WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

Investigation of Water Resources, Water Quality, and Seawater Intrusion, Anderson Island, Pierce County, Washington

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Investigation of Water Resources, Water Quality, and Seawater Intrusion, Anderson Island, Pierce County, Washington

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by
L. Wildrick, C.M. Neumiller, R. Garrigues, and K. Sinclair

Water Resources and Environmental Assessment Programs
Olympia, Washington 98504-7775

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Water Resource Inventory Area 15

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Table of Contents

Page

List of Figures and Tables

Page

Figures

Tables

Horizontal and Vertical Datums

The horizontal datum used in this report is the North American Datum of 1983 (NAD83). The vertical datum is the North American Vertical Datum of 1988 (NAVD88), which is a fixed datum derived from a simultaneous, least squares, minimum constraint adjustment of sea level observations. For the purposes of this report, “mean sea level” refers to NAVD88.

Abstract

Anderson Island (Island) is a small island in southern Puget Sound, Washington. Due to steady population growth, Islanders have become concerned about the sustainability of ground-water resources. The goals of this study were to: (1) summarize and supplement existing geologic and hydrologic information, especially water quantity and quality; (2) evaluate the extent of seawater intrusion; and (3) assess the need for future monitoring of ground-water levels and chloride concentrations.

Geologic processes occurring over the past 1.6 million years created and modified the Island's shape, surface topography, and complex geology. The most significant of these processes includes several glacial advances and retreats.

The Island is capped by a thin, discontinuous layer of Vashon *till*[*] - a glacially deposited, highly compacted mixture of clay, silt, sand, gravel, and boulders that functions as weak *aquitard*. Enough water percolates through the Vashon till and into the underlying sediments to create a high quality, freshwater supply. Ground water on the Island is withdrawn from two main *aquifers*. The uppermost Vashon aquifer, is *semi-confined* to *unconfined* and is composed of Vashon *advance outwash*, a permeable, glacially deposited mixture of sand and gravel. Underlying the Vashon aquifer is a silty, low permeability, nonglacial and glaciolacustrine unit that serves as an aquitard. Below the silt unit lies the Sea Level aquifer, the most widely tapped aquifer on the Island. The Sea Level aquifer is *confined* and is composed of permeable sand and gravel glacial deposits of pre-Vashon age. The top of this aquifer is at sea level, while the bottom extends well below sea level. Ground-water elevations (*heads)* have not declined noticeably in either aquifer over the past ten years.

Twenty-three small streams and numerous springs drain from the Island. Based on long-time Islander's recollections, flows have not diminished noticeably over the past 50 years, though few actual measurements are on record. Water levels in the Island's two lakes, Florence and Josephine, have not progressively diminished, although they vary by several feet within a given year.

Seawater intrusion is not a widespread problem on the Island – although there are three areas near the shoreline where it appears to be occurring in the Sea Level aquifer. Four wells in these areas have consistently produced chloride concentrations exceeding 100 mg/L – a level considered indicative of seawater intrusion. Historical data shows similar results. Specific conductance values in these areas were correspondingly elevated. Nitrogen concentrations were well within acceptable limits. pH levels were also within acceptable limits, with the exception of water samples from three springs.

Future periodic monitoring of ground-water heads, chloride concentrations, and specific conductance in select wells is recommended.

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[*] definitions of italicized words can be found in the Glossary.

Acknowledgments

The authors sincerely thank the Islanders who initiated, encouraged, and supported this study, particularly Nancy Hill, Alan Hill, and Dennis Johnson. In addition, Dennis Kennedy, Chuck Cunningham, Joe Blashka, Darline Thompson, and Rick Anderson assisted with sampling and measurements. Together, these volunteers contributed hundreds of hours to the project. They contacted well owners in preparation for the study, assisted with water sampling and analyses, and measured water levels in wells each month. Without their assistance, the study would not have been possible.

Tacoma-Pierce County Health Department (TPCHD) purchased and loaned field instruments and supplies to the project. Brad Harp, TPCHD hydrogeologist, helped design the study.

U. S. Geological Survey, Water Resources Division assisted greatly in this study. Gary Turney helped design the study and provided comments on the final draft. Robert Crist – himself a part-time Islander - provided electronic versions of the site-numbering system and seawater intrusion figures.

Dr. Duncan Foley, assistant professor of geology at Pacific Lutheran University (PLU), spent several days on the Island conducting the initial *Global Positioning System (GPS*) measurements of well locations and elevations. He also provided base station data for subsequent measurements. Aaron Sonnichsen, a geology student at PLU, assisted with GPS measurements and interpreted well logs from the northern end of the Island for his senior thesis.

Terry Bibby, maintenance manager for Riviera Development, provided access to Riviera's water-supply wells and assisted during measurement of the wells.

The Washington State Department of Natural Resources, Division of Geology and Earth Resources assisted greatly in delineating Island geology. Geologists Wendy Gerstal and R. Josh Logan accompanied the senior author on a one-day boat trip along the southern and southwestern shore of the Island to map geologic exposures in coastal bluffs. Geologist Michael Polenz was instrumental in providing a draft copy of the newly revised geologic map for the Island and giving insight on the latest geologic findings.

Kathy Troost, University of Washington, graciously provided an electronic version of her Quaternary stratigraphic column for the Puget Lowland.

Several Department of Ecology employees contributed to this study. Deb Hunemuller and Connie Juneau assisted with water sampling. Jill Walsh, water resources specialist, researched Island water rights and claims and assisted the secondary author in an evening presentation to the Islanders. Hydrogeologist Tom Culhane provided review and comments on the final draft.

Introduction

This report describes the findings of an investigation of geology, ground- and surface-water quantity, ground-water quality, and seawater intrusion on Anderson Island, Pierce County, Washington (Figure 1). The population of Anderson Island (Island) has been increasing steadily over the past decade. This has raised concerns about the adequacy of freshwater supplies, including the risk of seawater intrusion.

The study commenced at the request of a group of the Islanders. Financial support was provided by the Tacoma-Pierce County Health Department. Financial and staff support was provided by the Department of Ecology's (Ecology) Environmental Assessment Program. Ecology's Water Resources Program conducted the majority of the work.

Purpose and Scope

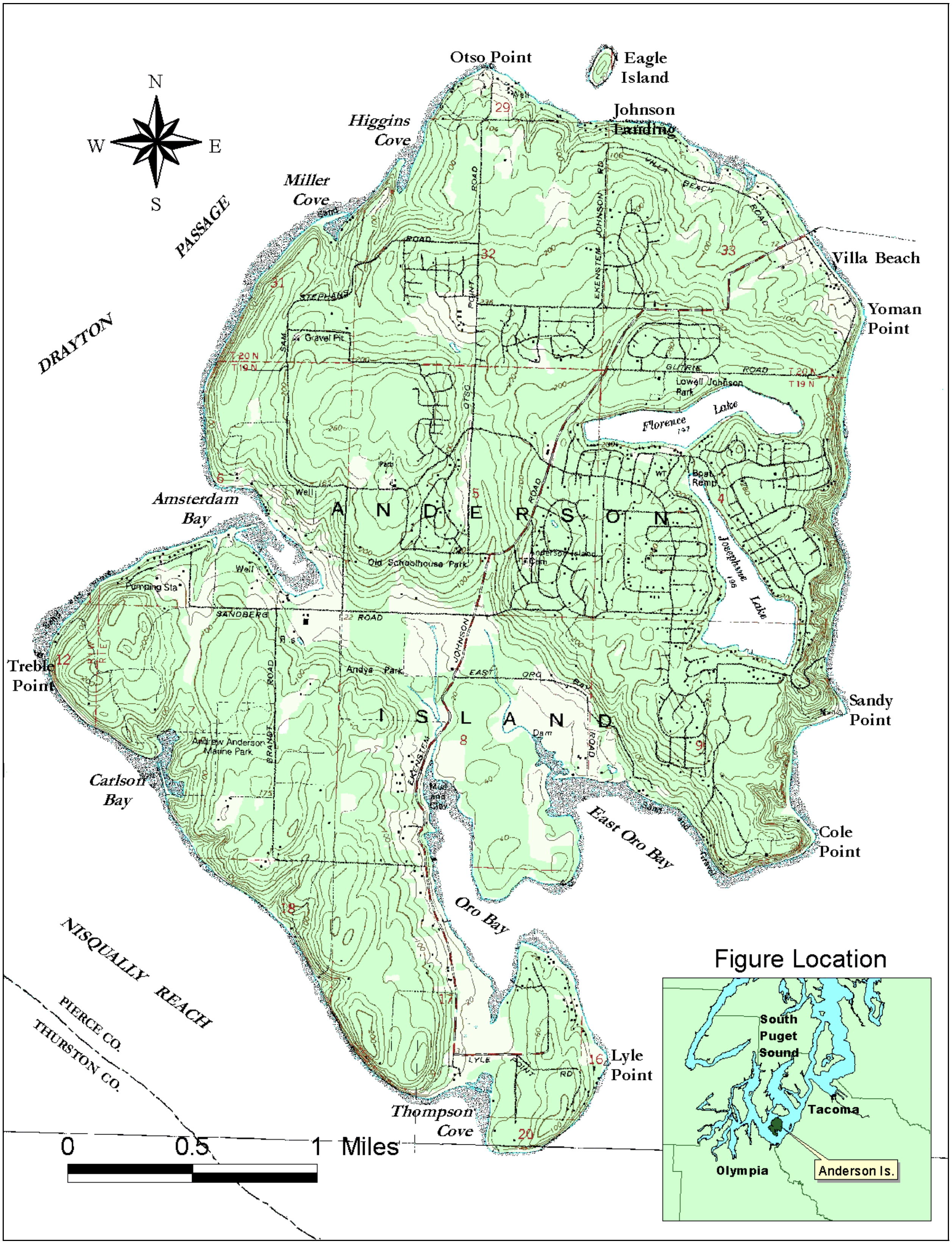
This study involved one year of ground-water sampling and analyses, measurement of ground-water levels, surface-water discharge measurements, and geologic mapping. The purpose of this work was to:

1. Summarize and supplement existing geologic and hydrologic information, especially water quantity and quality;
2. Evaluate the extent of seawater intrusion; and
3. Assess the need for future monitoring of ground-water heads and chloride concentrations.

