz
tz
Qgom(ee)
KJmm(l)
0 1,500 3,000 Feet
Geology
Qb, beach deposits
Qgdm(e), Everson glaciomarine drift, (sand and gravel dropstones in a fine grained matrix)
Qgom(ee), emergence beach deposits, (sand, gravel, local boulders)
Ec(cp), Chuckanut sandstone - Padden member
KJmm(l), Lummi formation, marine metasedimentary rocks (metamorphosed sandstone, siltstone, greywacke)
Ji(f), Fidalgo ophiolite, intrusive igneous rocks
Jm(l), Lummi formation, metasedimentary and metavolcanic rocks
tz, tectonic zone
Faults
Fault, unknown offset
Fault, unknown offset, concealed
Fault, unknown offset, concealed, queried
Folds
Anticline
Syncline
Syncline (extrapolated by Sullivan, 2005)
Sources: DNR (2001), Laper (2000), Carroll (1980)
Aspect consulting
Geology Map
Northern Lummi Island, Washington
Nov 2006
ACM
ACM
ACM
050039
2.1

0249


Point Migley
LUMMI BAY
Richards Mtn
The Willows
Lummi Point
Gooseberry Point
Fishermans Cove
Grange Hall

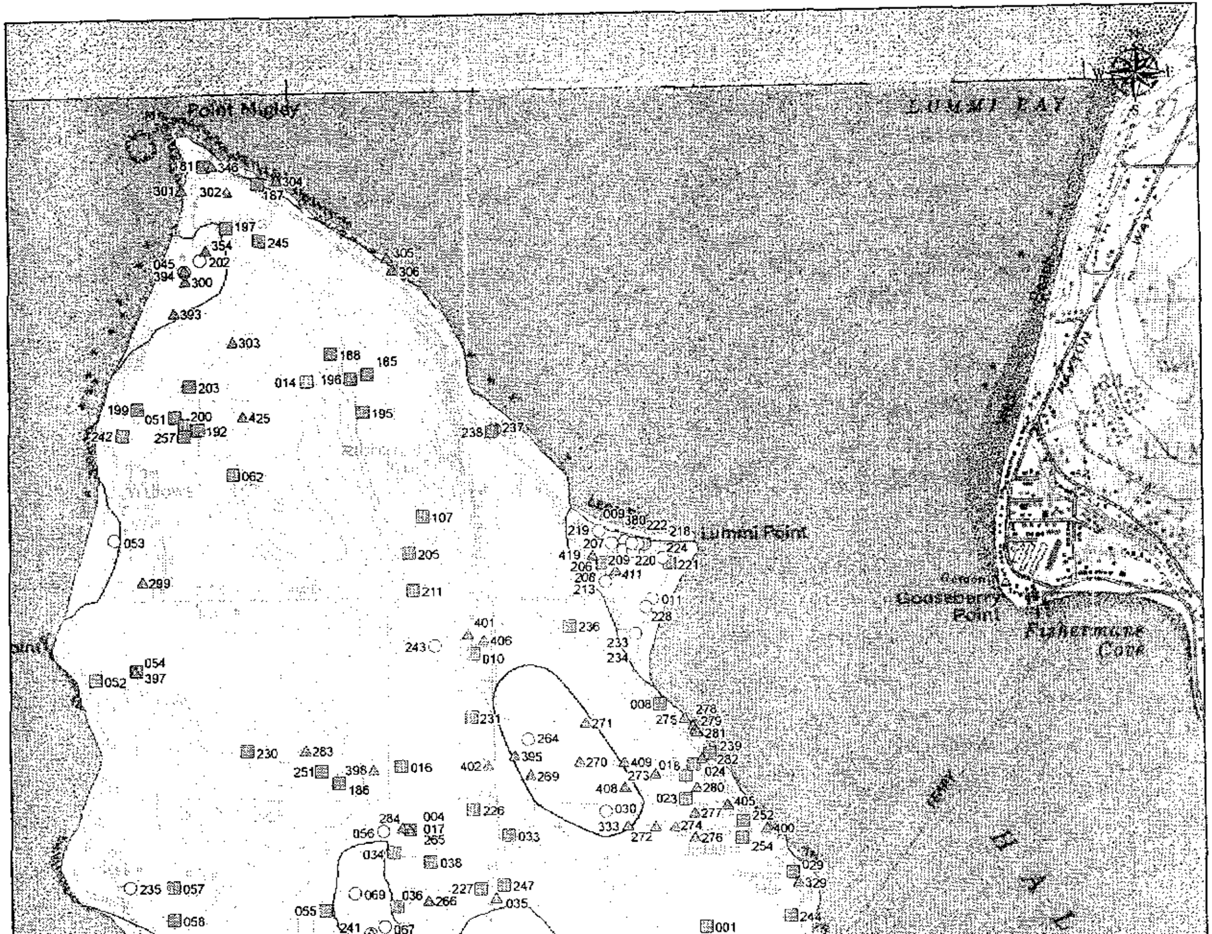

Village Point
Legoe Bay
Lovers Bluff
Rumstead Spit
Note: surveyed/located wells are shown on this map.
See text for discussion of data sources and locational accuracy.
0 1,500 3,000 Feet
Completion unit
Bedrock Aquifer
Unconsolidated Aquifer
Unknown
Aspect
Well Location Map
Northern Lummi Island, Washington
Nov 2006
ACM
050039
2.2


Point Migley
LUMMI BAY
Qgom(ee)
Qgdm(e)
Lummi Point
Gooseberry Point
Fishermans Cove
Ec(pp)

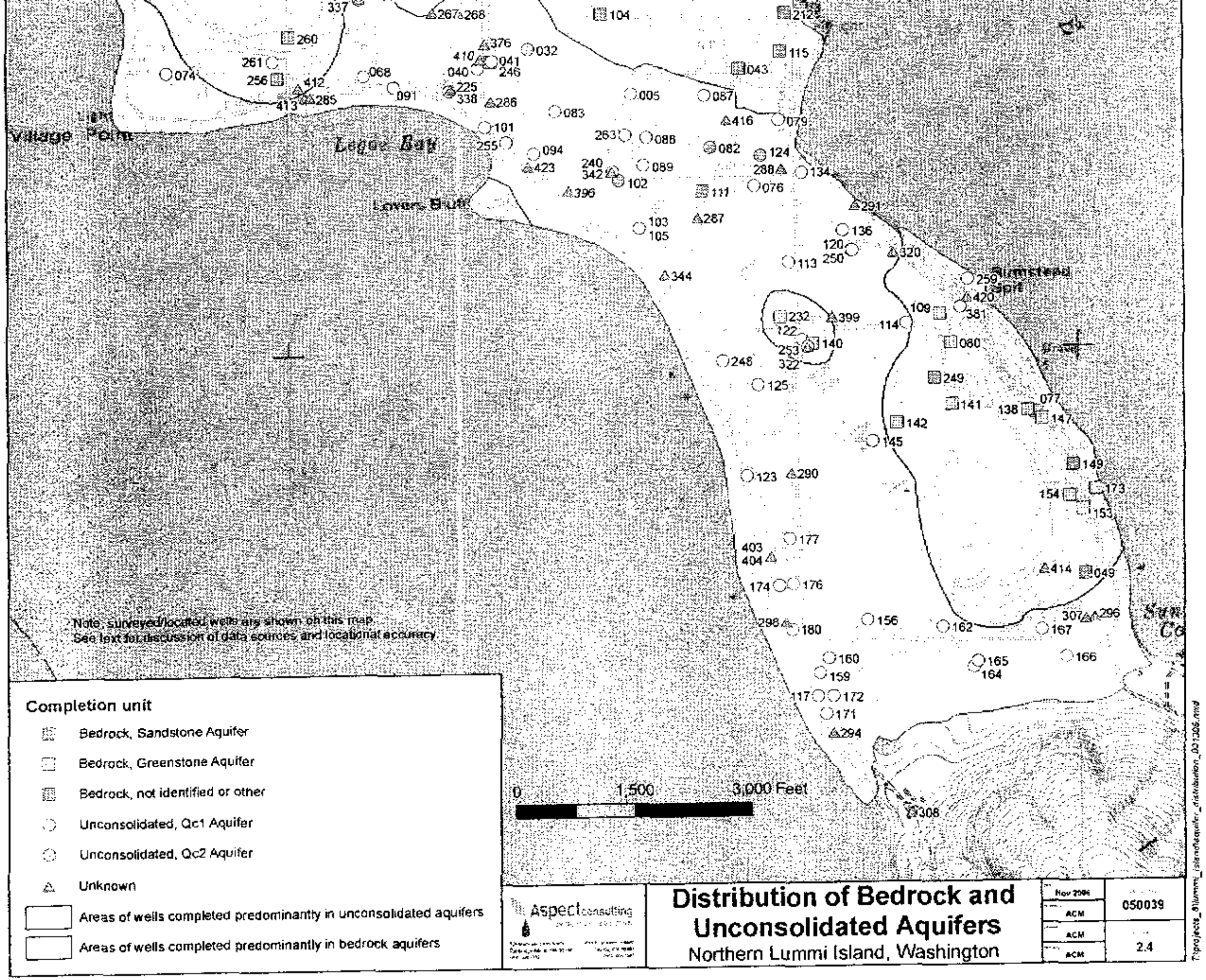


Village Point
Legoe Bay
Lovers Bluff
Burnstead Spit
Qgom(ee)
Qgdm(ee)
KJmm(l)
Note, surveyed/located wells are shown on this map.
See text for discussion of data sources and locational accuracy.
Bedrock well - bedrock elevation
Unconsolidated well - highest possible bedrock elevation
Approximate elevation contour of top of modeled bedrock, 20 foot contour interval
Geology
Qb, beach deposits
Qgdm(e), Everson glaciomarine drift, (sand and gravel dropstones in a fine grained matrix)
Qgom(ee), emergence beach deposits, (sand, gravel, local boulders)
Ec(cp), Chuckanut sandstone - Padden member
KJmm(l), Lummi formation, marine metasedimentary rocks, (metamorphosed sandstone, siltstone, greywacke)
Jt(f), Fidalgo ophiolite, intrusive igneous rocks
Jmt(l), Lummi formation, metasedimentary and metavolcanic rocks
tz, tectonic zone
Faults
Fault, unknown offset
Fault, unknown offset, concealed
Fault, unknown offset, concealed, queried
Folds
Anticline
Syncline
Syncline (extrapolated by Sullivan, 2005)
Sources: DNR (2001), Lapen (2000), Carroll (1980)
0 1,500 3,000 Feet
Aspect consulting
Bedrock Elevation Map
Northern Lummi Island, Washington
Nov 2006
ACM
ACM
ACM
050039
2.3

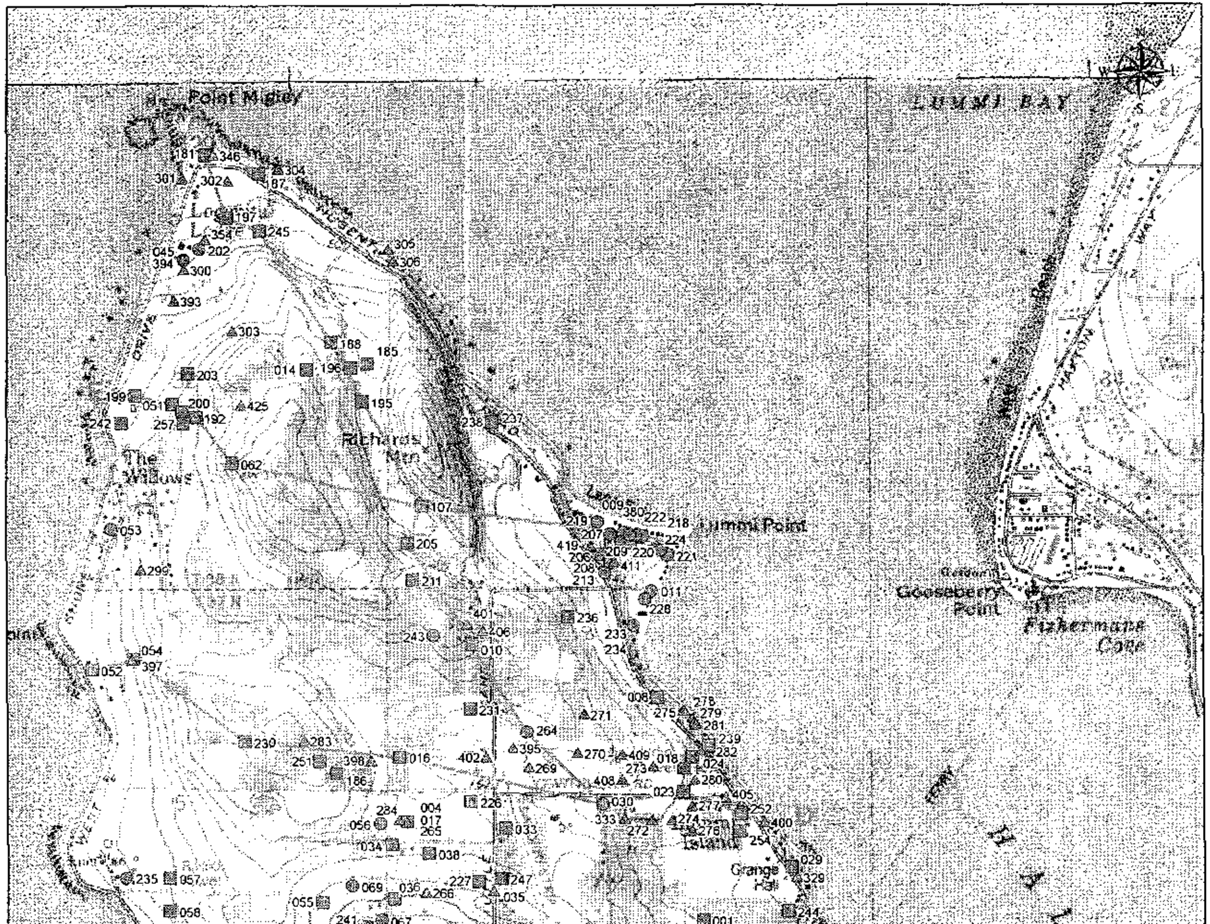
0251

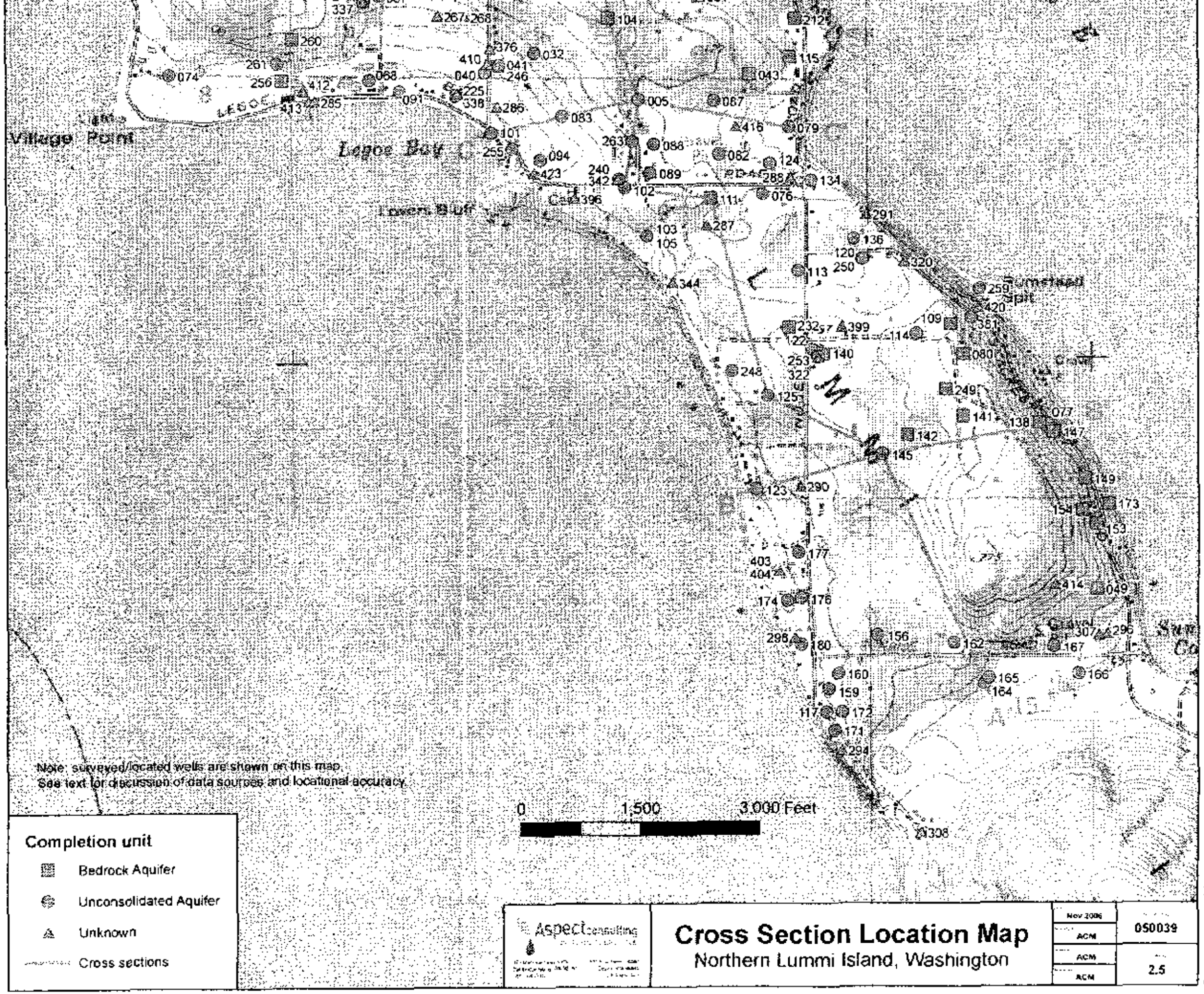


Point Migley
LUMMI BAY
Lummi Point
Gooseberry Point
Fishermans Cove

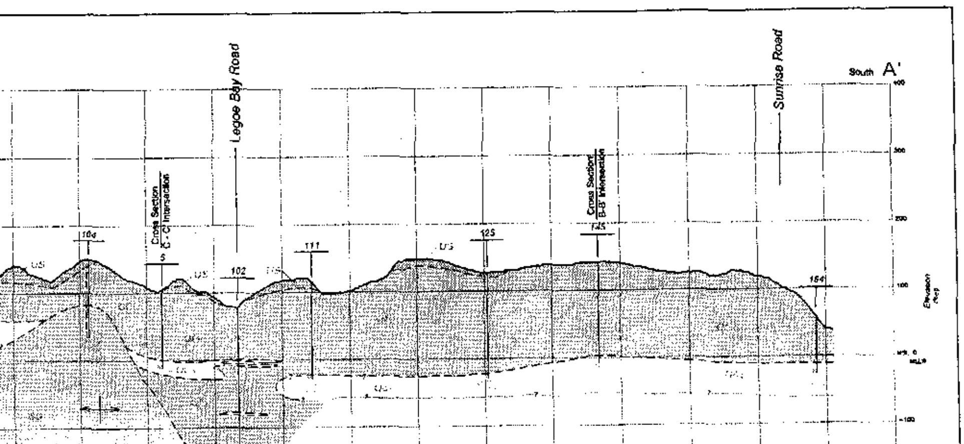

Village Point
Legoe Bay
Lovers Bluff
Migley Spit
Note: surveyed/located wells are shown on this map.
See text for discussion of data sources and locational accuracy.
Completion unit
Bedrock, Sandstone Aquifer
Bedrock, Greenstone Aquifer
Bedrock, not identified or other
Unconsolidated, Qc1 Aquifer
Unconsolidated, Qc2 Aquifer
Unknown
Areas of wells completed predominantly in unconsolidated aquifers
Areas of wells completed predominantly in bedrock aquifers
0
1,500
3,000 Feet
Aspect consulting
Distribution of Bedrock and Unconsolidated Aquifers
Northern Lummi Island, Washington
Nov 2006
ACM
ACM
ACM
050039
2.4