The study does not provide new estimates of the Island's water-budget components, such as precipitation, surface-water runoff, evapotranspiration, ground-water recharge, and water use. It should also not be construed as a complete and detailed investigation of the hydrogeologic units, the quantity of water available for all future appropriations, or the full extent of seawater intrusion in water-supply wells on the Island.

Regional Setting, Land Use, and Topography

Anderson Island is located in southern Puget Sound, western Pierce County, about 18 miles southwest of Tacoma and 15 miles northeast of Olympia (Figure 1). The Island is part of *Water Resource Inventory Area* 15 (Kitsap). Access to the Island is by Pierce County Transit ferry or private boat. Anderson Island is primarily residential, with the exception of several small retail establishments and a golf course. Much of the Island was originally logged for steamship boiler fuel. At one time, there were several dairy farms located on the Island's interior and a brick manufacturing facility operated on the flat headland that separates Oro Bay from East Oro Bay (Heckman, 1967).



Base from U.S. Geological Survey McNeil Island and Nisqually quadrangles, 1:24,000

Figure 1. Location and topography of Anderson Island.

The surface area of the Island is approximately 7.9 square miles (5,076 acres; RH2 Engineering, 1996). The topography ranges from steep, coastal bluffs to gently rolling uplands (Figures 1&2). Most of the shoreline consists of steep bluffs with narrow beaches. Gentler slopes occur around Oro, East Oro, and Amsterdam Bays, Thompson Cove, and Lyle Point peninsula. The maximum elevation of the northern part of the Island is approximately 280 feet above mean sea level (msl), while that of the southern part is roughly 220 feet above msl. Between Oro Bay and Amsterdam Bay is a southeast-northwest-trending area of low elevation. The maximum elevation of this low-lying area is less than 30 feet above msl. It divides the Island - with roughly 2/3 of the landmass lying to the northeast and about 1/3 lying to the southwest (Figures 1&2). There is another low-lying area at the south end of the Island. It trends north-south between Oro Bay and Thompson Cove. The maximum elevation of this area is less than 20 feet above msl, nearly isolating the Lyle Point peninsula from the rest of the Island.

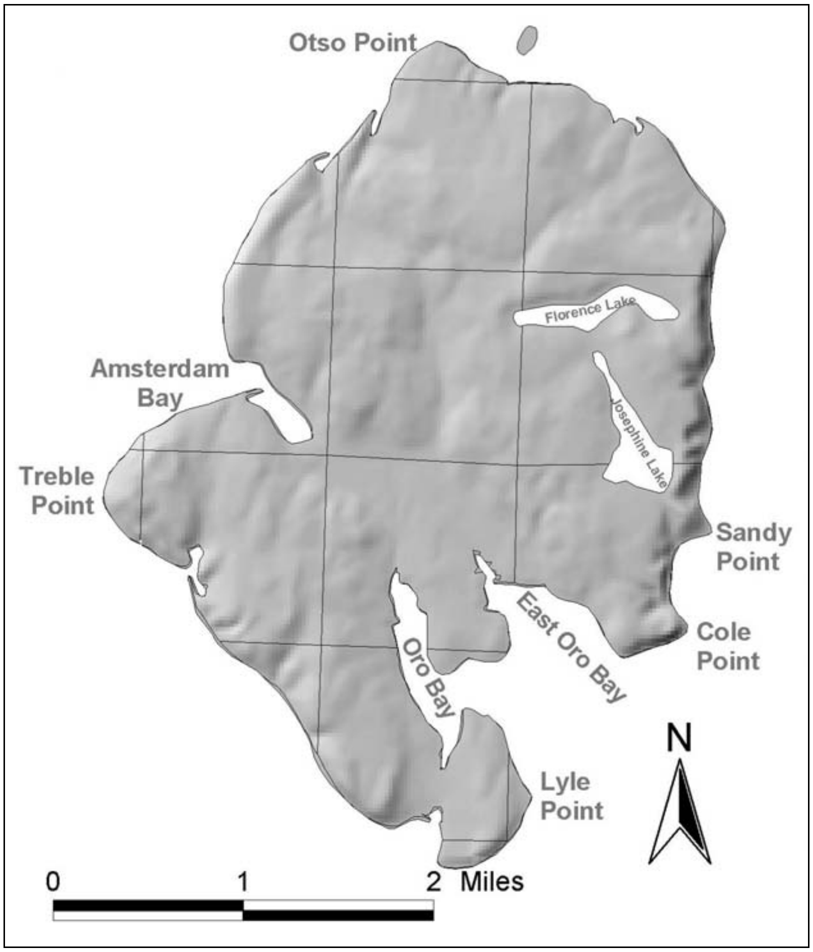


Figure 2. Shaded relief map of Anderson Island.

Previous Investigations

Although Anderson Island has never been the focus of a geologic or hydrologic investigation, it has been included in several broad-scale investigations conducted in the Puget Lowland.

Bretz (1913) was the first to delineate the glacial history and geology of the south Puget Lowland. This study is very general as it covers a large area.

Anderson Island was the southern-most area included in a geologic and ground-water resources study of the Kitsap Peninsula and adjacent islands by Garling, et al. (1965). During this study, the geology of the Island was mapped, but well logs were not analyzed. Most of the sub-surface detail was extrapolated from coastal exposures and well logs for adjacent landmasses. Twenty-three small streams were mapped and the discharge estimated. At that time, there was little development on the Island. Only eight surface-water applications, permits, and/or certificates were on record, mainly for irrigation. Domestic water was primarily supplied by springs and relatively shallow dug and drilled wells.

Walters (1971) included six Anderson Island wells in a survey of seawater intrusion along Washington's coastal regions (Figure 3, Table 1). Wells were sampled for *chloride* and *specific conductance*. Evidence suggesting seawater intrusion was found on the northeastern portion of Lyle Point peninsula (19N/01E-17J1; 504 mg/L chloride) and the north shore of East Oro Bay (19N/01E-09M1; 561 mg/L chloride). Slightly elevated chloride concentrations were found on the northern portion of Treble Point (19N/01E-06P1; 27 mg/L chloride) and east of Otso Point (20N/01E-29Q3; 64 mg/L chloride). Walters (1971) also made note of another well east of Otso Point (20N/01E-29Q1) that was abandoned prior to his study because the water became unusable due to excessive salinity. One deep well (20N/01E-33R1) on the eastern side of the Island, south of Yoman Point, showed no evidence of seawater intrusion.

As part of the Coastal Zone Atlas for Washington, the Washington Department of Ecology (1979) mapped the geology in a half-mile-wide strip along the shoreline of Anderson Island. Several landslides were mapped along the perimeter of the Island.

In a follow-up study of coastal Washington seawater intrusion, Dion and Sumioka (1984) sampled three wells originally sampled by Walters (1971) on Anderson Island (Figure 3, Table 1). Wells were sampled for chloride and specific conductance. The results were very similar to those of Walters (1971).

In more recent investigations, Anderson Island was included in revisions of geologic maps for the south half of the Tacoma quadrangle (*scale* 1:100,000; Walsh, 1987) and the Washington-Southwest quadrant (scale 1:250,000; Walsh, et al., 1987). Logan, et al. (2001) recently revised the geology in the McNeil Island *7.5 minute quadrangle*, which includes all but the southern-most tip of Anderson Island. This map is a larger scale (1:24,000), which means it covers a smaller area and includes more detail than the previously mentioned maps. The revised geology is discussed later in this report. This map is still in draft form but has been incorporated into this report with permission of the authors.

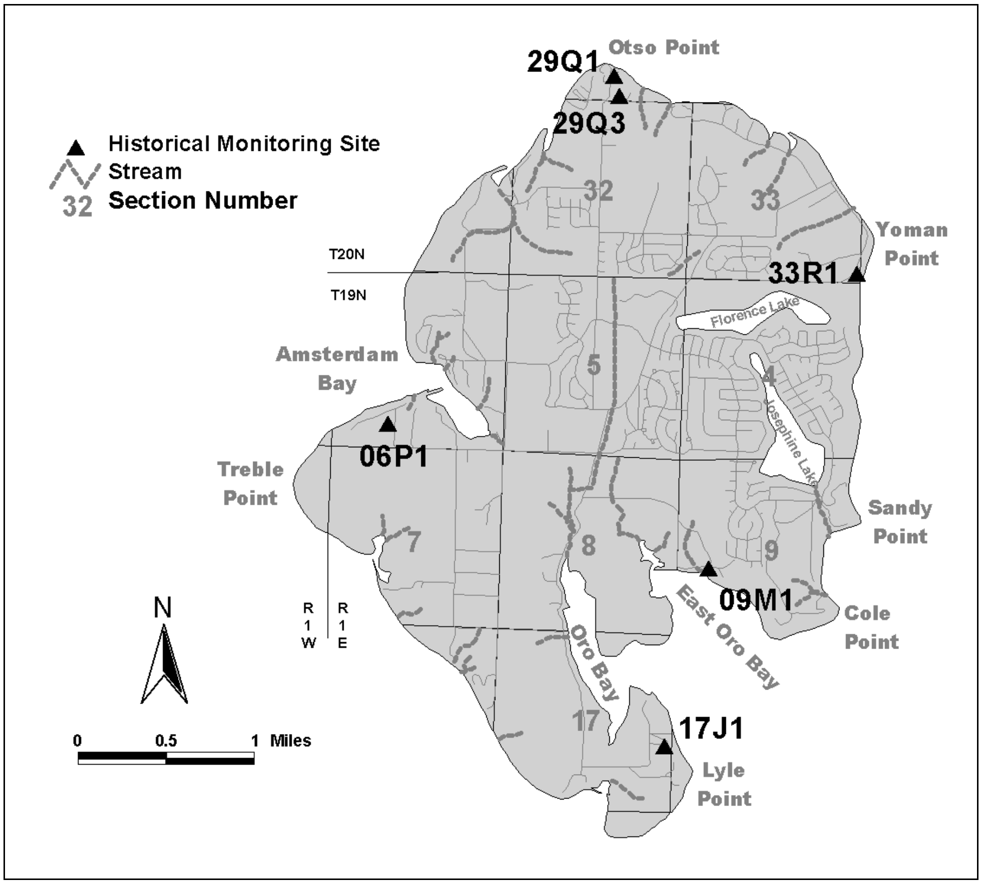


Figure 3. Historical monitoring site locations.

Table 1. Data from previous investigations.

W = Walters (1971); D&S = Dion and Sumioka (1984); SL = Sea Level aquifer; * = abandoned prior to 1968 due to excessive salinity

Study	Site Location (section, township, range)	Land Surface Elevation (feet msl)	Well Depth (feet)	Well Bottom Elevation (feet msl)	Source Aquifer	Chloride (mg/L)	Specific Conductance (umhos/cm2)	Date Sampled
W '71	19N/01E-6P1	50	62?	-12?	SL?	27	248	7/12/1968
W '71	19N/01E-9M1	20	52	-32	SL	561	2,060	7/12/1968
W '71 D&S '84	19N/01E-17J1	50	?	?	SL?	504 474	1,910 1,965	7/12/1968 5/22/1978
W '71*	20N/01E-29Q1	10	87	-77	SL	-	-	-
W '71 D&S '84	20N/01E-29Q3	75	82	-7	SL	64 44	431 370	7/12/1968 5/22/1978
W '71 D&S '84	20N/01E-33R1	170	228	-58	SL	2.5 2.7	138 125	7/12/1968 5/22/1978

Methods of Investigation

Well Numbering and Location System

Metal tags imprinted with a unique identification number were affixed to casings or plumbing of monitoring wells in this study. The unique identification number consists of three letters followed by three numbers (ex. AAB123). These well tags will enable future researchers to verify that they are visiting the same wells and springs measured and sampled during this study. Well tags are now required by Washington State law on all new water-supply wells.

Approximate locations of monitoring wells and springs are identified using the Public Land Survey system of Township, Range, Section (approximately one square mile), and Subsection (approximately 40 acres). Sections are numbered 1-36 and subsections are lettered A-R (I and O are excluded; Figure 4). Subsections are equivalent to quarter-quarter sections. Sometimes there is more than one well or spring in a Subsection. These are designated by 01, 02, etc., following the Subsection number. For example, 19N/01E-33R02 represents the second well in Township 19 North (of the Willamette Base Line), Range 01 East (of the Willamette Meridian), Section 33, Subsection R.

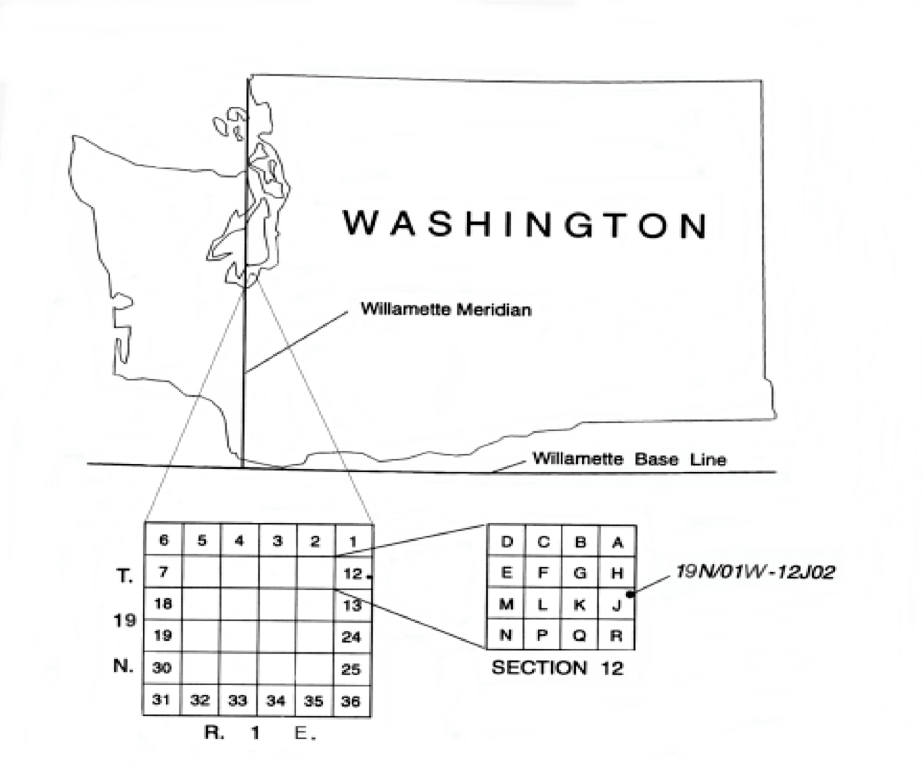


Figure 4. Site-numbering system in Washington.

Selection of Monitoring Sites

Ecology has records for 104 wells on Anderson Island, 82 of which have been drilled since Dion and Sumioka's (1984) seawater intrusion study. This is probably a conservative estimate of actual wells on the Island. Prior to 1972, Ecology did not require wells logs to be submitted.

Wells used for monitoring were selected based on several criteria, including:

1. completion depth,
2. surface elevation,
3. location (even spacing between monitoring wells was key to obtaining uniform aerial coverage of the Island),
4. availability of a well log, and
5. the owner's willingness to let their well be monitored.

Wells with intakes both above and below mean sea level were chosen.

In all, 45 monitoring wells, two springs with collector trenches (very shallow wells), and two additional springs were sampled and measured (Figure 5, Table 2).

Ground-Water Levels in Monitoring Wells

Water levels in wells were measured either with an electric tape (e-tape) or with a graduated steel tape coated with blue carpenter's chalk. The former is accurate to roughly 0.05-foot and the latter to about 0.01-foot.

Depth-to-water measurements were made in 44 of the 45 monitoring wells and the two springs with collector trenches (Appendix A, Tables A1&A2). One well was not measurable due to blockage by wires or pipes inside the well casing. Most of the 44 monitoring wells were measured at three-month intervals for a year (four total measurements). A few have only one or two measurements. A subset of 14 wells was intended to be measured monthly for a year (12 total measurements), but most were actually measured 10 times (data not collected in July and August).

Depth to water was converted to elevation above mean sea level (msl) by subtracting depth to water from the land-surface elevation at the *wellhead* (Appendix A, Tables A1&A2). Water-level elevations (heads) in the Vashon and Sea Level aquifers were plotted on maps (Figures16&17). *Potentiometric surface* maps were not created because there was not adequate data on all parts of the Island to accurately represent the ground-water surface.

Depth to water is listed to the nearest ±0.1 foot. Head also is listed to the nearest ±0.1 foot to preserve the *precision* (variability) of the measurements, but the *accuracy* is only ±7 feet. This is based on the accuracy of the land-surface elevations, determined using *Global Positioning System* (GPS) equipment as discussed later in this report under "Wellhead Elevations."

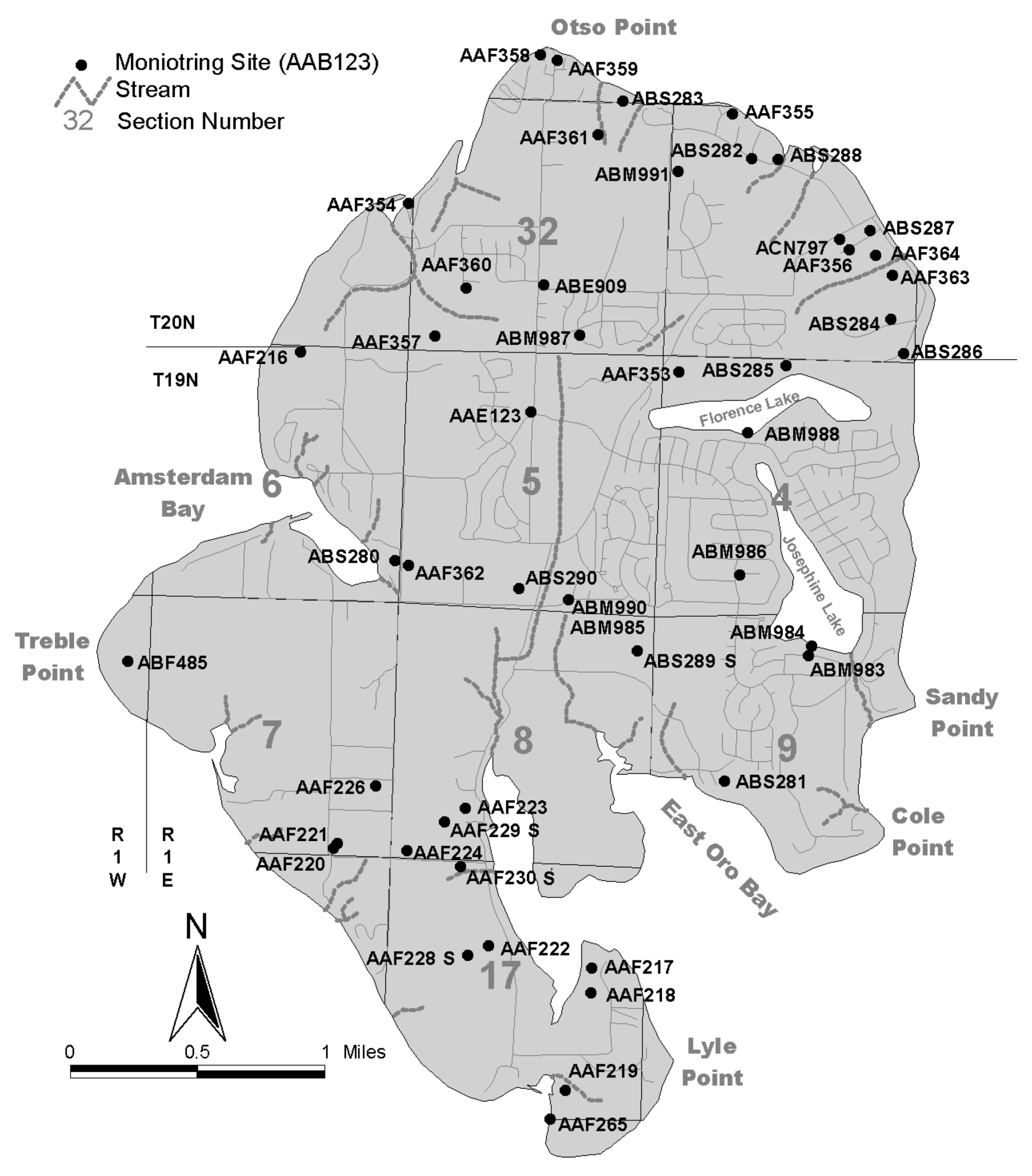


Figure 5. Monitoring well and spring locations.