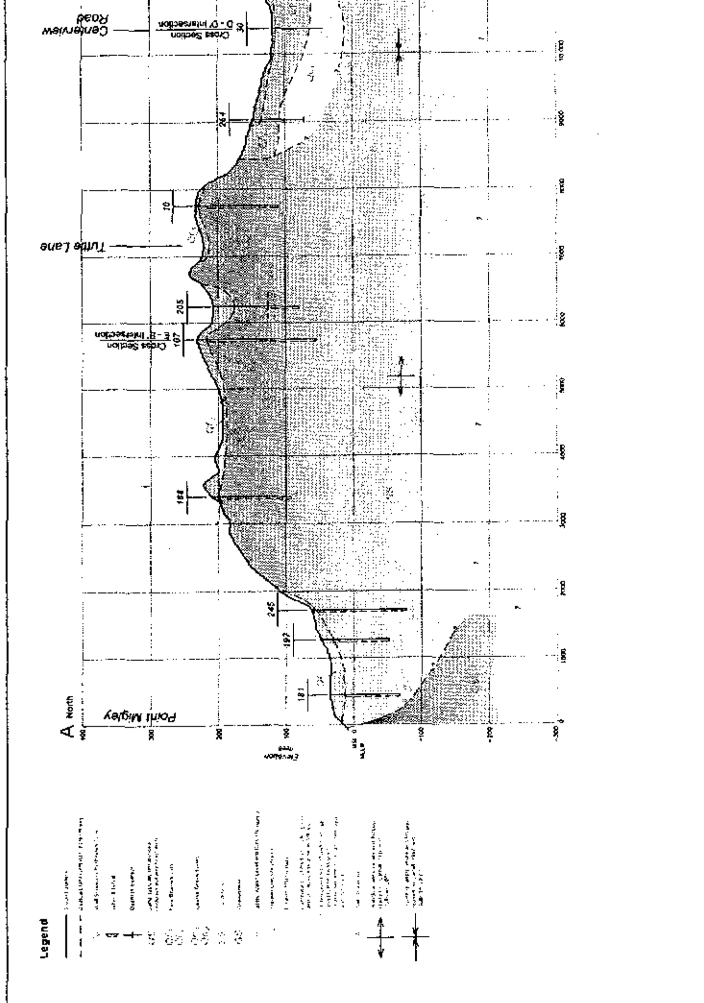
0252


Point Migley
LUMMI BAY
Richards Mtn
The Willows
Lummi Point
Gooseberry Point
Fishermans Cove
Grange Hall

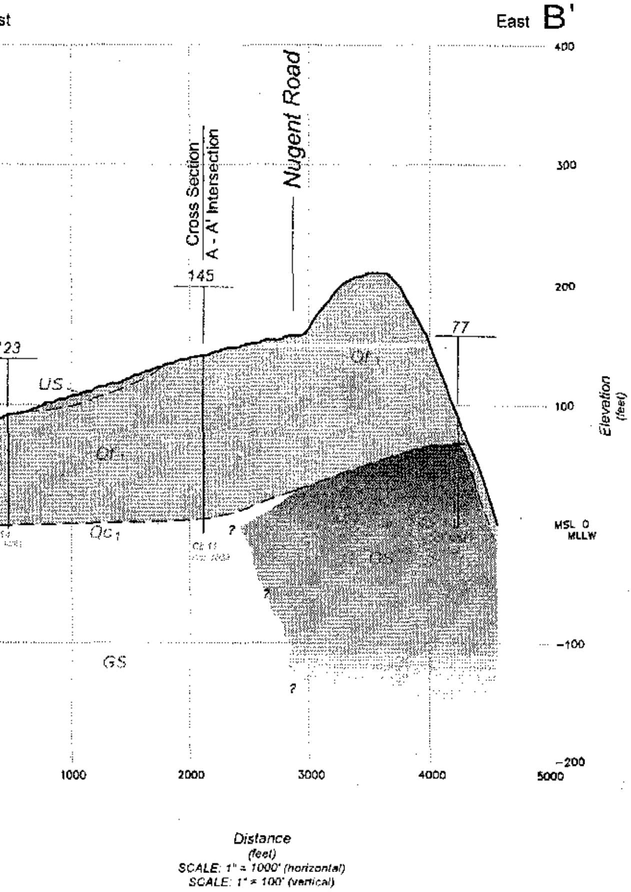

Village Point
Legoe Bay
Lovers Bluff
Note: surveyed/located wells are shown on this map.
See text for discussion of data sources and locational accuracy.
0
1,500
3,000 Feet
Completion unit
Bedrock Aquifer
Unconsolidated Aquifer
Unknown
Cross sections
Aspect consulting
Cross Section Location Map
Northern Lummi Island, Washington
Nov 2006
ACM
ACM
ACM
050039
2.5

0253


South A'
Sunrise Road
Legoe Bay Road
Cross Section B-B' Intersection
Cross Section C - C' Intersection
104
5
102
111
125
145
154
Elevation (feet)
Distance (feet)
11,000
12,000
13,000
14,000
15,000
16,000
17,000
18,000
19,000
20,000
21,000
22,000
23,000
24,000
Aspect Consulting
Cross Section A-A'
Northern Lummi Island Hydrogeologic Investigation
Northern Lummi Island, Washington
PROJECT NO.
050038
FIGURE NO.
2.6


A North
Point Migley
181
197
245
184
Cross Section E - E' Intersection
107
205
Turtle Lane
10
264
Cross Section D - D' Intersection
30
Centerview Road
Elevation (feet)
MLLW
Legend

0254



Aspect consulting
IN-DEPTH PERSPECTIVE

Cross Section B-B'

Northern Lummi Island Hydrogeologic Investigation
Northern Lummi Island, Washington

Nov 2006	PROJECT NO. 050039
JWC	
PMB	FIGURE NO. 2.7

Q:\Lummi\050039 Lummi\2006-11\050039-BB.dwg

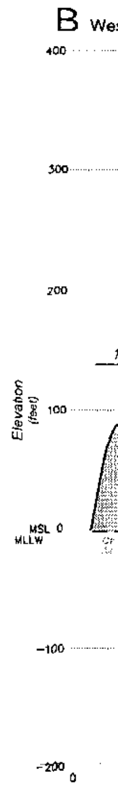
Legend

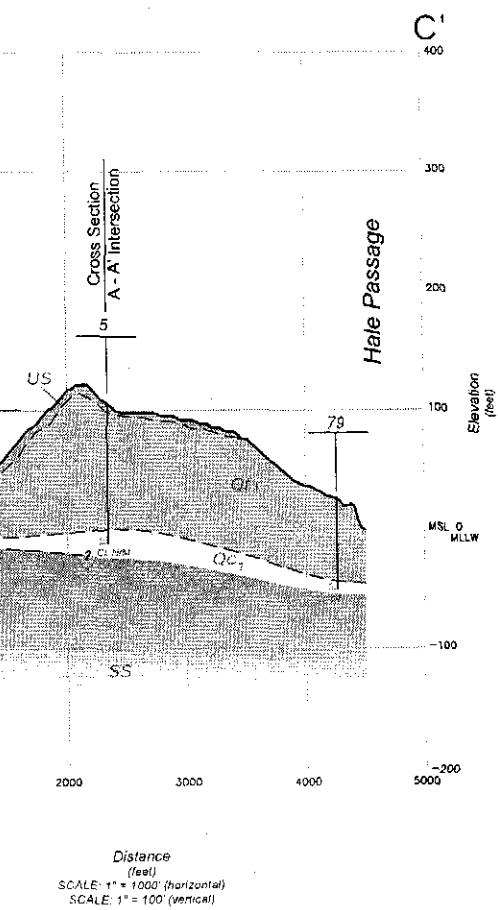
- Ground Surface
- Geologic Unit Contact (Approximate)
- Well Screen or Perforated Zone
- Open Interval
- Depth to Bedrock
- US — Sand, typically unsaturated (includes soil and forest duff)
- Qf_1 Qf_2 — Fine Grained units
- Qc_1 Qc_2 — Coarse Grained units
- SS — Sandstone
- GS — Greenstone
- Static Water Level and Date Measured
- Median Chloride (mg/L)
- Median Arsenic (ug/L)

Computation of median involving non detect values was done as follows:

1.) if detection limit < 10 ug/l, then half detection limit was used.
2.) if detection limit > 10 ug/l, then value was not used.

- N/M — Not Measured
- Anticline, approximate axis location (based on Carroll, 1980 and Sullivan, 2005)
- Syncline, approximate axis location (based on Carroll, 1980 and Sullivan, 2005)





Aspect consulting

Cross Section C-C'

Northern Lummi Island Hydrogeologic Investigation

Northern Lummi Island, Washington

Nov 2006

JWC

PMB

PROJECT NO. 050039

FIGURE NO. 2.8

Q:\Lummi\050039 Lummi2006-11\050039-CC.dwg

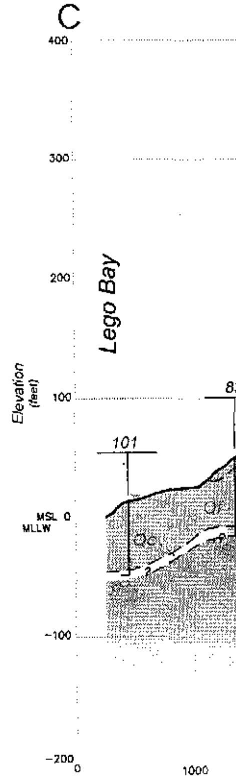
Legend

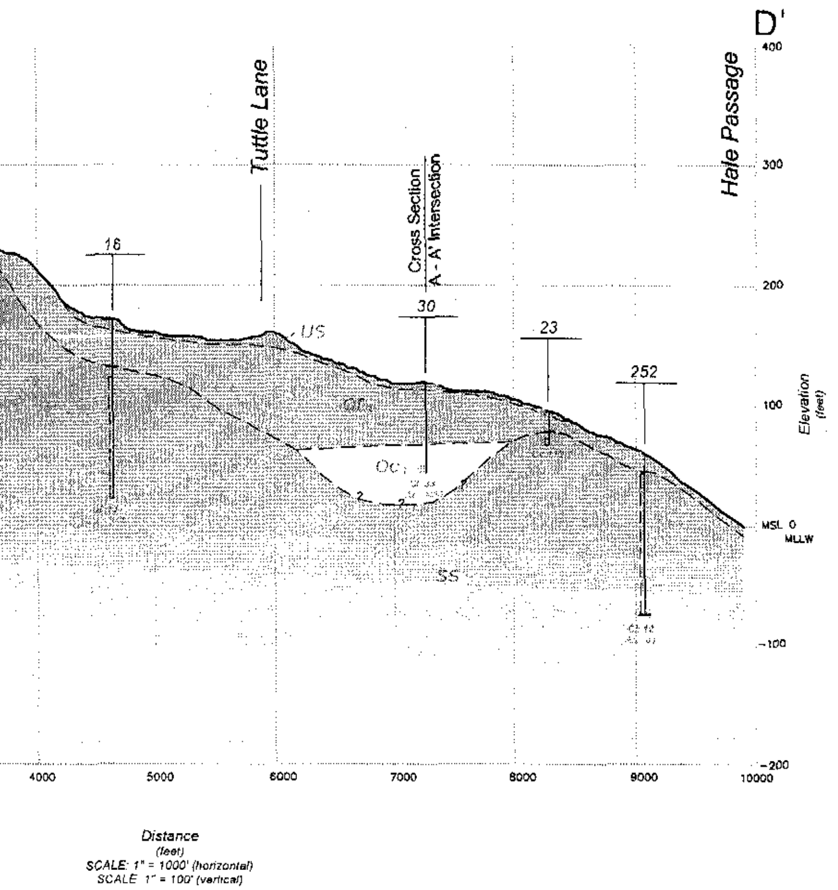
- Ground Surface
- Geologic Unit Contact (Approximate)
- Well Screen or Perforated Zone
- Open Interval
- Depth to Bedrock
- US — Sand, typically unsaturated (includes soil and forest duff)
- QF_1, QF_2 — Fine Grained units
- QC_1, QC_2 — Coarse Grained units
- SS — Sandstone
- GS — Greenstone
- Static Water Level and Date Measured
- Median Chloride (mg/L)
- Median Arsenic (ug/L)

Computation of median involving non detect values was done as follows:

1.) if detection limit ≤ 10 ug/l, then half detection limit was used.
2.) if detection limit > 10 ug/l, then value was not used.

- N/M — Not Measured
- Anticline, approximate axis location (based on Carroll, 1980 and Sullivan, 2005)
- Syncline, approximate axis location (based on Carroll, 1980 and Sullivan, 2005)





Aspect consulting
IN-DEPTH PERSPECTIVE

Cross Section D-D'

Northern Lummi Island Hydrogeologic Investigation
Northern Lummi Island, Washington

Nov 2006
AWC
PMB

PROJECT NO. 050039
FIGURE NO. 2.9

Q:\Lummi\050039 Lummi\2006-1\1050039-DD.dwg

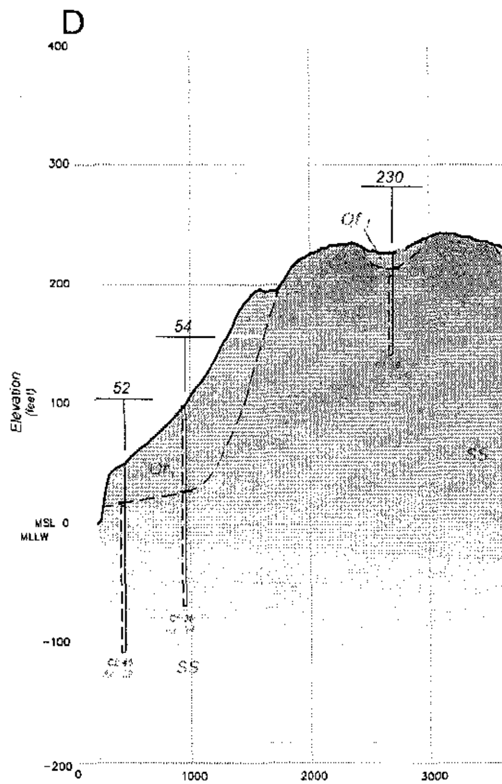
Legend

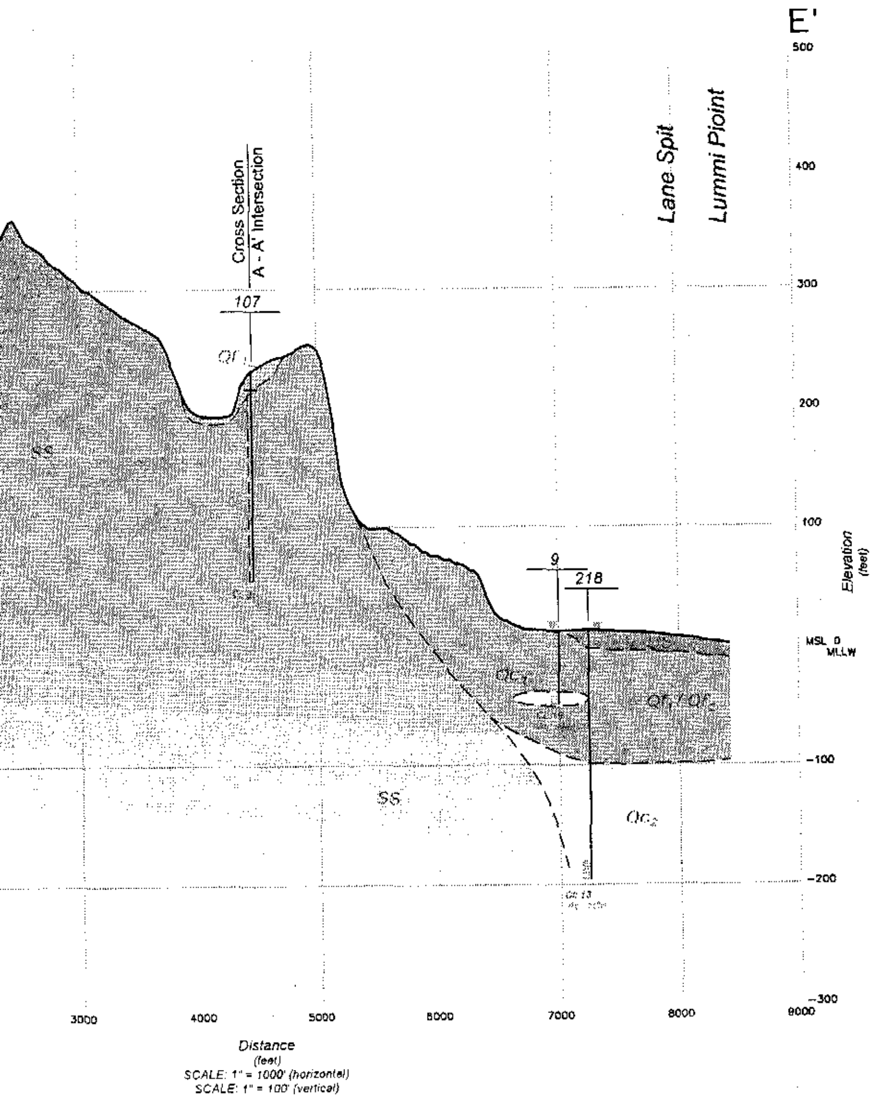
- Ground Surface
- Geologic Unit Contact (Approximate)
- Well Screen or Perforated Zone
- Open Interval
- Depth to Bedrock
- US — Sand, typically unsaturated (includes soil and forest duff)
- Qf_1, Qf_2 — Fine Grained units
- Qc_1, Qc_2 — Coarse Grained units
- SS — Sandstone
- GS — Greenstone
- Static Water Level and Date Measured
- Median Chloride (mg/L)
- Median Arsenic (ug/L)

Computation of median involving non detect values was done as follows:

1.) If detection limit < 10 ug/l, then half detection limit was used.
2.) If detection limit > 10 ug/l, then value was not used.