Table 2. Monitoring wells and springs.

S = spring; * = collector trench (spring w/very shallow well); SL = Sea Level aquifer; V = Vashon aquifer; W = water level; N = nitrate; C = Chloride; W, N, & C include number of times measured/sampled

Unique Well ID	Well Location (township/range section, ¼¼ section)	Latitude	Longitude	Land Surface Elevation (feet msl)	Well Depth (feet)	Well Bottom Elevation (feet msl)	Source Aquifer	Measured/ Sampled For		
								W	N	C
AAE123	19N/01E-05C	47 10 00	122 42 19	136	255	-119	SL	2	0	1
AAF216	19N/01E-06B	47 10 10.6846	122 43 33.8207	173	218	-45	SL	14	1	4
AAF217	19N/01E-17H01	47 08 05.9930	122 42 00.1475	34	48	-14	SL	4	1	4
AAF218	19N/01E-17H02	47 08 02.2395	122 41 56.5025	44	39	5	SL	10	1	4
AAF219	19N/01E-17R01	47 07 43.3557	122 42 06.0308	33	46	-13	SL	4	1	4
AAF220	19N/01E-07R01	47 08 31	122 43 13	175	78	97	V	4	1	4
AAF221	19N/01E-07R02	47 08 29.8930	122 43 19.0513	172	60	112	V	10	1	4
AAF222	19N/01E-17F01	47 08 08.3521	122 42 29.3418	56	66	-10	SL	10	1	4
AAF223	19N/01E-08P	47 08 38.1351	122 42 40.0283	49	no log	-	?	0	1	2
AAF224	19N/01E-08N01	47 08 28.2827	122 42 58.6867	177	no log	-	V	4	1	4
AAF226	19N/01E-07M	47 08 43.6281	122 43 04.5749	159	69	90	V	4	1	4
AAF228S*	19N/01E-17F002	47 08 09	122 42 33	125	~16*	~109*	V	10	1	4
AAF229S	19N/01E-08N2	47 08 36	122 42 41	80	-	-	V	0	1	1
AAF230S	19N/01E-17C	47 08 27	122 42 36	90	-	-	V	0	1	1
AAF265	19N/01E-17R02	47 07 36.5548	122 42 09.9428	39	no log	-	?	0	1	2
AAF353	19N/01E-04D	47 10 05.5515	122 41 42.1923	255	116	139	V	10	0	5
AAF354	20N/01E-31H	47 10 42	122 42 57	60	155	-95	SL	0	1	4
AAF355	20N/01E-33D	47 11 00.8578	122 41 25.7864	35	57	-22	SL	1	1	1
AAF356	20N/01E-33K01	47 10 33.7304	122 40 49.1697	92	116	-24	SL	4	1	4
AAF357	20N/01E-32N01	47 10 14.8049	122 42 51.7059	183	69	114	V	4	1	3
AAF358	20N/01E-20P	47 11 11.9656	122 42 23.6223	42	60	-18	SL	10	1	4
AAF359	20N/01E-29Q	47 11 10.1001	122 42 17.8984	47	115	-68	SL	4	1	3
AAF360	20N/01E-32N02	47 10 58.9539	122 42 39.9609	179	40	139	V	4	1	5
AAF361	20N/01E-32B	47 10 58.9539	122 42 05.4422	133	147	-14	SL	10	0	1
AAF362	19N/01E-05N	47 09 28.5033	122 43 00.0448	96	116	-20	SL	10	1	4
AAF363	20N/01E-33J01	47 10 30	122 40 32	35	no log	-	SL	1	1	1
AAF364	20N/01E-33J02	47 10 32.7694	122 40 41.6701	50	75	-25	SL	4	1	4
ABE909	20N/01E-32K	47 10 26	122 42 16	228	97	131	V	10	1	3
ABF485	19N/01W-12H	47 09 07.0317	122 44 24.6151	180	196	-16	SL	8	1	3
ABM983	19N/01E-09B01	47 09 14	122 40 53	198	no log	-	SL	2	0	1
ABM984	19N/01E-09B02	47 09 13.0482	122 40 58.1542	193	222	-29	SL	1	0	2
ABM985	19N/01E-05Q01	47 09 20.9112	122 42 11.7799	111	139	-28	SL	2	0	6
ABM986	19N/01E-04P	47 09 24.2399	122 41 18.2003	254	270	-16	SL	2	0	4
ABM987	20N/01E-32Q	47 10 13.6545	122 42 09.4560	195	246	-51	SL	2	0	1
ABM988	19N/01E-04F	47 10 49.8083	122 41 18.0123	200	250	-50	SL	2	0	1
ABM990	19N/01E-05Q02	47 09 22	122 42 06	106	165	-54	SL	3	0	5
ABM991	20N/01E-33E	47 10 49.8083	122 41 41.7419	156	244	-88	SL	2	0	1
ABS280	19N/01E-06R	47 09 28.8633	122 43 02.6906	56	85	-29	SL	4	1	4
ABS281	19N/01E-19L	47 08 45.2035	122 41 13.3519	100	117	-17	SL	10	1	4
ABS282	20N/01E-33C01	47 10 52.4899	122 40 12.6709	34	39.5	-5	SL	4	1	4
ABS283	20N/01E-29R	47 11 02.9611	122 41 59.6528	97	96	-16	SL	4	1	3
ABS284	20N/01E-33R01	47 10 20.6918	122 40 36.7267	125	206	-81	SL	4	1	4
ABS285	19N/01E-04C	47 10 11	122 41 03	210	228	-18	SL	2	1	2
ABS286	20N/01E-33R02	47 10 11.7439	122 40 36.7267	181	no log	-	SL	1	1	1
ABS287	20N/01E-33H	47 10 37.7609	122 40 44.1281	49	83	-34	SL	10	1	4
ABS288	20N/01E-33C02	47 10 51.8533	122 41 20.2857	65	86	-21	SL	4	1	4
ABS289S*	19N/01E-08A	47 09 12	122 41 45	170	~6*	164*	V	1	1	1
ABS290	19N/01E-05P	47 09 23.8433	122 42 25.3088	72	94	-22	SL	10	1	2
ACN797	20N/01E-33K02	47 10 38.3119	122 40 48.8671	60	146	-66	SL	1	0	5

Tidal Influence in Monitoring Wells

Three wells were continuously monitored for a period of 24 or more hours each. This interval was chosen to encompass at least one tidal cycle.

Two wells in the Sea Level aquifer were monitored for tidal influence. One well in the Vashon aquifer was monitored as a control well, since no tidal influence was expected. An In-Situ Inc. miniTROLL[*] vented transducer/datalogger was used in all wells. Water levels were measured at five-minute intervals.

Streamflows

Discharge was either measured or estimated in selected streams on the Island. Discharge was measured in three streams using three different methods. A Cutthroat *flume* was used in stream 582. A top setting *wading rod* and Swoffer propeller-driven *current meter* combination was used in stream 570 (Schoolhouse Creek). In stream 569, a 4.5-gallon bucket and stopwatch were used under the culvert at East Oro Bay Road to measure discharge. Discharge was estimated visually in streams 560, 562, 563, 577, and 578.

Wellhead Elevations

Accurate knowledge of ground-water elevations (head) is necessary for determining the extent of seawater intrusion. In this study, initial estimates of freshwater heads in the Sea Level aquifer were made using (1) measured ground-water levels and (2) wellhead elevations estimated from topographic maps (McNeil and Nisqually 7.5 minute quadrangles). This method yielded some freshwater heads of 20 feet or more below mean sea level, which are not seen under natural conditions in the Puget Lowland. Diminished heads do occur in areas where large volumes of water have been pumped from the ground. There are no large withdrawals are occurring on the Island, let alone in any of the measured wells.

Accurately locating a well can be difficult. When using a *topographic map*, the horizontal position of a well can be difficult to determine if reference points such as road intersections are not near the well. The horizontal location can be off by 100 feet or more. This can lead to errors in accurately determining wellhead elevations, especially in areas of steep terrain. Use of topographic maps introduce additional room for error. The topographic maps for Anderson Island have elevation *contour intervals* of 20 feet. *Contour lines* themselves can be inaccurately positioned.

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[*] Mention of commercial products is for descriptive purposes only and does not imply endorsement.

Traditional surveying methods using tripod-mounted levels or *Theodolites* would have been the most accurate way to determine wellhead elevations on Anderson Island. However, these methods were deemed too costly and time-consuming for this study. Instead, wellhead elevations were surveyed using Global Positioning System (GPS) equipment. Use of GPS has become common for navigational, tracking, and mapping purposes. Navigational units costing only a few hundred dollars yield reasonably accurate horizontal locations, but not elevations. A more accurate, mapping-grade unit (Trimble Pro XRS with tripod-mounted antenna and TSC1 datalogger) was used for this study. Signals from a minimum of five satellites were recorded for a period of at least 10 minutes. Wellhead locations and elevations were then calculated using digital post-processing methods, including base station corrections. The specified horizontal accuracy of the equipment is ±1 meter (±3.28 feet) or less. The specified vertical accuracy is double that. Measurements made at a benchmark of known elevation (accuracy of ±0.01 foot) were within this range. Therefore, it is assumed that wellhead elevations and resulting freshwater heads derived from GPS are accurate to ±7 feet. The results of these elevation measurements are presented in Table 2.