- NM — Not Measured
- Anticline, approximate axis location (based on Carroll, 1980 and Sullivan, 2005)
- Syncline, approximate axis location (based on Carroll, 1980 and Sullivan, 2005)





Aspect consulting
IN-DEPTH PERSPECTIVE

Cross Section E-E'

Northern Lummi Island Hydrogeologic Investigation
Northern Lummi Island, Washington

Nov 2006	PROJECT NO. 050039
JWC	
PMB	FIGURE NO. 2.10

Q:\Lummi\050039 Lummi\2006-11\050039-EE.dwg

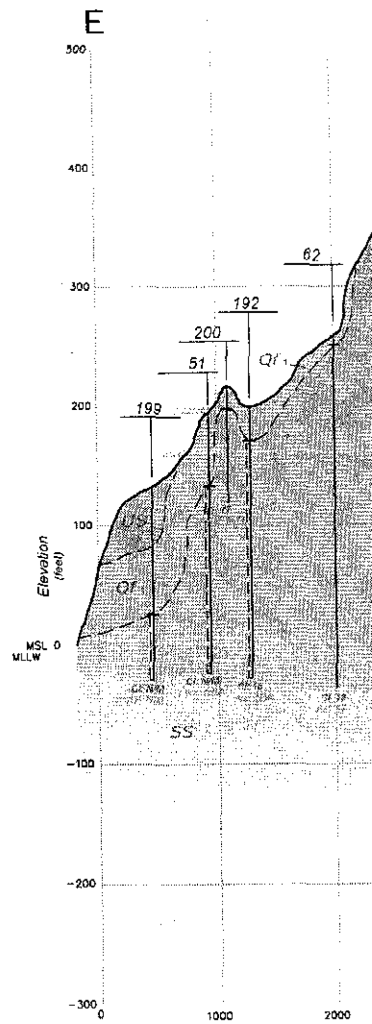
Legend

- Ground Surface
- Geologic Unit Contact (Approximate)
- Well Screen or Perforated Zone
- Open Interval
- Depth to Bedrock
- US — Sand, typically unsaturated (includes soil and forest duff)
- Qf_1, Qf_2 — Fine Grained units
- Qc_1, Qc_2 — Coarse Grained units
- SS — Sandstone
- GS — Greenstone
- Static Water Level and Date Measured
- Median Chloride (mg/L)
- Median Arsenic (ug/L)

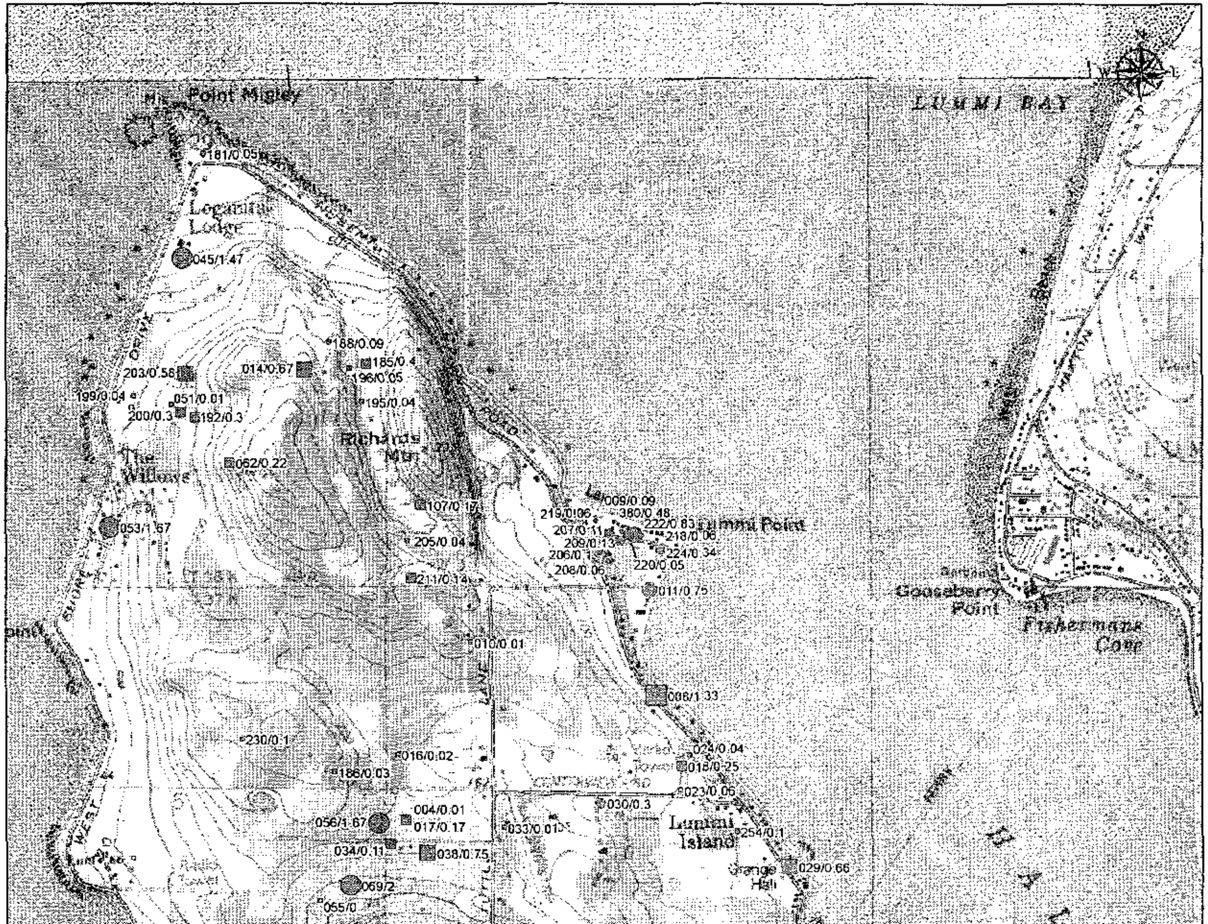
Computation of median involving non detect values was done as follows:

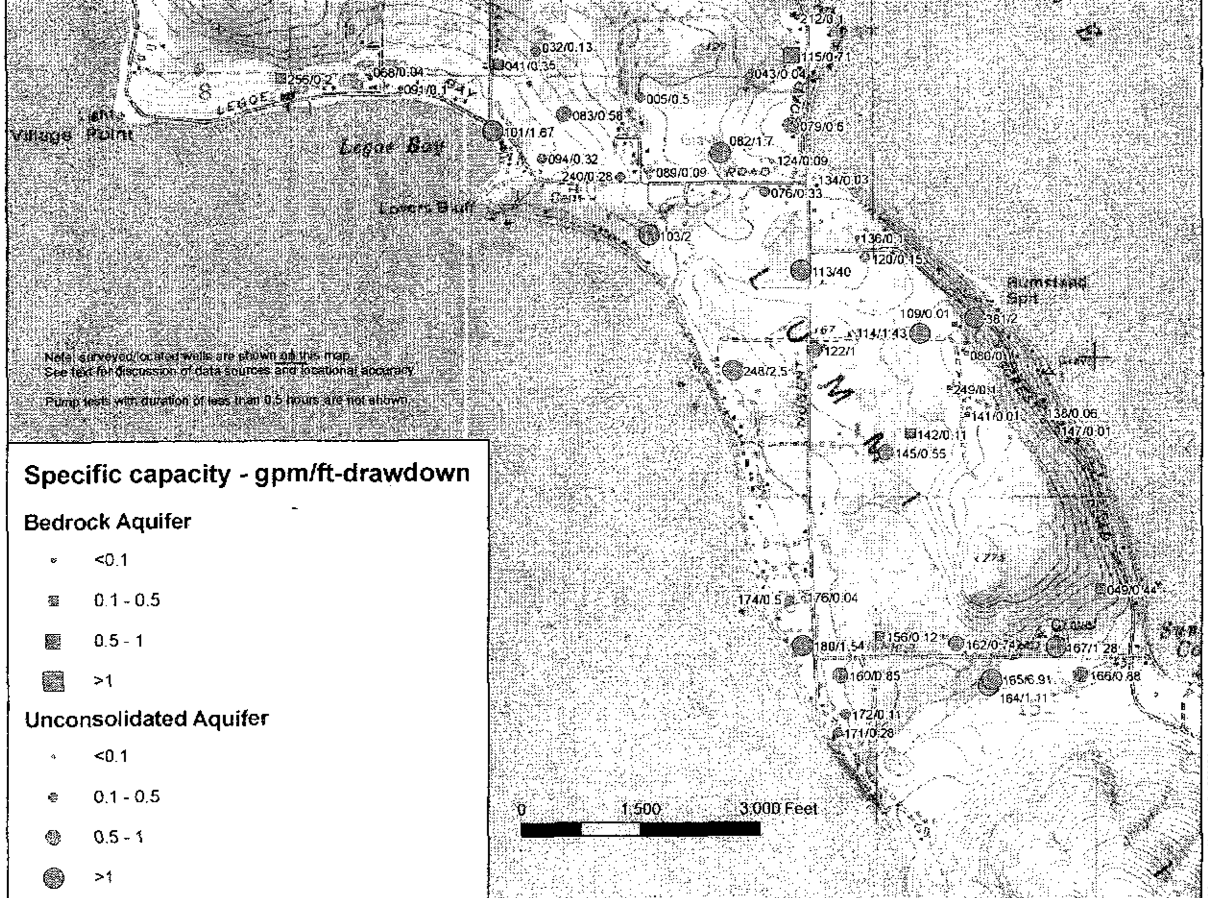
1.) If detection limit < 10 ug/l, then half detection limit was used.
2.) If detection limit > 10 ug/l, then value was not used.

- N/M — Not Measured
- Anticline, approximate axis location (based on Carroll, 1980 and Sullivan, 2005)
- Syncline, approximate axis location (based on Carroll, 1980 and Sullivan, 2005)



0258


Point Migley
LUMMI BAY
181/0.05
Loganita Lodge
045/1.47
188/0.09
185/0.4
196/0.05
203/0.58
014/0.67
199/0.04
051/0.01
195/0.04
200/0.3
192/0.3
Richards Mtn
The Willows
062/0.22
107/0.17
009/0.09
219/0.06
380/0.48
222/0.83
Lummi Point
207/0.11
218/0.06
209/0.13
206/0.1
224/0.34
208/0.06
220/0.05
053/1.67
205/0.04
211/0.14
011/0.75
Gooseberry Point
Fishermans Cove
010/0.01
008/1.33
230/0.1
016/0.02
024/0.04
018/0.25
186/0.03
023/0.06
030/0.3
004/0.01
056/1.67
017/0.17
033/0.01
Lummi Island
254/0.1
034/0.11
038/0.75
Grange Hall
029/0.66
069/2
055/0



Specific capacity - gpm/ft-drawdown

Bedrock Aquifer

- <0.1
- 0.1 - 0.5
- 0.5 - 1
- >1

Unconsolidated Aquifer

- <0.1
- 0.1 - 0.5
- 0.5 - 1
- >1
- Well was pumped/bailed dry during test

Aspect consulting

Specific Capacity of Unconsolidated and Bedrock Wells

Northern Lummi Island, Washington

Nov 2006	050039
ACM	
ACM	3.1
ACM	

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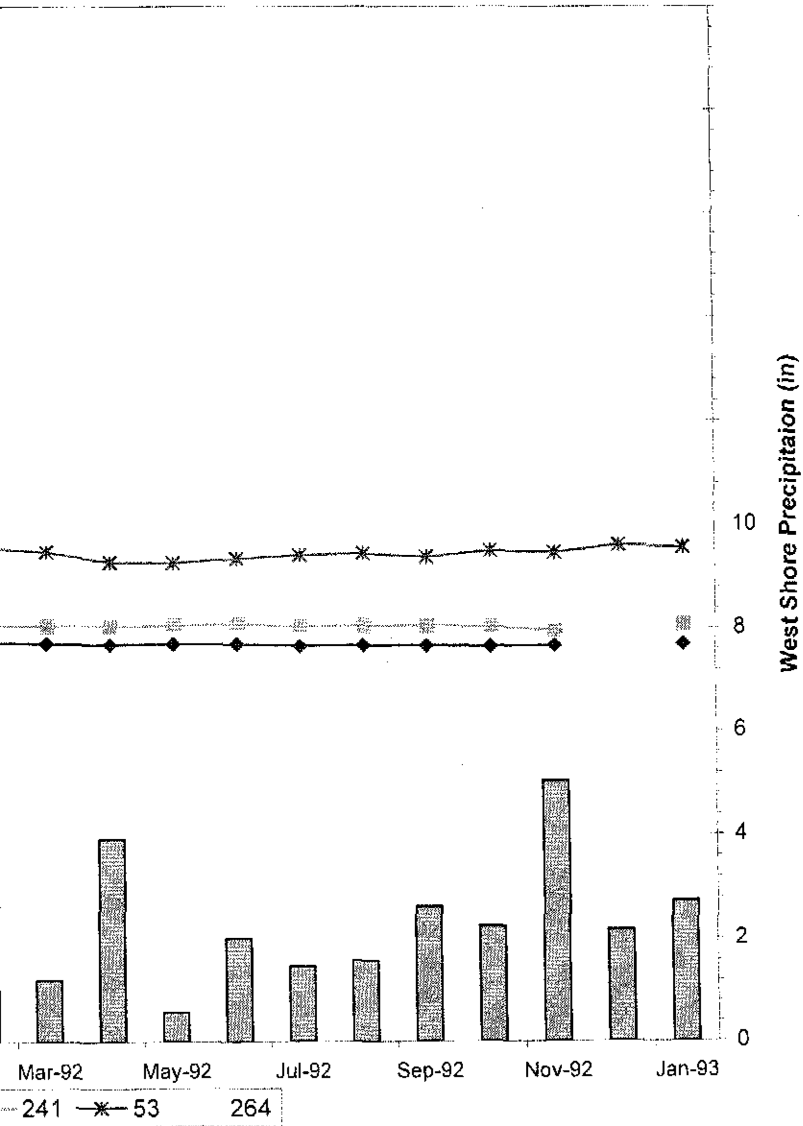
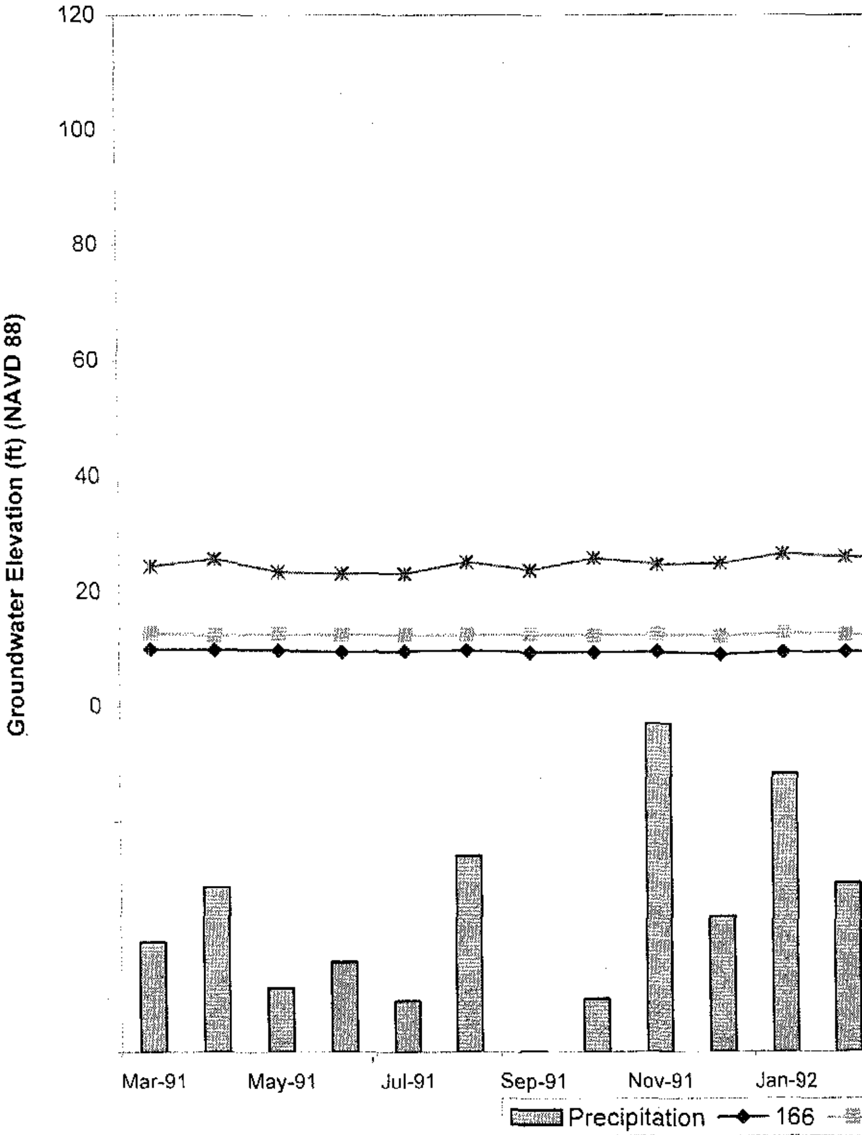
025