Water-Quality Methods

Sampling protocols followed the quality assurance plan (Garrigues, 1997). Water was taken from hose bibs as close to the well or *spring* as possible. Samples were also taken upstream from any water-treatment apparatus. Water was run into a bucket of known volume until both temperature and *specific conductance* were stable. The approximate volume of water discharged prior to sample collection was recorded. Ten to 20 gallons were typically discharged. Water samples were kept cool in ice chests and delivered to Ecology's Manchester Laboratory within three days following sampling.

Specific conductance and *pH* were measured in the field with a meter immediately following sample collection. Expected accuracy was about 20 micromhos (µmho) per centimeter (cm) and 0.2 pH units, respectively.

Approximate concentrations of *nitrate* were determined in the field using a cadmium reduction/color disc (Hach Test Kit NI-14). Range and accuracy were 0-10 mg/L and 0.2 mg/L, respectively. The maximum acceptable concentration for nitrate in ground water in Washington State is 10 mg/L. Since no values above 1 mg/L were identified by field tests, more accurate laboratory analyses were deemed unnecessary.

During the first round of sampling in June 1997, *chloride* concentrations were determined in the field using silver nitrate titration (Hach Test Kit 8-P). Range and accuracy were 5-100 mg/L and 5 mg/L, respectively. Test-kit values were used to choose which samples to submit for more accurate laboratory analyses. During the second, third, and fourth rounds of sampling, samples were sent directly to the laboratory for analyses without field screening. Samples were analyzed for chloride using EPA method 300 (ion chromatography). Funding for laboratory analyses limited the number of samples that could be analyzed during the study.

When both field and laboratory results were available during data analyses, laboratory results were used because they are more accurate.

Principal Physical Influences on Ground Water

Important parameters of ground water include (1) the amount of water stored in the ground, (2) the pattern of flow, (3) the flow velocity or discharge volume, and (4) water quality (including chemical composition and temperature). These parameters depend on climate, *topography*, and geology.

Climate

Precipitation, air temperature, and *evapotranspiration* are the primary components of climate that affect ground water (Toth, 1970). Of these components, precipitation is the most influential and easily measured. Ground water on Anderson Island is derived entirely from infiltration of precipitation. The average annual precipitation on Anderson Island is approximately 42.5 inches per year (Figure 6; Miller, et al., 1973). This equates to somewhere between 17,000 and 19,000 *acre-feet*/year. On a continuous basis, this equals between 23.5 and 26.4 cubic feet per second (cfs); 10,500 and 11,900 gallons per minute (gpm); or 15.1 and 17.0 million gallons per day (mgd).

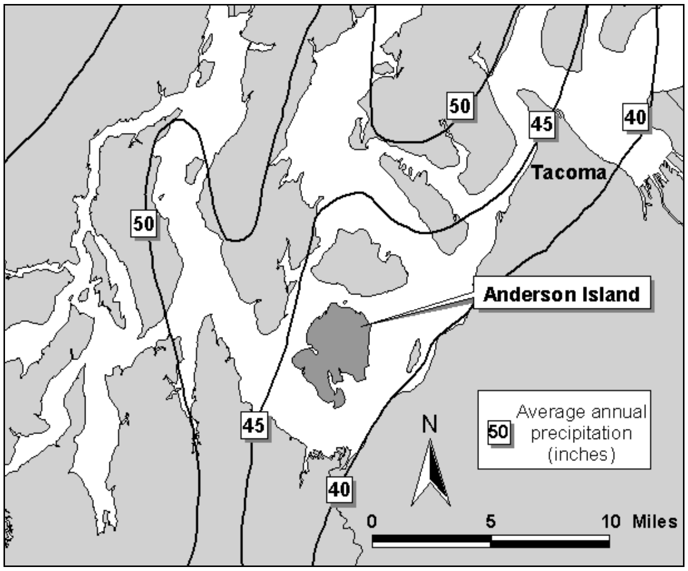


Figure 6. Average annual precipitation in Anderson Island vicinity (data from Miller, et al. 1973).

The monthly distribution of precipitation and evapotranspiration is highly variable. This variability is best examined from the perspective of a *water year* (October 1 through September 30). In the fall, rain replenishes soil moisture and stream flows. By late October, the *soil-moisture deficit* is normally satisfied and *ground-water recharge* commences. Ground-water recharge continues through the winter months. After March, evapotranspiration increases dramatically due to the rapid growth of vegetation. By late May, average evapotranspiration exceeds average precipitation and ground-water recharge decreases sharply. Eventually, a soil-moisture deficit develops. The deficit increases through the summer months, then tapers off through September. The variability in ground-water recharge is reflected in water levels in wells on Anderson Island. Water levels tend to be higher in the winter months and lower in the summer months.

Garling, et al. (1965) estimated the soil-water budget for the Grapeview, Washington area, as part of a study of the water resources on the Kitsap Peninsula and adjacent islands, including Anderson Island (Figure 7). On an annual basis, it was estimated that evapotranspiration equaled 33 percent of precipitation, leaving a water surplus of 67 percent. In other words, approximately one third of the water returns to the atmosphere and two thirds becomes runoff or ground-water recharge. Berris (1995) estimated an average of 32 percent evapotranspiration and 46 percent ground-water recharge for three watersheds in nearby Thurston County. Vaccaro, et al. (1998) estimated an average 31 percent evapotranspiration and 45 percent ground-water recharge for two parts of the nearby lower Puyallup River valley, Pierce County. Although these areas are similar in proximity and topography, it was assumed that ground-water recharge on Anderson Island is probably less – closer to 40 percent - due to the greater proportion of low permeability till at the surface. Assuming 42.5 inches of precipitation per year (Miller, et al. 1973), average ground-water recharge would be approximately 17 inches per year. This is only a rough estimate since no measurements were taken. However, it is similar to the average annual regression-based recharge estimate for Anderson Island made by Vaccaro, et al. (1998).

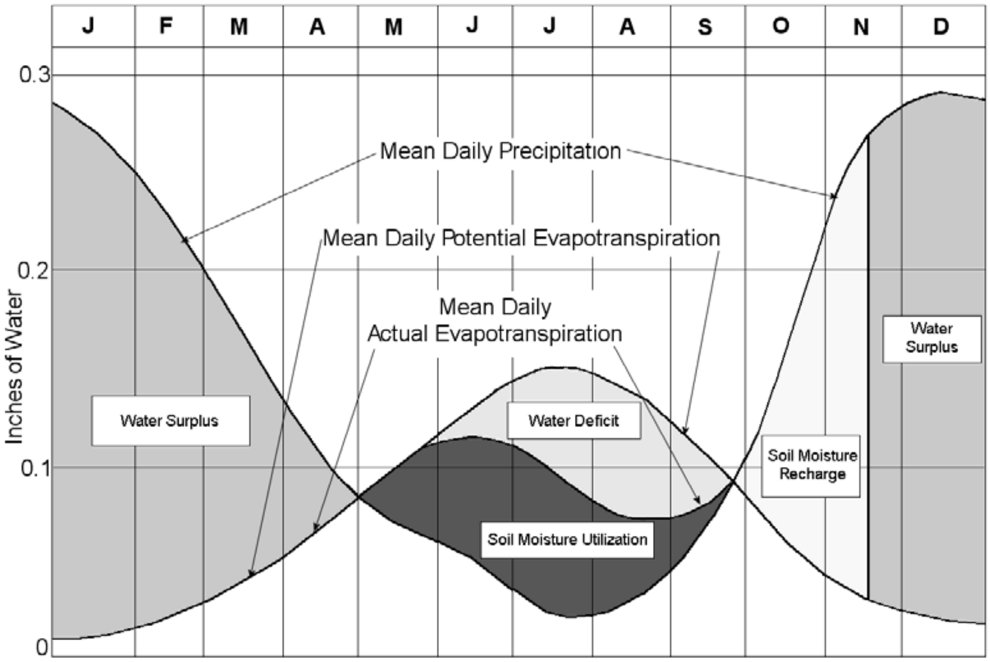


Figure 7. Mean annual soil-water budget at Grapeview, Washington (root-zone water-holding capacity 10 inches) (modified from Garling, et al., 1965).

Topography

Topography refers to the general configuration of the land surface, including surface relief. Toth (1970) and others have demonstrated that the shape of the *water table* typically approximates the surface topography, such that the *hydraulic head* of the water table tends to be higher under hills and lower under valleys. Gravity provides the driving force for ground-water flow. Water flows in the direction of lower *hydraulic head*, along the *hydraulic gradient*. Hence, topography is a controlling factor in the movement of ground water. In *recharge zones* flow is predominantly downward. In *discharge zones* flow is predominantly upward.

The approximate shape of the water table on Anderson Island can be visualized by looking at a shaded relief map of the Island (Figure 2). Toward the center of the Island, precipitation that infiltrates into the ground at higher elevations tends to flow downward and outward toward the nearest creek, wetland, or lake. The central portion of the Island is a primary *recharge zone*. Some precipitation will percolate more deeply, recharging the deeper aquifers and eventually discharging to Puget Sound near the perimeter of the Island. Along the margins of the Island, shallower ground water tends to flow toward streams or springs and seeps, eventually discharging to Puget Sound. The margins of the Island are the primary *discharge zones*.

Geology and Hydrogeology

Geology is defined by the physical and chemical properties and distribution of local rocks, as well as prevailing *tectonic* conditions (Toth, 1970). Geology influences the flow paths of ground water because water will flow more readily through materials of higher *permeability* for a given hydraulic gradient. For example, gravel and sand mixtures have much higher permeability than silt and clay mixtures. Therefore, water will flow more easily through the former than the latter.

Surficial geologic maps depict the geology closest to the surface. They do not include overlying soils, which are discussed below. Geologic units are mapped from exposures in surface outcrops and surface cuts (either man made, like excavations, or natural, like bluffs) and from interpretation of well driller's logs. Cross sections often accompany geologic maps. They depict a thin slice of subsurface geology. Cross sections are based on projections of surface geology, information from surface cuts, and interpretation of well driller's logs.