ompleted in Unconsolidated Aquifer
rogeologic Investigation
Island, WA

Figure 3.2A



Aspect Consulting
12/31/2006
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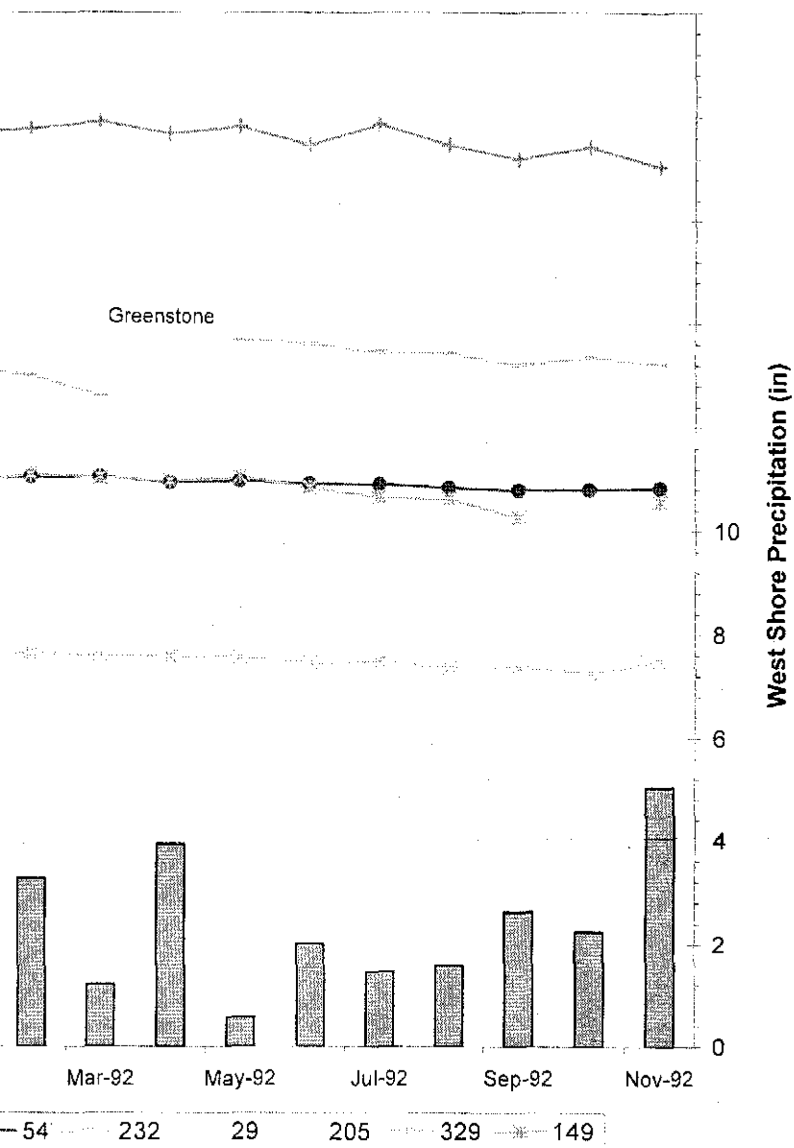
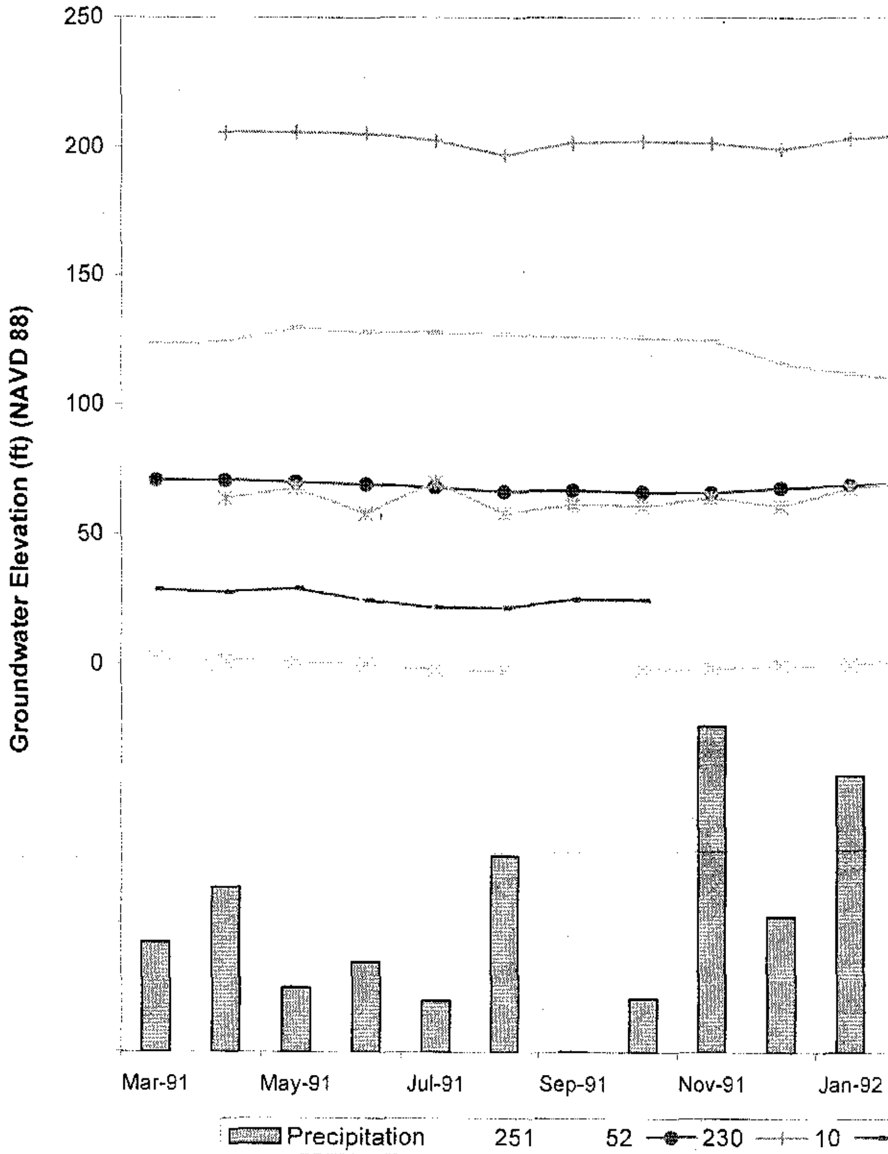
Well Hydrographs for Selected Wells Co
Northern Lummi Island Hyd
Northern Lummi

026



Completed in Bedrock Aquifer
geologic Investigation
sland, WA

Figure 3.2B



Aspect Consulting
12/31/2006
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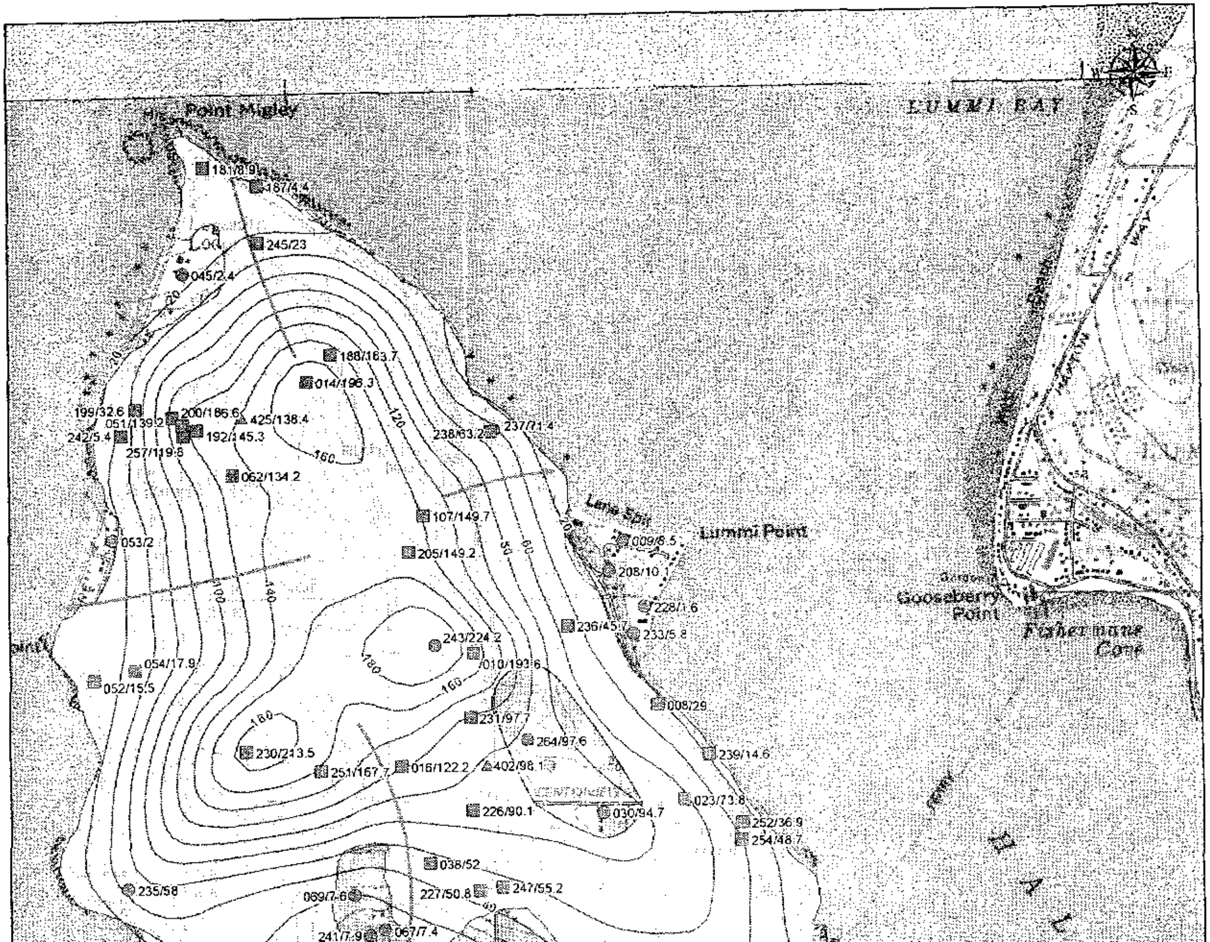
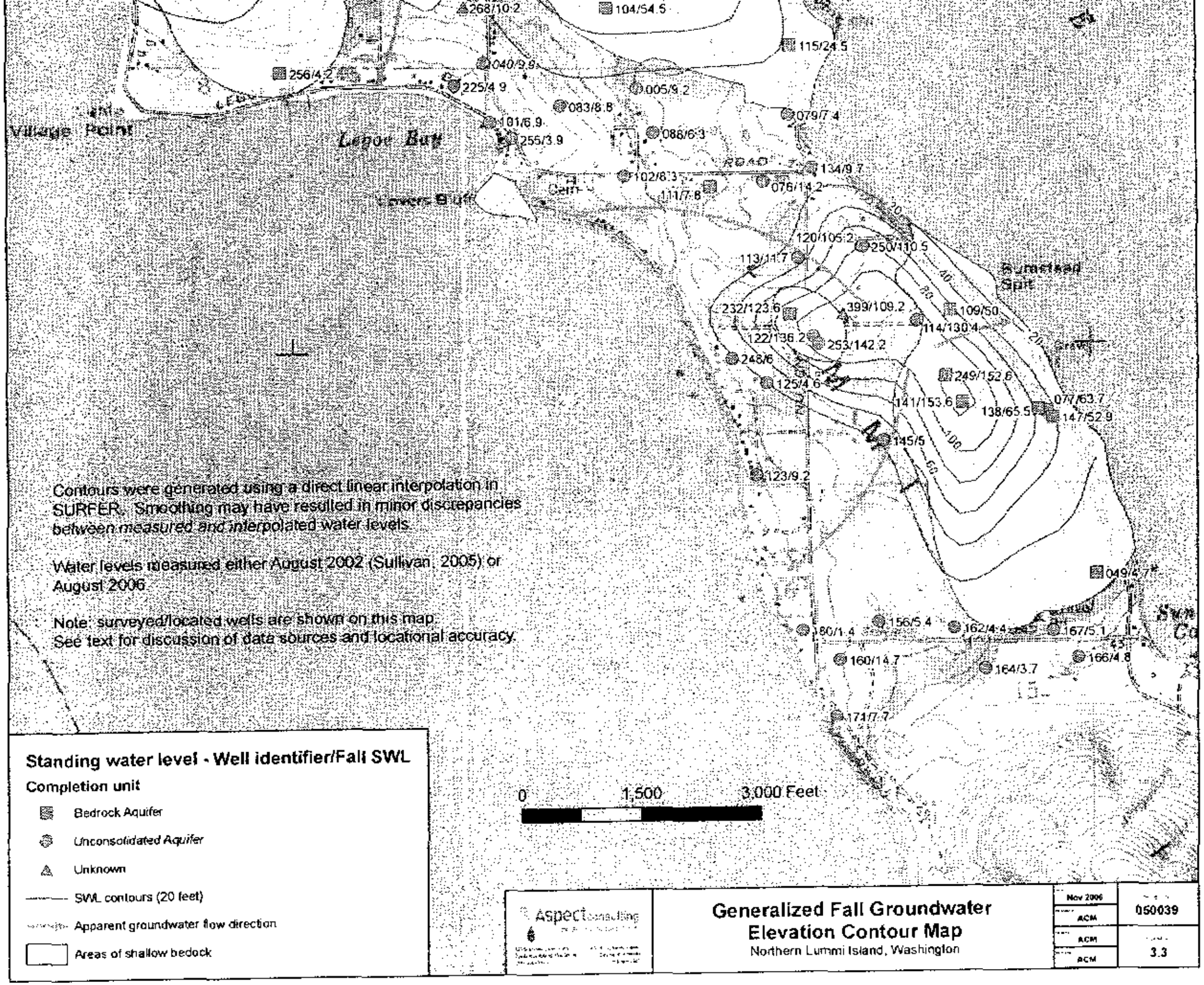
Well Hydrographs for Selected Wells
Northern Lummi Island Hydrog
Northern Lummi Is



Point Migley
LUMMI BAY
181/8.9
187/4.4
245/23
045/2.4
188/163.7
014/196.3
199/32.6
051/139.2
200/186.6
425/138.4
242/5.4
192/145.3
257/119.8
238/63.2
237/71.4
062/134.2
Lane Spit
Lummi Point
107/149.7
053/2
205/149.2
009/8.5
208/10.1
Gooseberry Point
Fishermans Cove
228/1.6
236/45.7
233/5.8
243/224.2
054/17.9
010/193.6
052/15.5
008/29
231/97.7
264/97.6
230/213.5
239/14.6
251/167.7
016/122.2
402/98.1
023/73.8
226/90.1
030/94.7
252/36.9
254/48.7
038/52
235/58
069/7.6
227/50.8
247/55.2
241/7.9
067/7.4



Generalized Fall Groundwater Elevation Contour Map
Northern Lummi Island, Washington