The geology of Anderson Island has been mapped by Garling, et al. (1965), the Washington State Department of Ecology (1979), Walsh (1987), Walsh, et al. (1987), and Logan, et al. (2001). The geology is difficult to map due to the flat, wooded terrain over much of the interior of the Island. Outcrops are rare. Additionally, the geology of steeper slopes along creeks is often covered by *colluvium* and vegetation.

The geologic units that make up the Island resulted in large part from the dramatic processes occurring around and beneath glaciers. At least six times during the past two million years (Figure 8; Troost, 1999), a lobe of the massive Cordilleran ice sheet moved south from British Columbia and filled the Puget Lowland (Figure 9). The sediments deposited during each glacial advance were subsequently modified by stream erosion and mass wasting. Non-glacial deposits

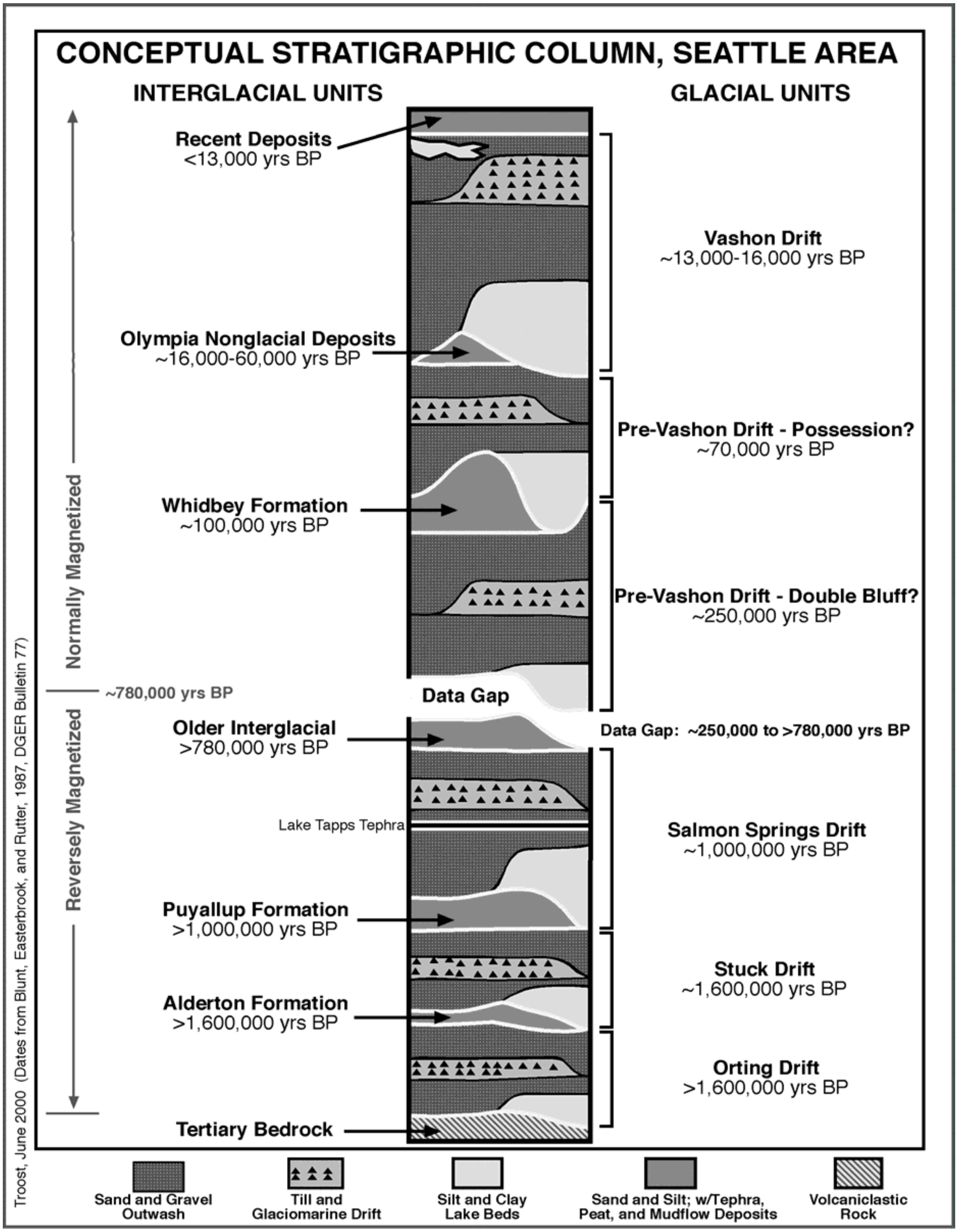


Figure 8. Conceptual Quaternary stratigraphic column for the Puget Lowland (from Troost, 1999). The uppermost units – Vashon Drift, Olympia Nonglacial, and Pre-Vashon Drift (Possession?) – are the most important with respect to the hydrogeology of Anderson Island.

were formed during *interglacial* periods, each of which lasted thousands of years under climates similar to the present. The last two glacial advances and intervening interglacial period were the most important episodes in the creation of Anderson Island (Figure 8). They occurred during the Quaternary Period of geologic time, which represents the period from 1.8 million years ago to present. This is relatively youthful, considering that geologic time extends back 4,500 million years (Table 3).

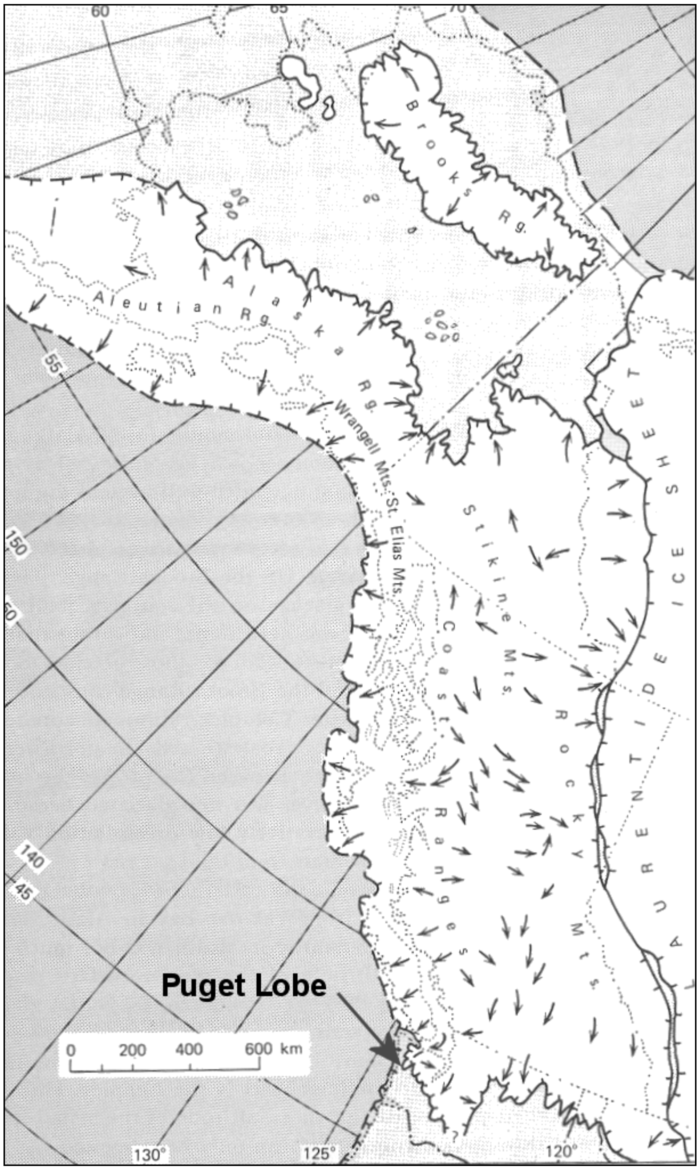


Figure 9. Extent of the massive Cordilleran ice sheet (modified from Flint, 1971).

The most recent glacial advance, the Vashon *Stade* of the Fraser glaciation, occurred between 13,000 and 16,000 years ago (Figure 8). This event sculpted the current topography of Anderson Island. During this period, the Puget lobe of the Cordilleran ice sheet moved south out of British Columbia into the Puget Sound basin, creating the Vashon glacier (Figures 9&10). The rate of advance has been estimated at roughly 100 meters per year (Booth and Goldstein, 1994). At its maximum extent, the Vashon glacier extended southward into modern-day Thurston County and was up to 2,000 feet thick in the vicinity of Anderson Island (Blunt, et al, 1987). Sediments deposited by the Vashon glacier are collectively referred to Vashon *Drift*. As the Vashon glacier advanced southward, meltwater streams emanating from the front of the glacier deposited well-sorted sand and gravel interspersed with lacustrine clay, silt, and sand (Logan, et al., 2001). These deposits are known as the Vashon advance outwash (map symbol Qga, meaning “Quaternary glacial advance outwash”). On Anderson Island, these deposits are exposed at the head of the Josephine Lake outlet channel (Figure 11; Logan. et al., 2001) and in gravel pits. This unit forms the uppermost aquifer on Anderson Island, herein called the Vashon aquifer. From well logs, this unit appears to be absent on the Lyle Point peninsula. Elsewhere, it averages roughly 30 feet in thickness but is 80+ feet thick in the north-central part of the

Island. The base of this unit ranges from 60+ feet above sea level to just a few feet below sea level in the Otso Point area. The aquifer is *semi-confined* to *unconfined* due to the somewhat discontinuous nature of the overlying *till*. Of 45 monitoring wells in this study, nine tap the Vashon aquifer, as do all four springs.

Table 3. Geologic time scale (data from U.S. Geological Survey, 1999).

y = years; my = million years

	Era	Period	Epoch
Phanerozoic Eon 544 my-present	**Cenozoic** 65 my-present	**Quaternary** - 1.8 my-present	**Holocene** – 8000 y-present
			Pleistocene – 1.8 my-8000 y
		Tertiary - 65-1.8 my	**Pliocene** – 5.3-1.8 my
			Miocene – 23.8-5.3 my
			Oligocene – 33.7-23.8 my
			Eocene – 55.5-33.7 my
			Paleocene – 56-55.5 my
	Mesozoic 248-65 my	**Cretaceous** - 145-65 my	
		Jurassic - 213-145 my	
		Triassic – 248-213 my	
	Paleozoic 544-248 my	**Permian** – 286-248 my	
		Pennsylvanian – 325-286 my	
		Mississippian – 360-325 my	
		Devonian – 440-360 my	
		Ordovician – 505-440 my	
		Cambrian – 544-505 my	
Precambrian Time 4500-544 my	**Proterozoic** 2500-544 my	**Vendian** – 650-544 my	
	Archean 3800-2500 my		
	Hadean Time 4500-3800 my		

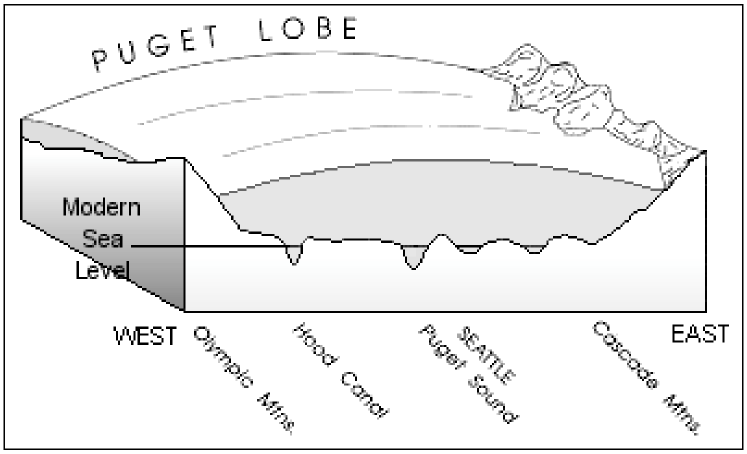


Figure 10. Conceptual drawing depicting the massive nature of the ice that covered the Puget Lowland (modified from Calvin, W.H., 2000).

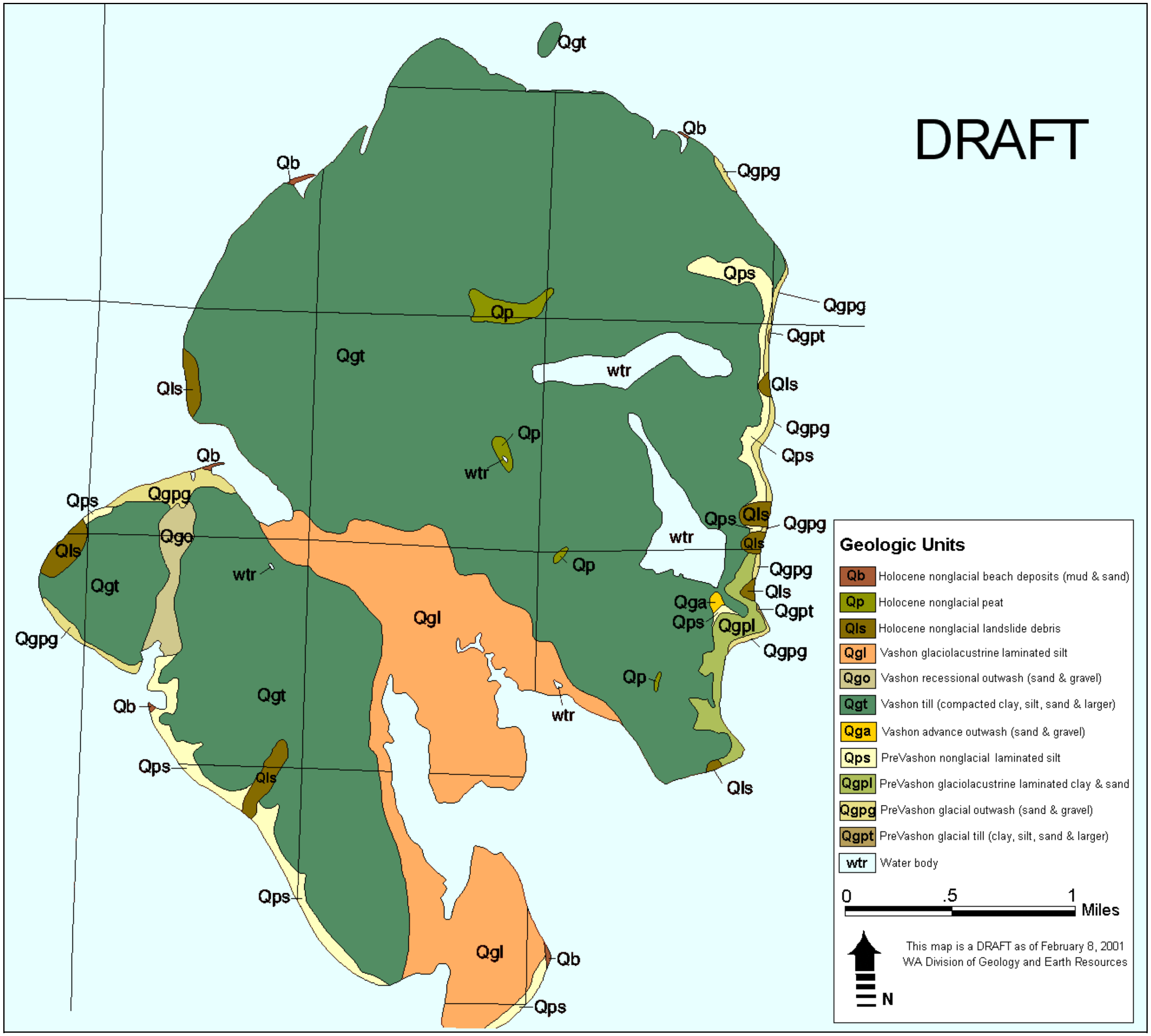


Figure 11. Surficial geology of Anderson Island (modified from Logan, et al., 2001).

As the Vashon glacier continued to move southward, it overrode and eroded parts of the Vashon advance outwash, as well as some of the older sediments. It subsequently deposited a layer of *till* beneath the ice (Figure 12A). Vashon till is a highly compacted, low permeability, poorly sorted mixture of sand and gravel in a silt and clay matrix with occasional cobbles and boulders. Commonly referred to as "hardpan" in well driller's logs, Vashon till caps most of Anderson Island (Figure 11; Qgt). The till does not create a very effective aquitard due to its somewhat discontinuous nature. Well logs indicate that this unit averages around 30 feet thick in most areas. However, it can be missing in upland areas and more than 30 feet thick along coastal bluffs (Logan, et al., 2001). It appears to be absent on the Lyle Point peninsula.

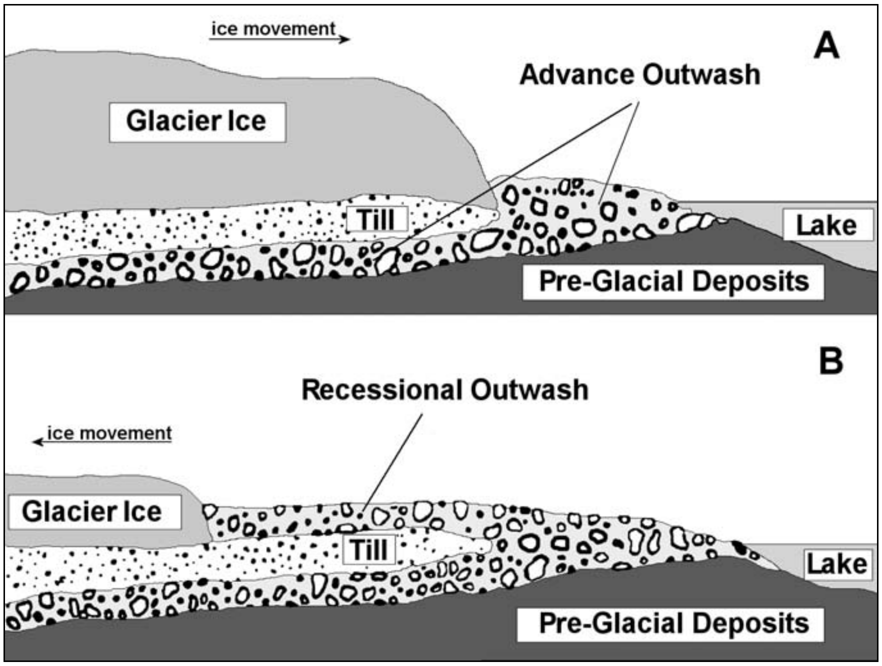


Figure 12. How various types of glacial sediments are deposited, including advance outwash and till (A) and recessional outwash (B) (modified from Brown and Caldwell, 1985).

Roughly 14,500 years ago, the climate started to warm and the Vashon glacier began thinning and retreating northward. As the glacier retreated, Vashon recessional outwash was deposited by massive amounts of meltwater and sediment pouring from the glacier (Figure 12B). These deposits are stratified, poorly to moderately sorted sand and gravel with some silt and clay. Vashon recessional outwash is absent on most of Anderson Island, expect in the low area between Amsterdam Bay and Carlson Bay near Treble Point (Figure 11; Qgo; Logan, et al., 2001). During the retreat, deep *proglacial lakes* also formed at the southern end of the retreating glacier (Figure 12). Laminated silts – evidence of proglacial *lacustrine* deposits - are found on Lyle Point peninsula and in the low area between Amsterdam Bay and Oro Bay (Figure 11; Qgl; Logan et al., 2001).

Underlying the Vashon Drift are older silts and clays, interbedded with sand and gravel. They were deposited during the Olympia *interglacial* period, between 16,000 and 60,000 years ago (Figure 8). The depositional processes occurring during that time were similar to those occurring today. Garling, et al. (1965) identified this unit as the Kitsap Formation. It might correlate to the Discovery Formation of Noble (1990). Troost (1999) refers to this unit as the Olympia Nonglacial (Figure 8). In most areas of southern Puget Sound, this unit forms a discontinuous aquitard. It was eroded in places by the Vashon glacier.

On much of Anderson Island, the base of this unit is near sea level. It is exposed in coastal bluffs, stream cuts, and has tentatively been identified in well logs. This unit is seen in the cliffs along the shore of Anderson Island (Figure 11; Qps; Logan, et al., 2001). In this report, the geologic unit will be called the Olympia silt and the corresponding hydrogeologic unit will be called the Olympia aquitard.