0262

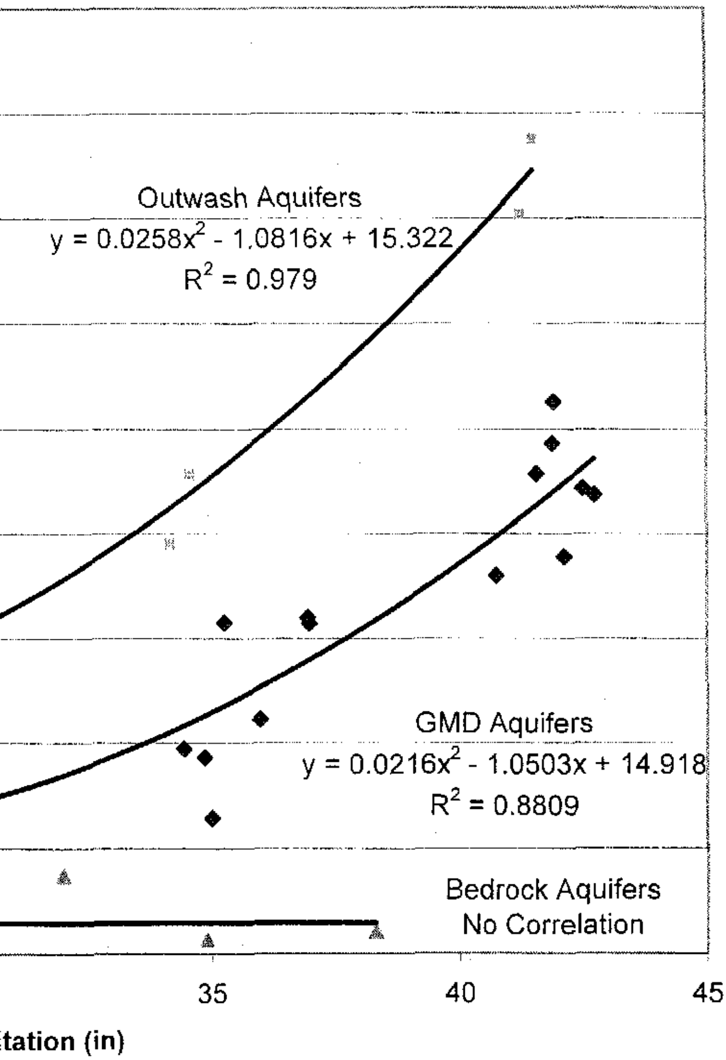
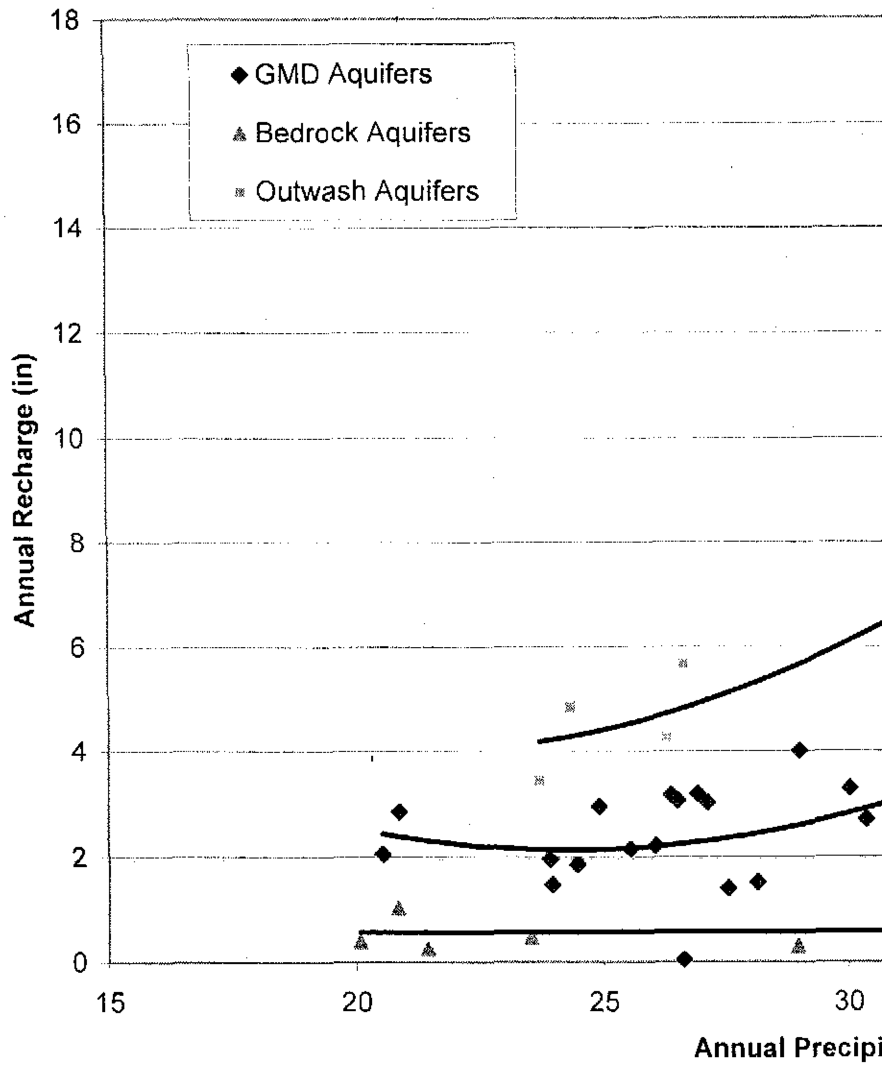


Figure 3.4

Correlation of Annual Precipitation to Recharge from Nearby Studies

Northern Lummi Island Hydrogeologic Investigation

Northern Lummi Island, WA



Aspect Consulting
12/31/2006
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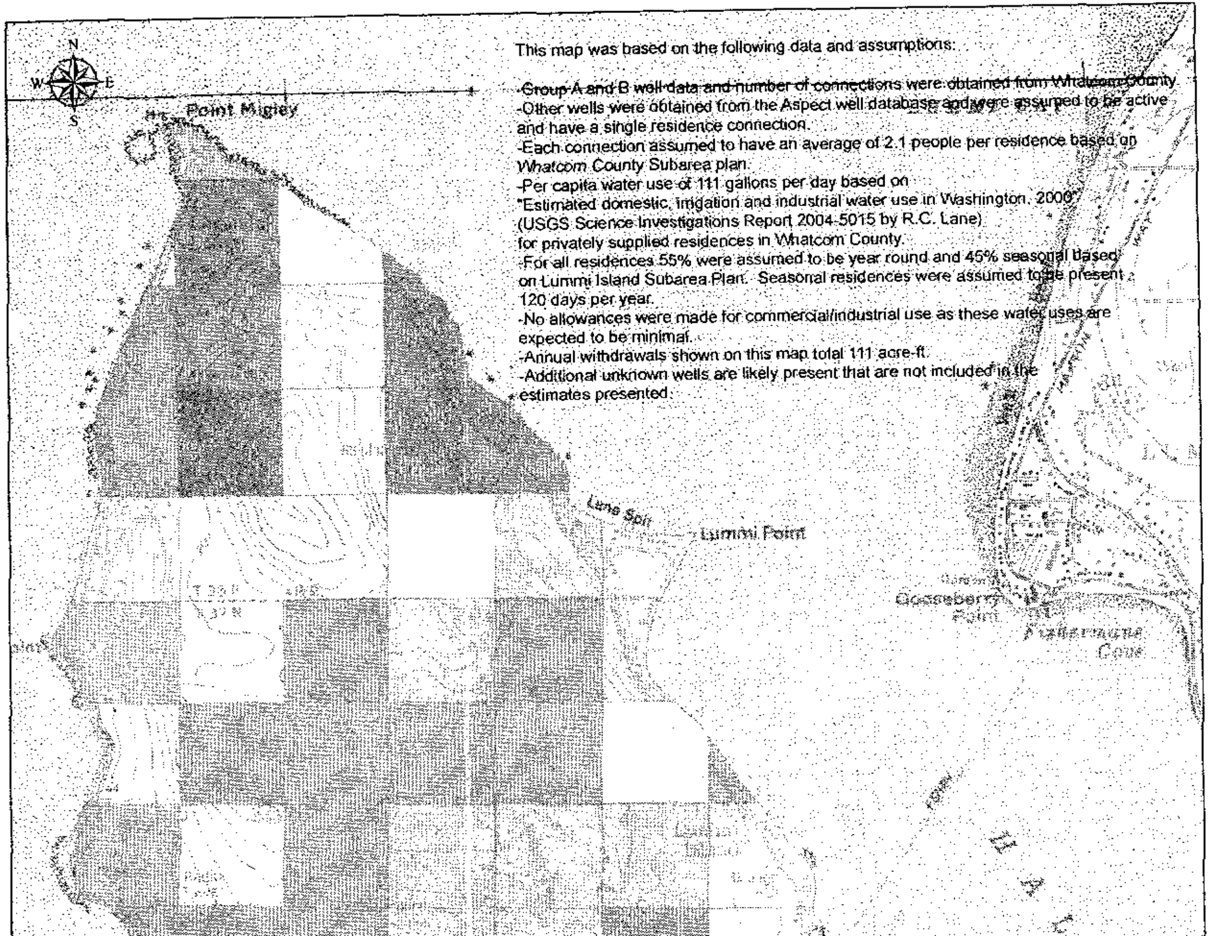
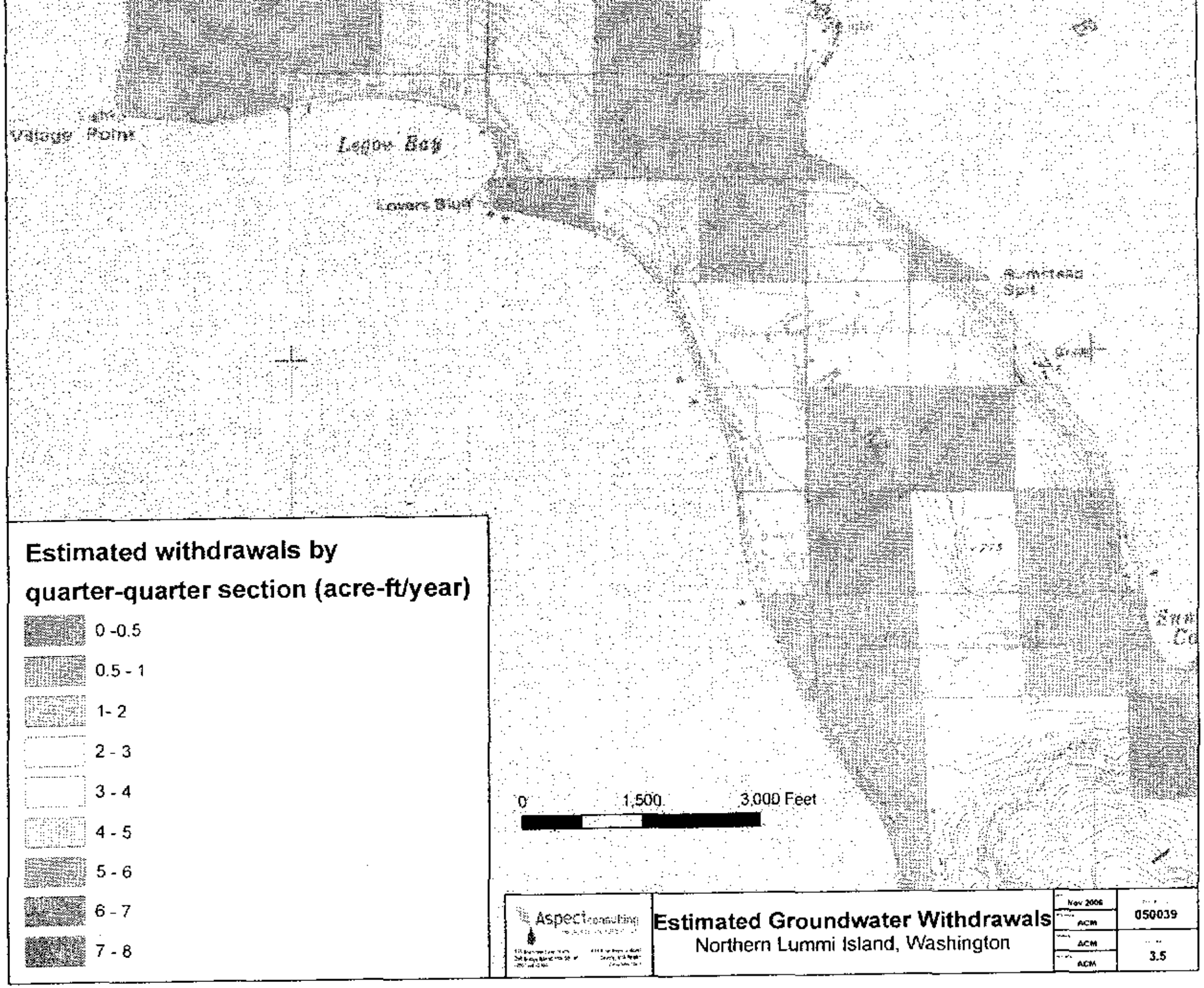
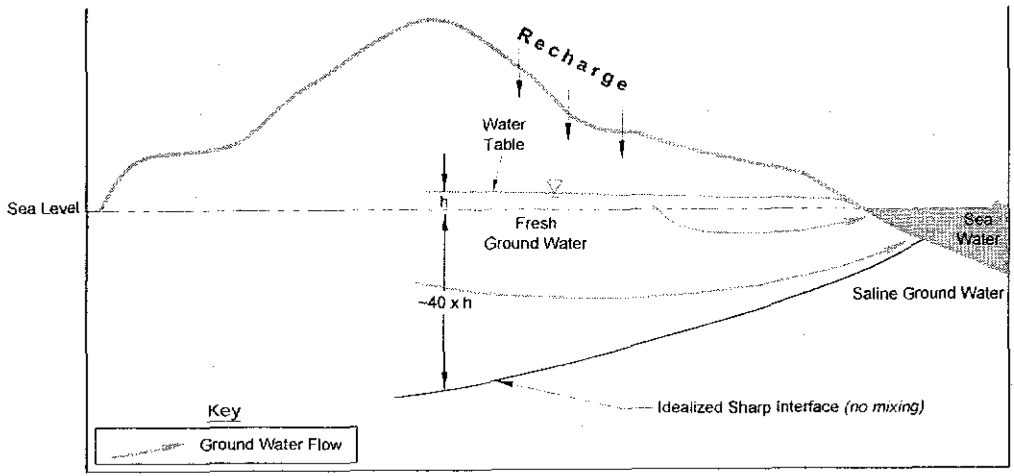
0263


N
S
W
E
Point Migley
Lane Spit
Lummi Point
This map was based on the following data and assumptions:
-Group A and B well data and number of connections were obtained from Whatcom County.
-Other wells were obtained from the Aspect well database and were assumed to be active and have a single residence connection.
-Each connection assumed to have an average of 2.1 people per residence based on Whatcom County Subarea plan.
-Per capita water use of 111 gallons per day based on "Estimated domestic, irrigation and industrial water use in Washington, 2000" (USGS Science Investigations Report 2004-5015 by R.C. Lane) for privately supplied residences in Whatcom County.
-For all residences 55% were assumed to be year round and 45% seasonal based on Lummi Island Subarea Plan. Seasonal residences were assumed to be present 120 days per year.
-No allowances were made for commercial/industrial use as these water uses are expected to be minimal.
-Annual withdrawals shown on this map total 111 acre-ft.
-Additional unknown wells are likely present that are not included in the estimates presented.

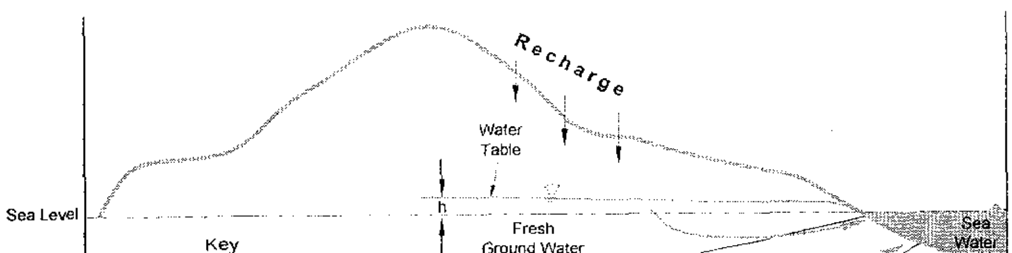


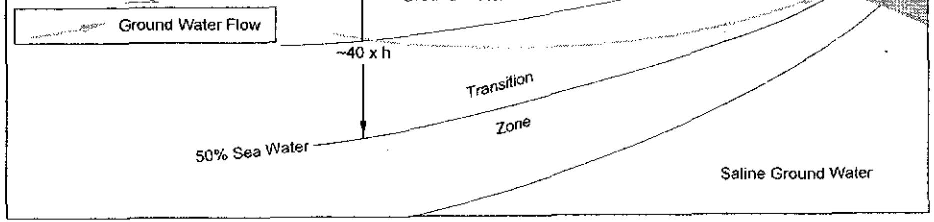
Legoe Bay
Lovers Bluff
Estimated withdrawals by quarter-quarter section (acre-ft/year)
0 -0.5
0.5 - 1
1- 2
2 - 3
3 - 4
4 - 5
5 - 6
6 - 7
7 - 8
0
1,500
3,000 Feet
Aspect consulting
Estimated Groundwater Withdrawals
Northern Lummi Island, Washington
Nov 2006
ACM
ACM
ACM
050039
3.5

026

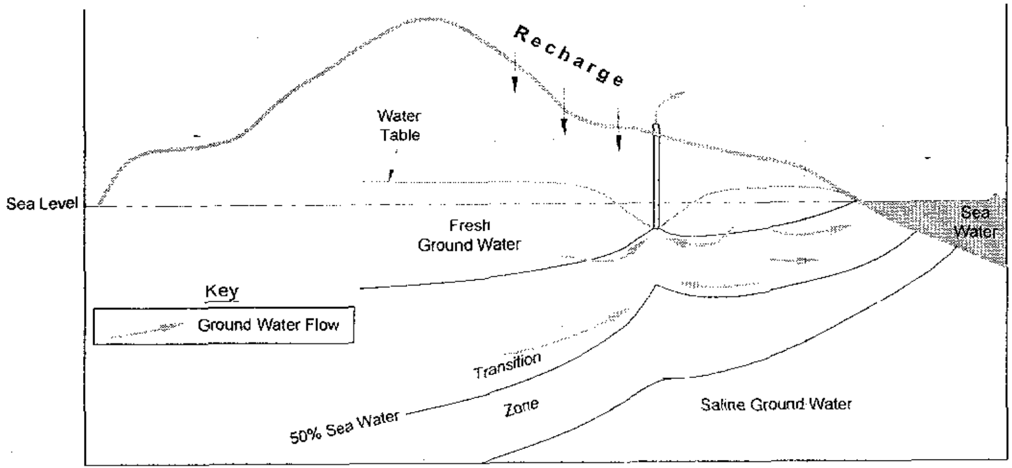


a) Idealized Fresh Water - Salt Water Interface





b) Fresh Water - Salt Water Interface with Transition Zone



c) Salt Water Upconing Due to Pumping From Well

not to scale

Aspect consulting

Schematic Cross Sections of Salt Water Intrusion

Northern Lummi Island Hydrogeologic Investigation

Northern Lummi Island, Washington

Nov 2006	PROJECT NO. 050039
EWM	
PMB	FIGURE NO. 3.6

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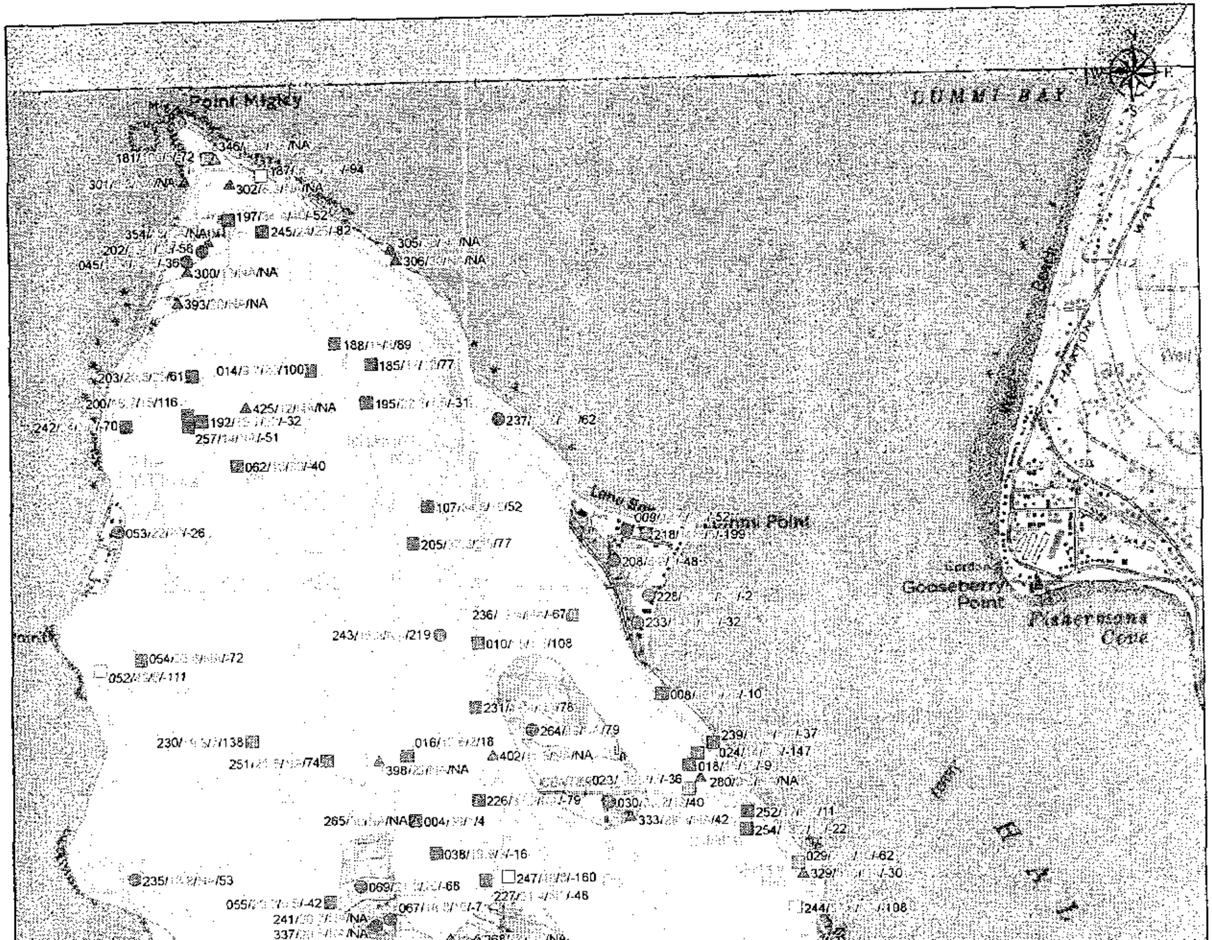
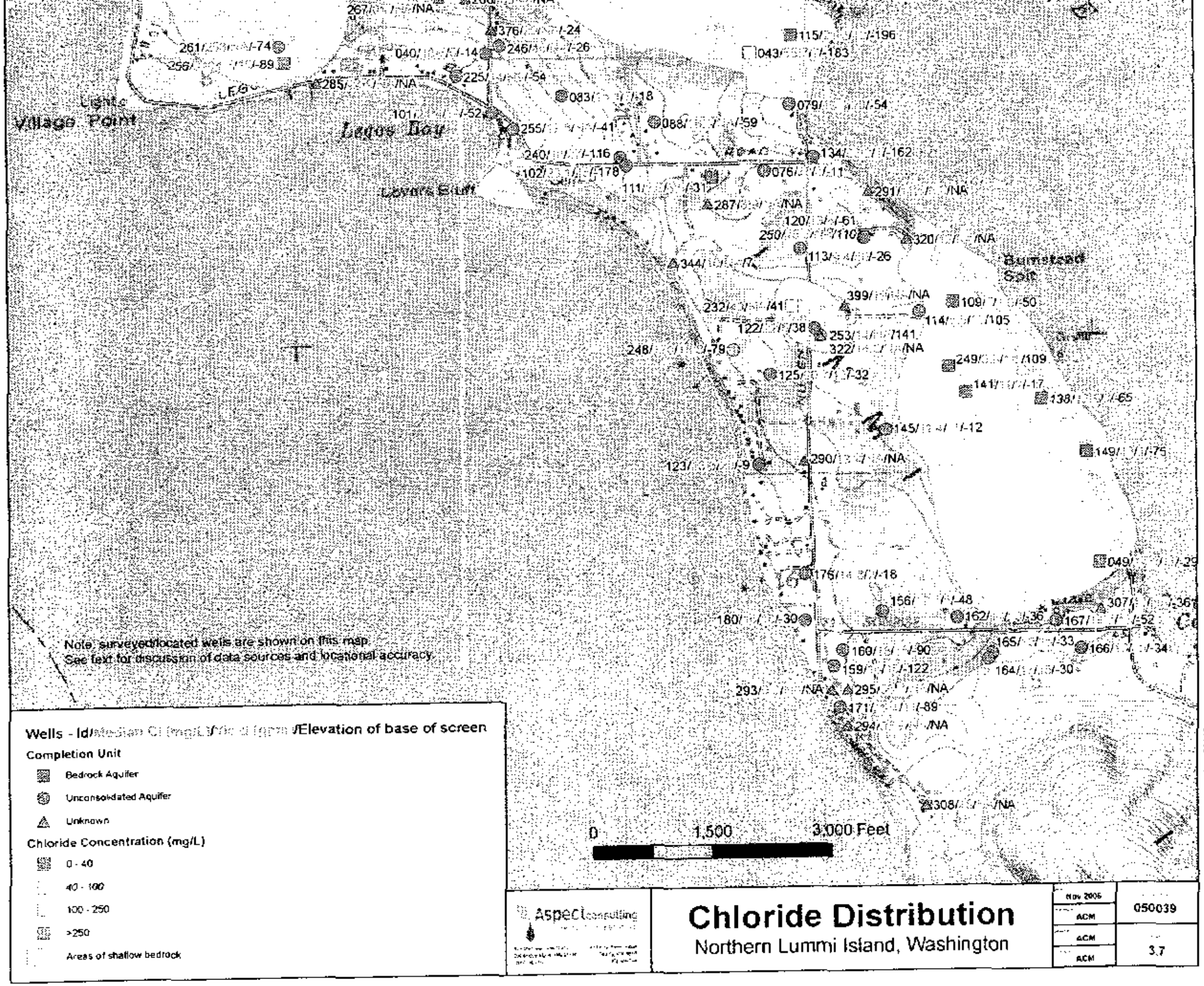
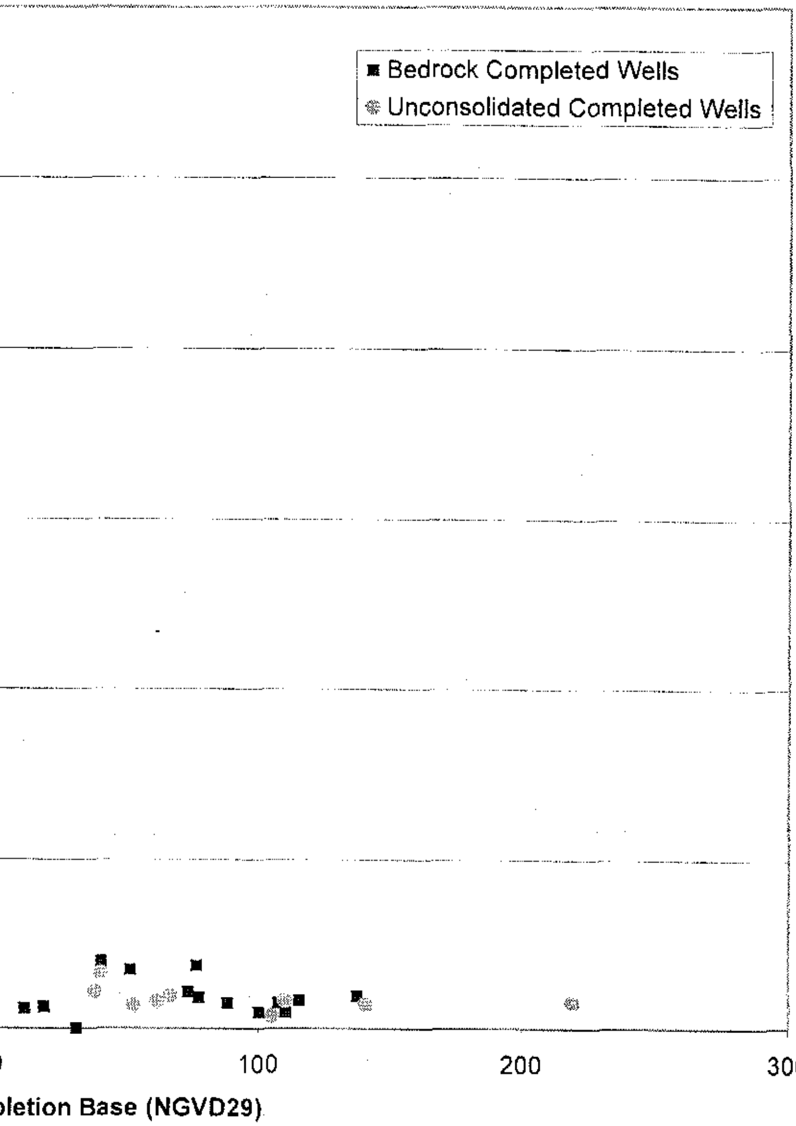
0265


Point Migley
Lummi Point
Gooseberry Point
Fishermans Cove



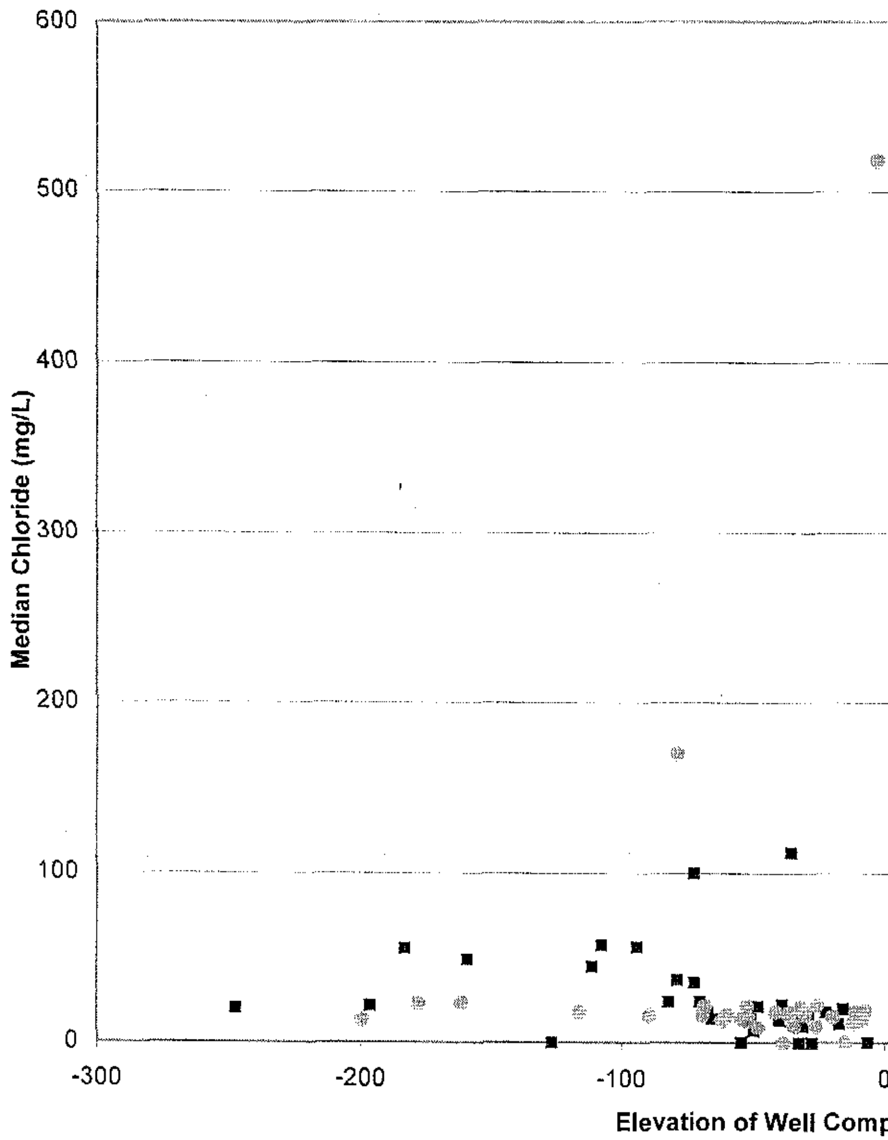
Village Point
Legoe Bay
Lovers Bluff
Bumstead Spit
Note: surveyed/located wells are shown on this map.
See text for discussion of data sources and locational accuracy.
Wells - Id/Median Cl (mg/L)/Elevation of base of screen
Completion Unit
Bedrock Aquifer
Unconsolidated Aquifer
Unknown
Chloride Concentration (mg/L)
0 - 40
40 - 100
100 - 250
>250
Areas of shallow bedrock
0
1,500
3,000 Feet
Aspect consulting
Chloride Distribution
Northern Lummi Island, Washington
Nov 2005
ACM
ACM
ACM
050039
3.7
T:\projects_8\lummi_island\chloride_distribution_031306.mxd

0266



Median Chloride Concentration
ogeologic Investigation
sland, WA

Figure 3.8



Aspect Consulting
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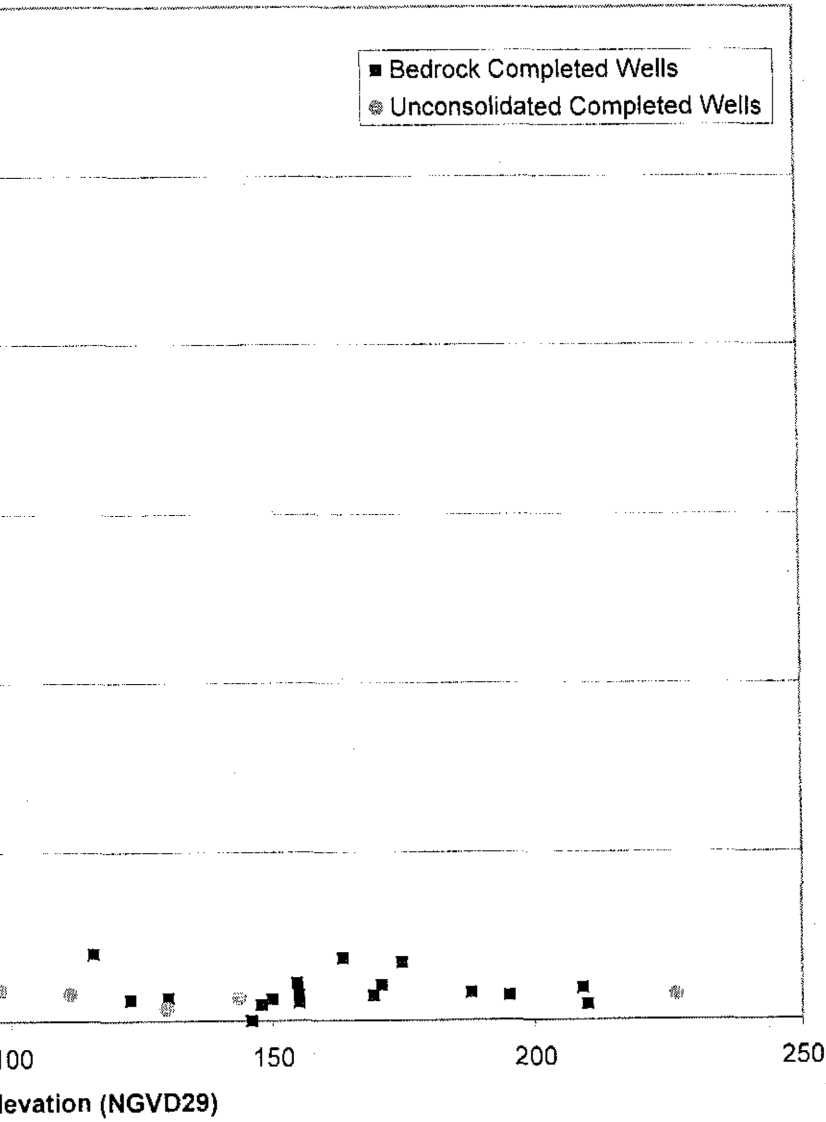
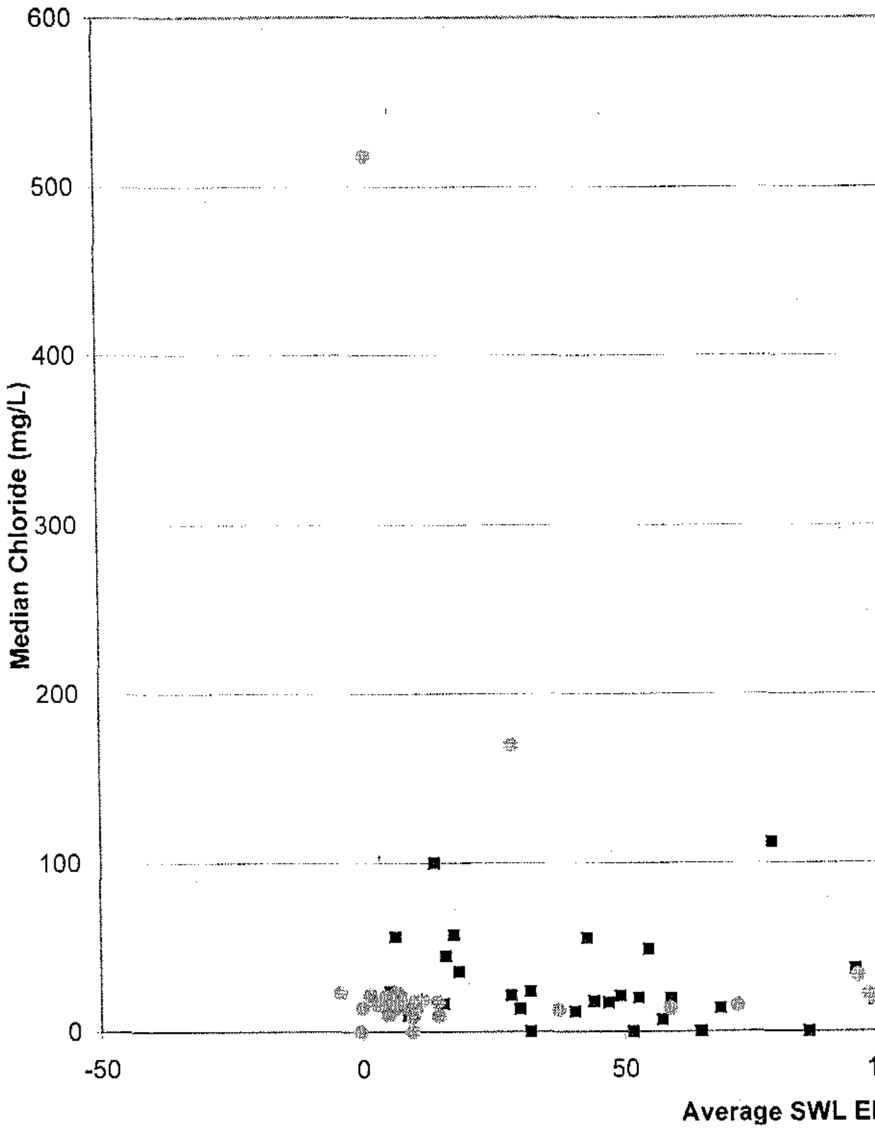
Elevation of Well Completion Base vs
Northern Lummi Island Hydro
Northern Lummi I

0267



edian Chloride Concentration
rogeologic Investigation
i Island, WA

Figure 3.9



Aspect Consulting
12/31/2006
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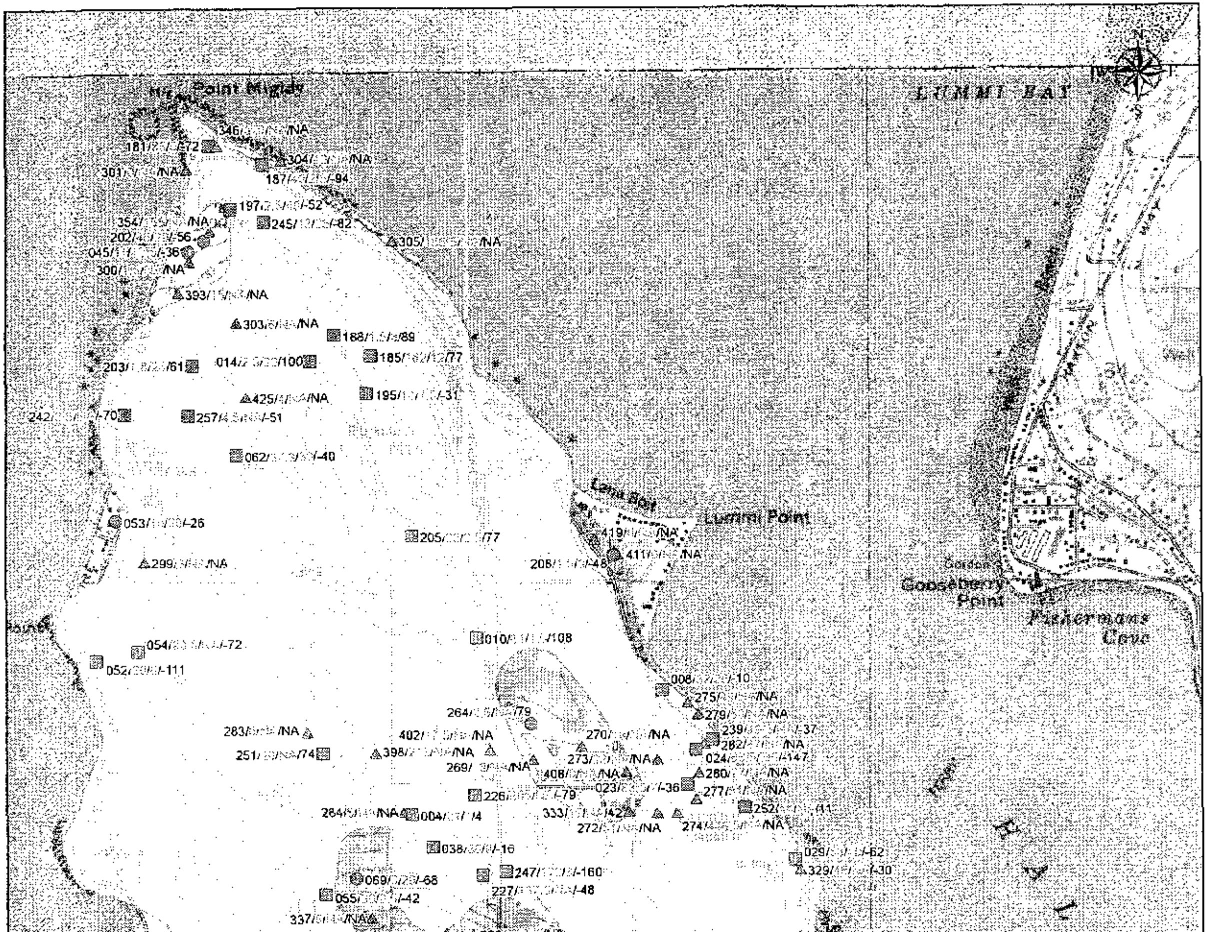
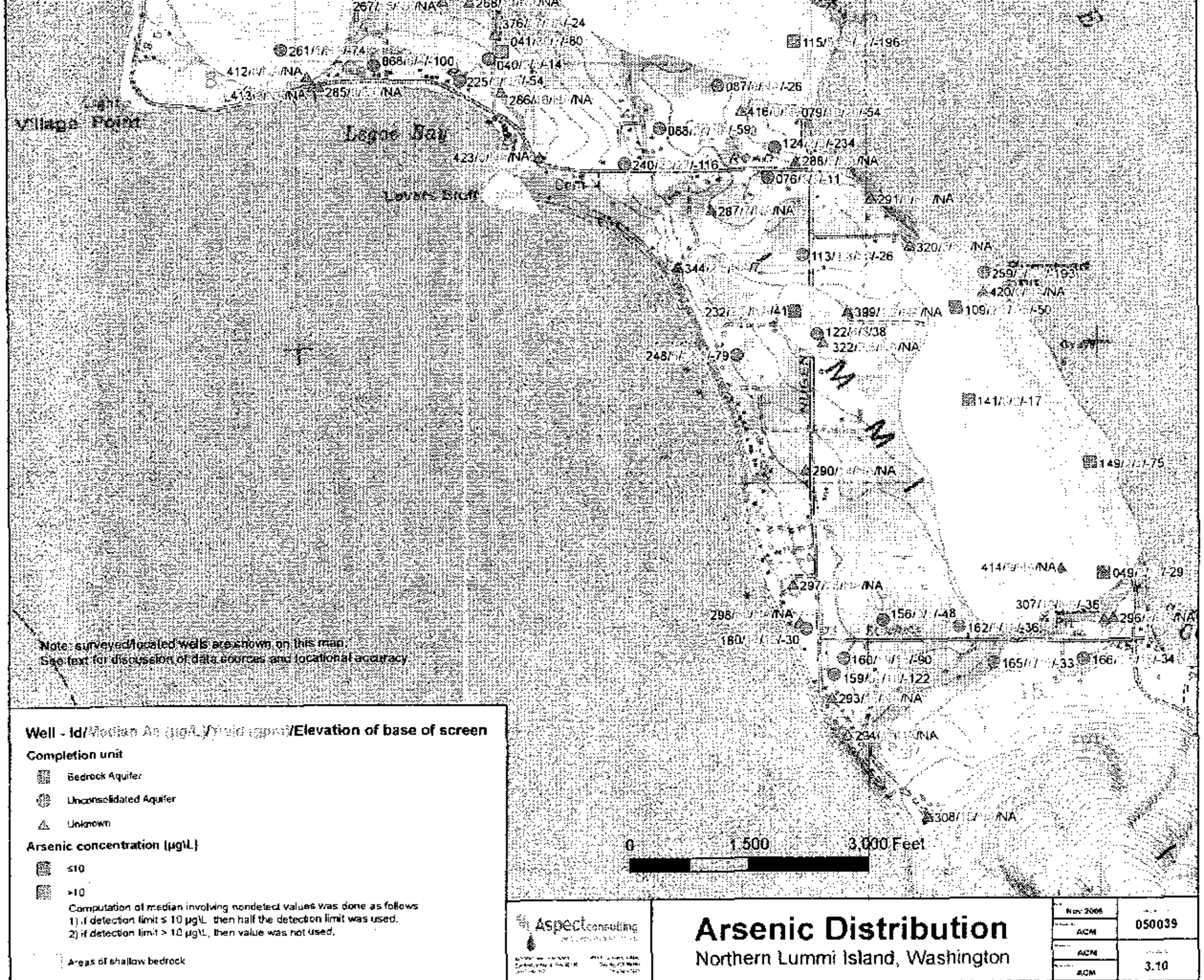
Static Water Level Elevation vs M
Northern Lummi Island Hyd
Northern Lummi

0268



Point Migley
LUMMI BAY
Lummi Point
Gooseberry Point
Fishermans Cove



Village Point
Legoe Bay
Lovers Bluff
Note: surveyed/located wells are shown on this map.
See text for discussion of data sources and locational accuracy.
0
1,500
3,000 Feet
Well - Id/Median As (µg/L)/Yield (gpm)/Elevation of base of screen
Completion unit
Bedrock Aquifer
Unconsolidated Aquifer
Unknown
Arsenic concentration (µg\L)
≤10
>10
Computation of median involving nondetect values was done as follows
1) if detection limit ≤ 10 µg\L then half the detection limit was used.
2) if detection limit > 10 µg\L, then value was not used.
Areas of shallow bedrock
Aspect consulting
Arsenic Distribution
Northern Lummi Island, Washington
Nov 2006
ACM
ACM
ACM
050039
3.10
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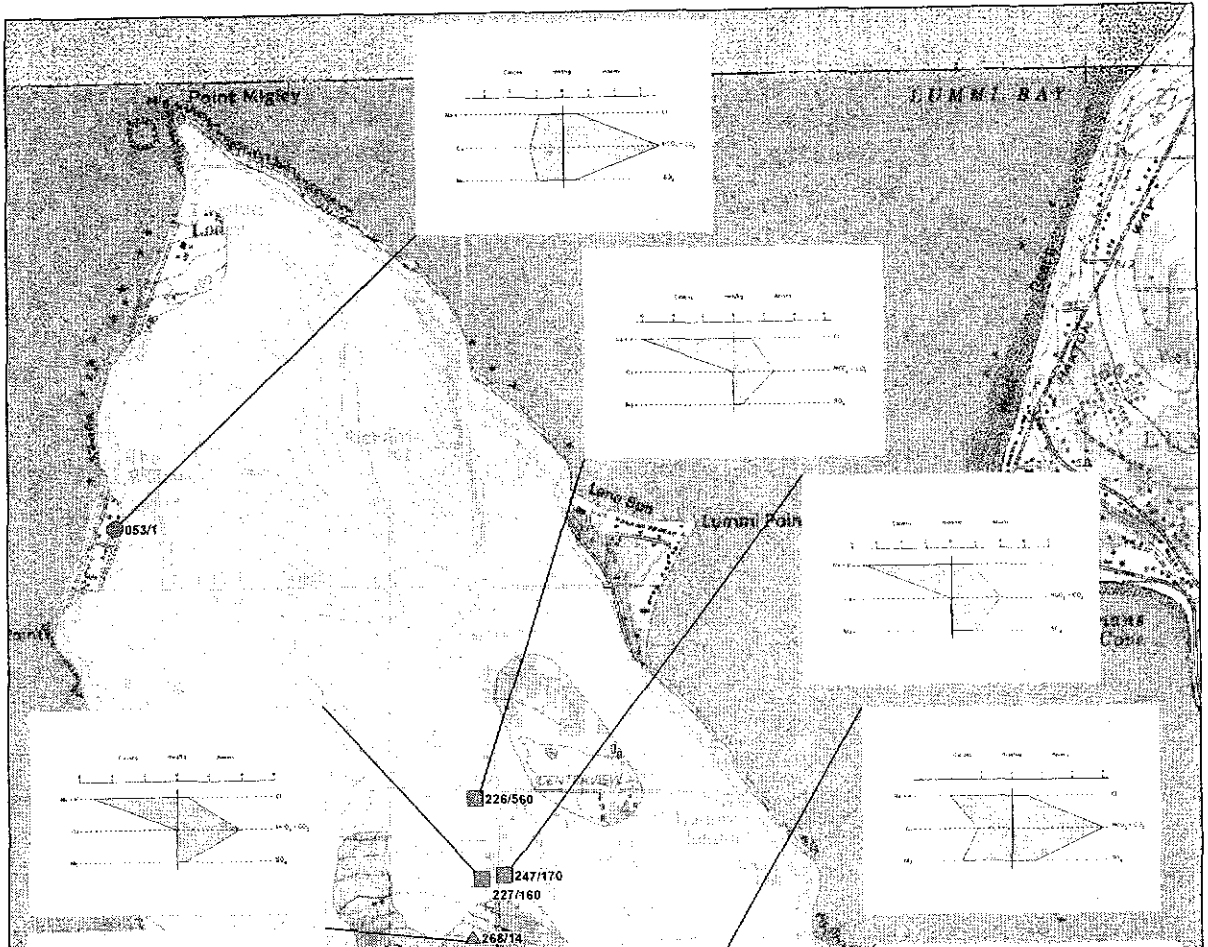
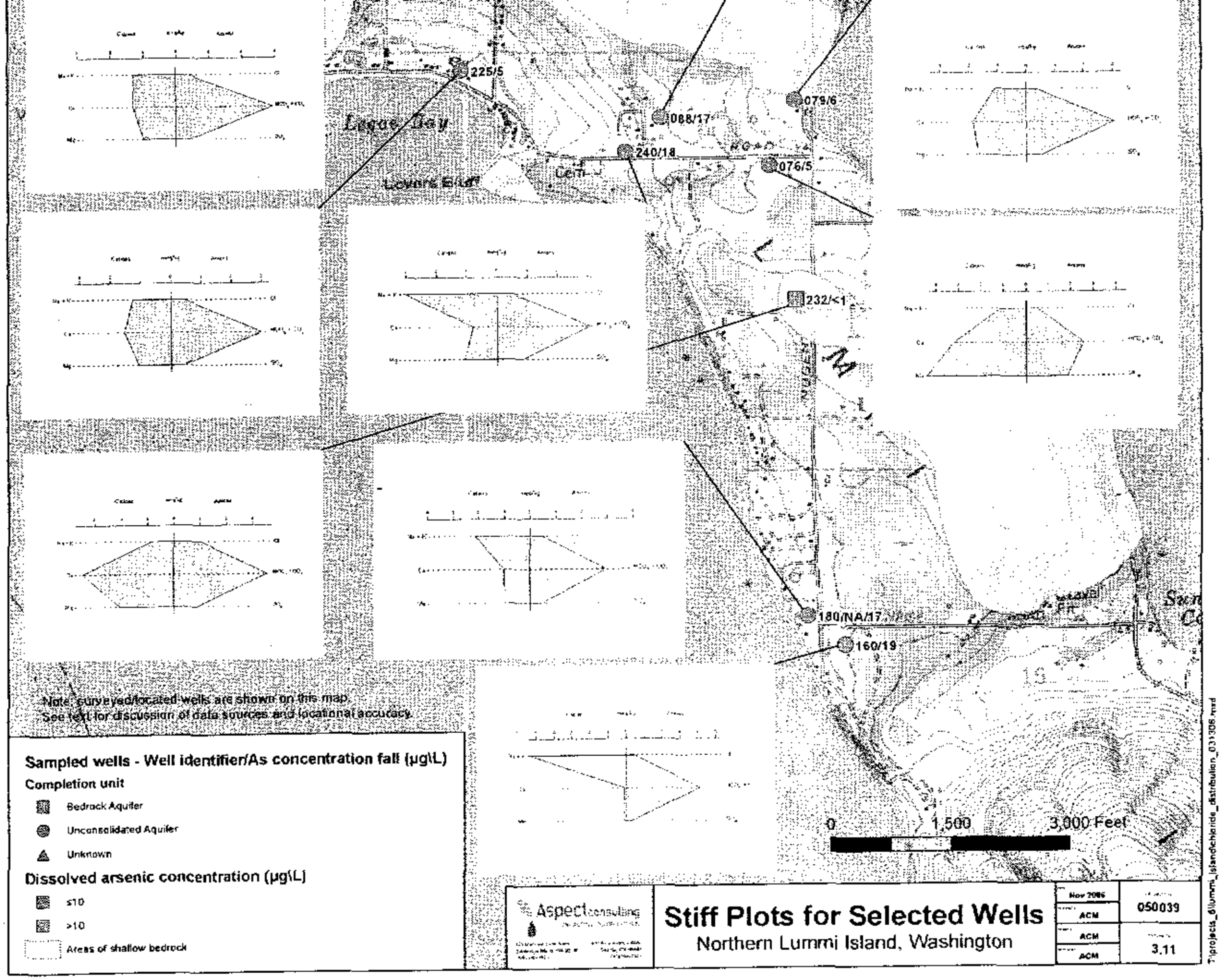
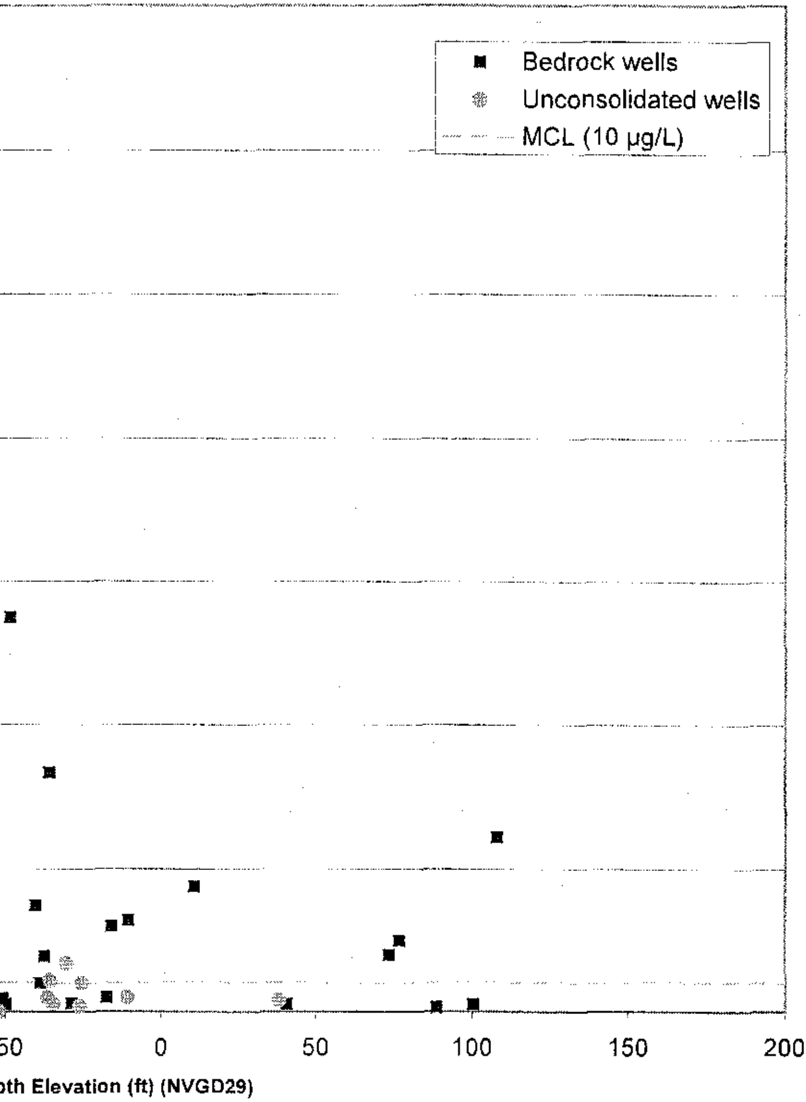

Point Migley
LUMMI BAY
Lummi Point
053/1
226/560
247/170
227/160
268/14

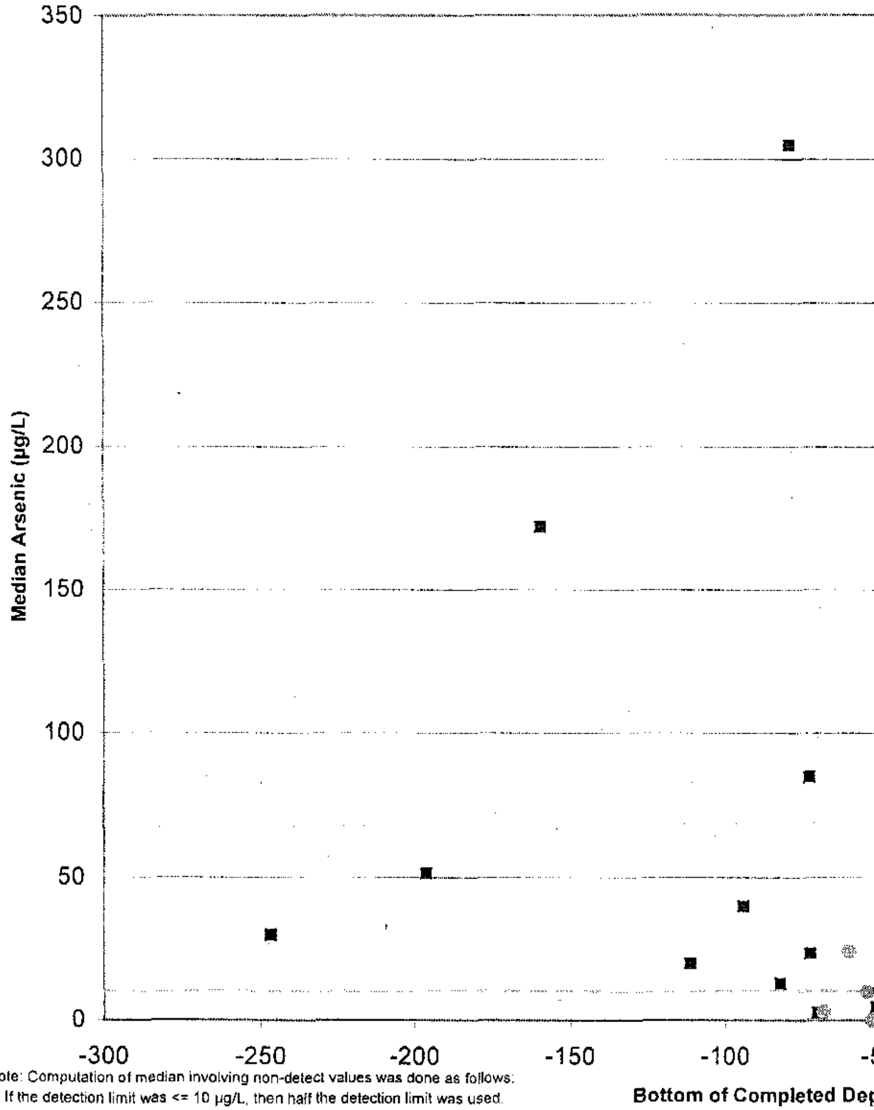

225/5
088/17
079/6
240/18
076/5
232/<1
180/NA/17
160/19
Legoe Bay
Lovers Bluff
Cem
Note: surveyed/located wells are shown on this map.
See text for discussion of data sources and locational accuracy.
Sampled wells - Well identifier/As concentration fall (µg\L)
Completion unit
Bedrock Aquifer
Unconsolidated Aquifer
Unknown
Dissolved arsenic concentration (µg\L)
≤10
>10
Areas of shallow bedrock
0
1,500
3,000 Feet
Aspect consulting
Nov 2006
ACM
050039
3.11
Stiff Plots for Selected Wells
Northern Lummi Island, Washington

0270



s Median Arsenic Concentration
geologic Investigation
sland, WA

Figure 3.12



Note: Computation of median involving non-detect values was done as follows:
1) If the detection limit was <= 10 µg/L, then half the detection limit was used.
2) If detection limit was > 10 µg/L then the value was not used.

Bottom of Completed Depth Elevation v
Northern Lummi Island Hydro
Northern Lummi I

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12/31/2006
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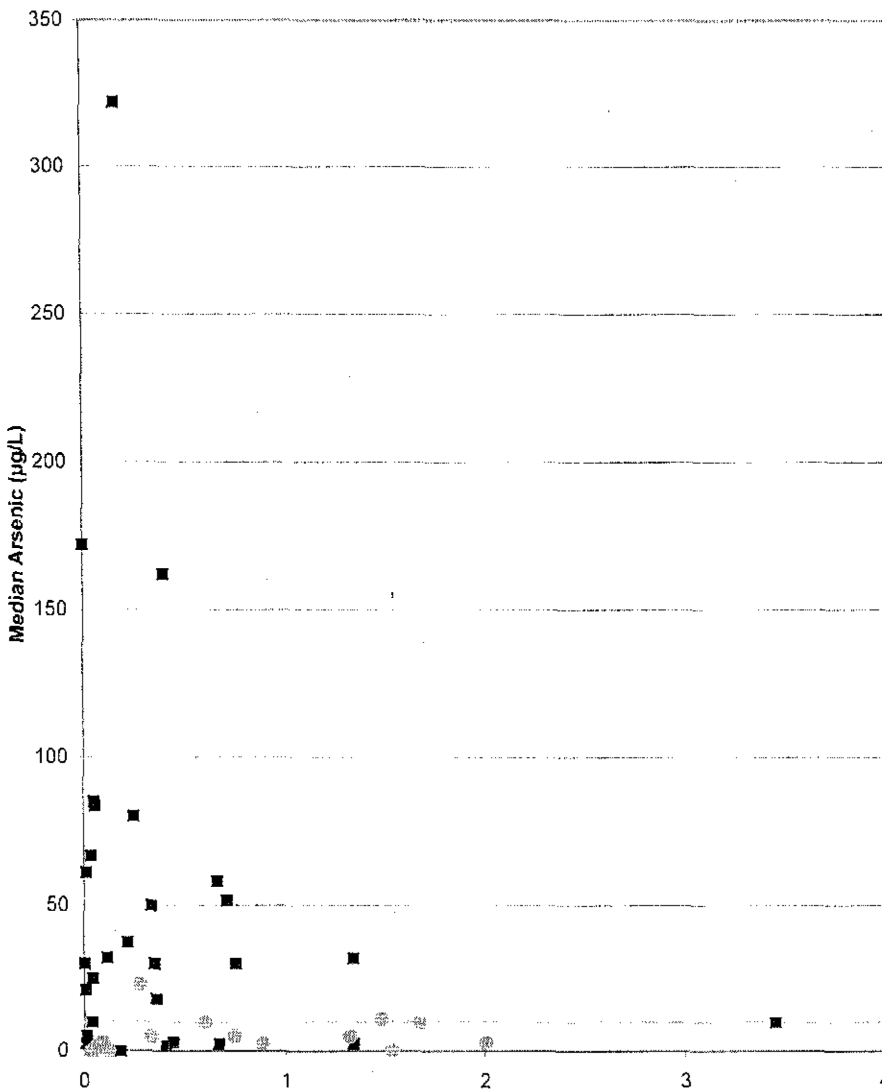
0271

dian Arsenic Concentration
ogeologic Investigation
Island, WA

Figure 3.13



Note: Computation of median involving non-detect values was done as follows:
1) If the detection limit was <= 10 µg/L, then half the detection limit was used.
2) If detection limit was > 10 µg/L then the value was not used.

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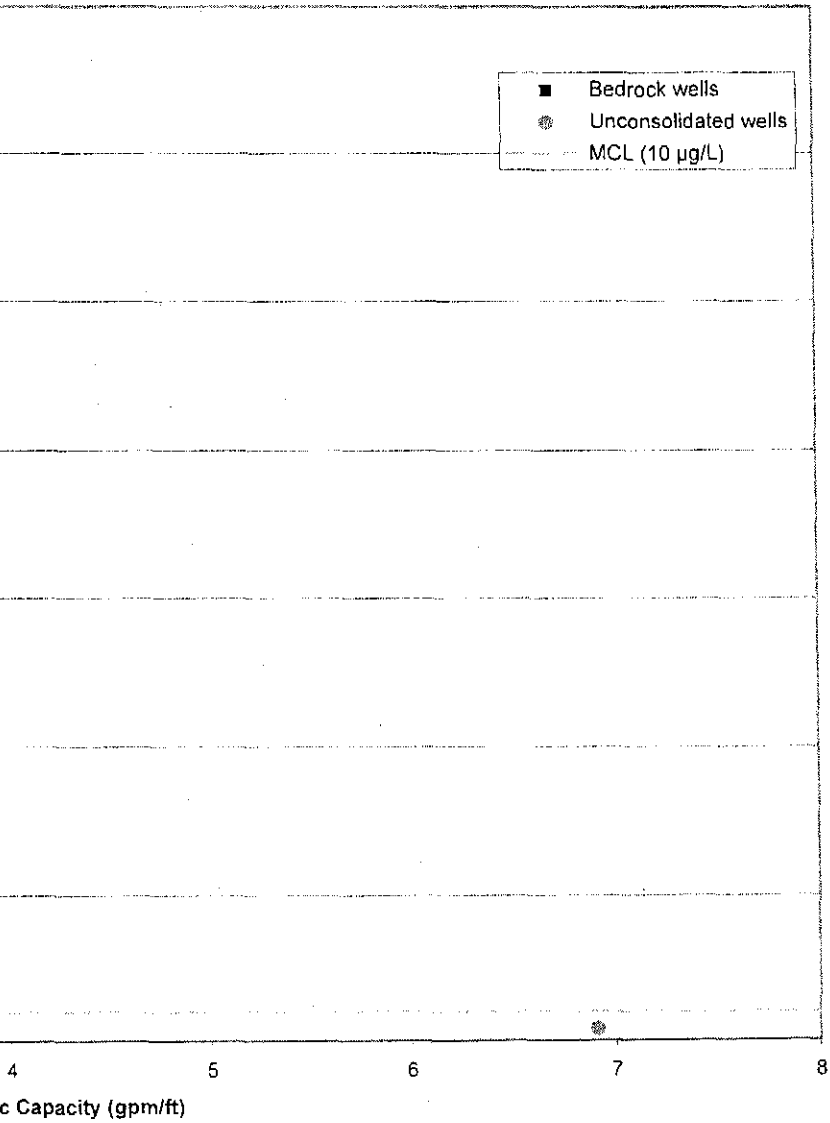
Average Specific Capacity vs Me
Northern Lummi Island Hydr
Northern Lummi

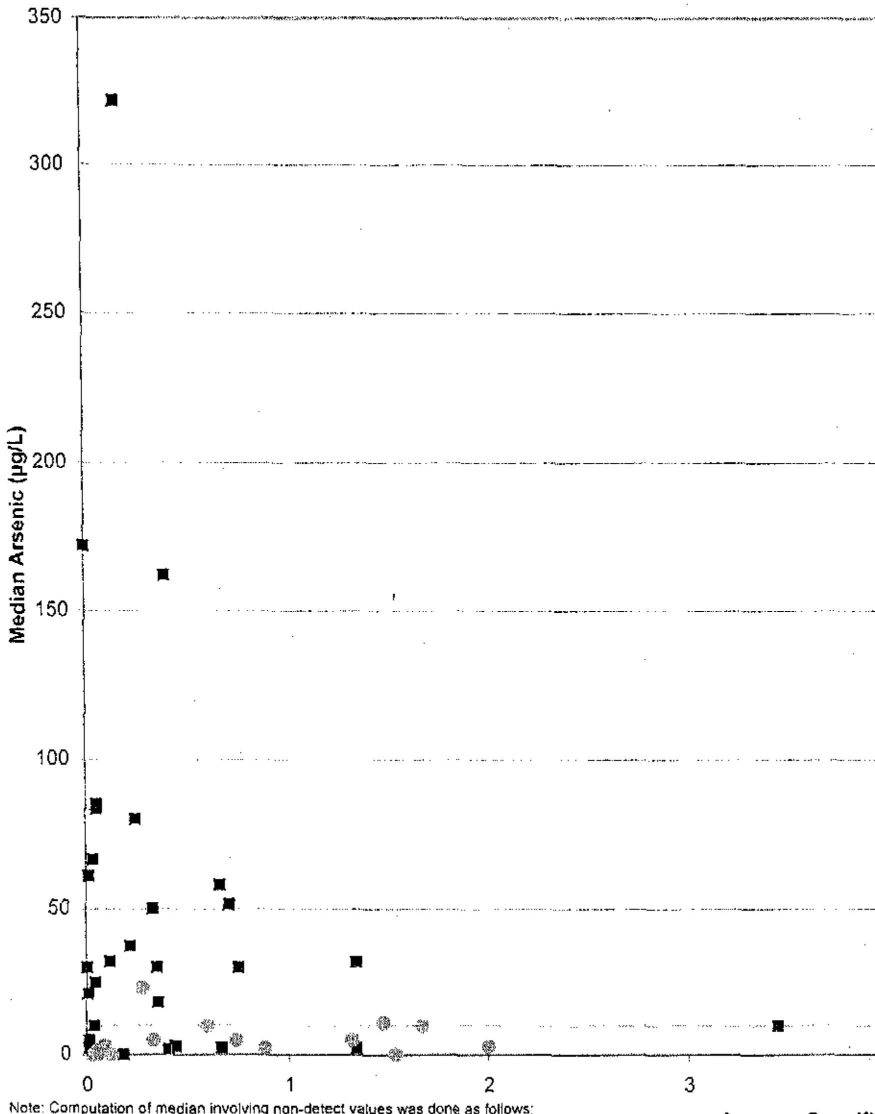
APPENDIX A

Well Database



edian Arsenic Concentration
rogeologic Investigation
Island, WA

Figure 3.13



Note: Computation of median involving non-detect values was done as follows:
1) If the detection limit was <= 10 µg/L, then half the detection limit was used.
2) If detection limit was > 10 µg/L then the value was not used.

Average Specific Capacity vs Me
Northern Lummi Island Hyd
Northern Lummi

Aspect Consulting
12/31/2006
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0272