Prior to the Olympia Nonglacial period, a glacial advance occurred around 70,000 years ago. These deposits have been tentatively correlated to the Possession Drift (Figure 8; Troost, 1999), which is prominent in the northern part of Puget Sound. The uppermost part of this pre-Vashon glacial unit is laminated glaciolacustrine clay intermixed with some sand. This is prominent in the bluffs between Sandy Point and Cole Point (Figure 11; Qgpl; Logan, et al., 2001). In this report, this unit is also considered part of the Olympia aquitard. Analyses of well logs indicate that the thickness of the Olympia aquitard is highly variable – from 3 feet in the Otso Point area to an average of 40 feet in other areas.

Below the glaciolacustrine sediments lies a pre-Vashon glacial outwash deposit composed primarily of sand and gravel (Logan, et al., 2001). This unit is important to the hydrogeology of Anderson Island because it forms what shall herein be called the Sea Level aquifer. This unit is exposed near the base of the bluffs on the eastern side of Anderson Island and on the western side between Carlson and Amsterdam Bays (Figure 11; Qgpg). The top of the Sea Level aquifer is near sea level on most parts of the Island, whereas the base is well below sea level. Most wells on Anderson Island tap this aquifer, but very few penetrate the entire thickness. A survey of deep well logs indicates that this unit is up to 67+ feet thick, with an average thickness of about 50 feet. This unit is probably a *confined aquifer.*

Below the Sea Level aquifer lies a pre-Vashon till unit composed of compacted clay silt, sand, gavel, cobbles, and boulders (Logan, et al., 2001). This unit is exposed in only one place on the Island – on the northeast side of Sandy Point (Figure 11; Qgpt).

Soils

Zulauf (1979) mapped and described soils on Anderson Island. The Island soils retain much of the texture and hydraulic properties of the underlying geologic materials. Most of the surficial materials, except those which crop out on the lower parts of the sea bluffs, were deposited within the last 15,000 years. They have been weathered for less than 14,000 years, since the Vashon glacier retreated from the south Puget Lowland (Jones, 1999).

Soils of the Harstine Soil Association cover the Island. The Harstine Soil Association is found on nearly level to rolling uplands, mostly as moderately well-drained soils that formed in sandy glacial till on uplands. A weakly cemented layer of lower permeability occurs at a depth of 2 to 3 feet below ground surface. Predominant soils in this layer include the Harstine gravelly sandy loam, Bow silt loam, and Kitsap silt loam. Little surface runoff occurs on the Island because the soils have infiltration capacities high enough to accept the usually gentle Puget Sound rains, even if the forest *duff* has been removed.

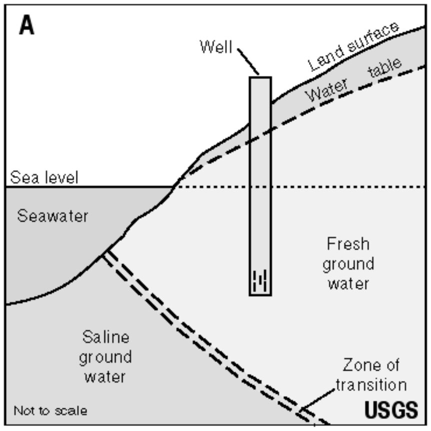
Mechanisms of Seawater Intrusion

Seawater intrusion is a water-supply concern on Anderson Island. Coastal aquifers, such as the Sea Level aquifer, are hydraulically connected to the adjacent marine water body. Consequently, they contain both fresh and saline (salty) ground water. Fresh ground water normally flows seaward within coastal aquifers, eventually intercepting saline ground water. The lighter, freshwater (1 gram per cubic centimeter - g/cm^3) tends to override and "float" on the denser, saline water (1.025 g/cm^3), but mixing also occurs. This mixing zone is known by several names, including the "freshwater-seawater interface," the "zone of transition," and the "zone of diffusion" (Figure 13A). The zone of diffusion is typically located near the marine shoreline. The exact location depends on several conditions, including the volume of freshwater discharge and the nature of the aquifer (confined or unconfined). In a typical coastal aquifer, the zone of diffusion dips down beneath the land surface (Figure 13A). In the case of an island or peninsula, the zone of diffusion can extend beneath the entire land surface (Figure 14).

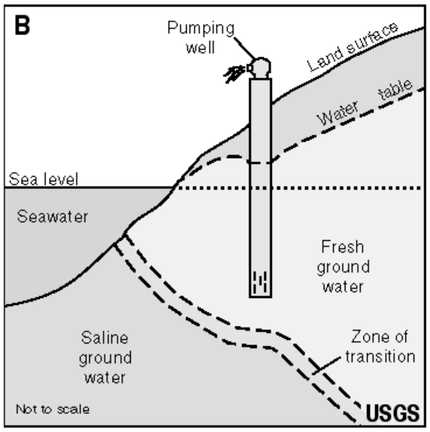
As with most aquifers, coastal aquifers are recharged primarily by precipitation. Under natural conditions, aquifer recharge is in equilibrium with ground-water discharge. Consequently, the zone of diffusion maintains a position of relative stability, moving slightly landward or seaward in response to varying climatic and tidal conditions (Figure 14). When ground water is pumped from coastal aquifers, freshwater that would normally discharge to the sea is intercepted, disrupting the natural equilibrium. This causes the zone of diffusion to migrate landward and/or locally upward. Ground water drawn into pumping wells can become increasingly saline (Figure 13B&C). Over time, the water can become unfit for consumption. This is especially true for wells located near the shoreline, on islands, and/or on peninsulas.

The distance that the freshwater lens extends above sea level is an approximate indication of how deep it extends below sea level. For each foot a freshwater lens extends above sea level, it theoretically extends 40 feet below sea level (Figure 15). This is called the Ghyben-Herzberg relation after the two European scientists who discovered it a century ago. It occurs because freshwater is less dense than seawater. For example, if freshwater occurs 10 feet above sea level, it theoretically extends 400 feet below sea level. This assumes the hydrologic system is at equilibrium, which is rarely the case. In actuality, freshwater can extend anywhere between 25 and 50 feet below sea level for every foot it extends above sea level.

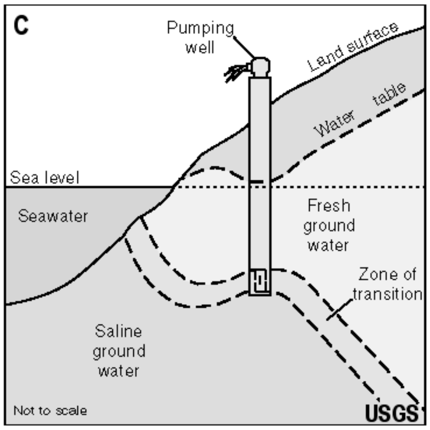
Seawater intrusion on Anderson Island is discussed in this report under "Water Quality."



Nonpumping well in an unconfined (water-table) aquifer under conditions of equilibrium--no intrusion has occurred.



Well pumping from an unconfined (water-table) aquifer--seawater intrusion not affecting salinity of pumped water.



Well pumping from an unconfined aquifer--seawater intrusion affecting salinity of pumped water.

Figure 13. Conceptual diagram showing how seawater intrusion can occur due to pumping of wells (from Orr, 2000).

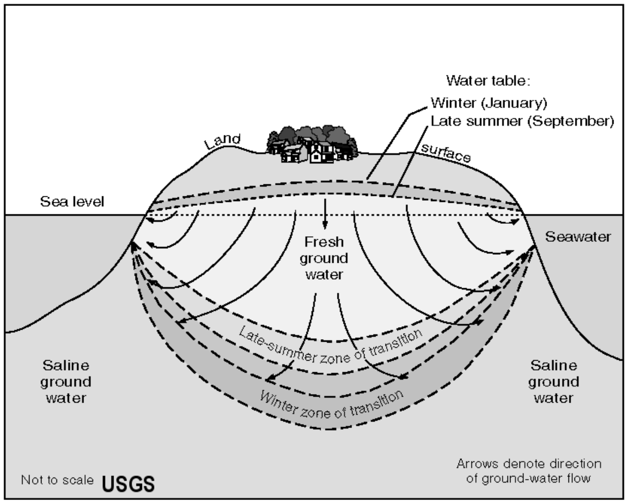


Figure 14. Conceptual diagram showing the relationship between fresh and saline ground water in a homogenous unconfined island aquifer. Fresh ground water flows both outward and upward while the zone of diffusion shifts seasonally (from Orr, 2000).

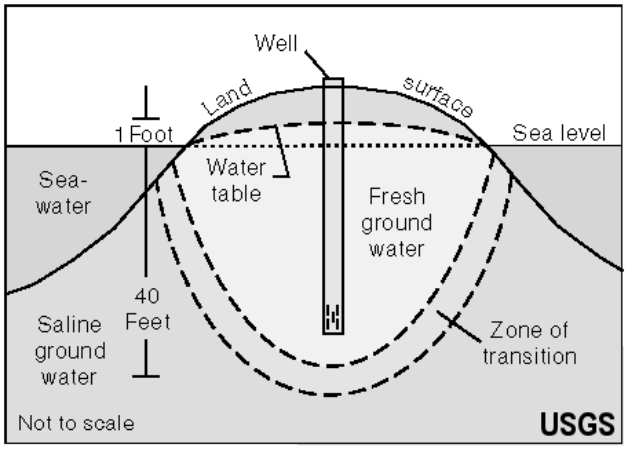


Figure 15. Conceptual diagram showing the Ghyben-Herzberg relation – that fresh ground water theoretically extends 40 feet below sea level for every foot it extends above sea level (from Orr, 2000).

Water Quantity

Ground Water

Heads

Ground-water elevation (head) data are presented in Appendix A. Heads in the Vashon aquifer are much higher than in the Sea Level aquifer. The mean head in the Vashon aquifer is 143.5 feet above mean sea level (msl), while the mean head in the Sea Level aquifer is 7.6 feet above msl.

Heads in the Vashon aquifer ranged between 117.8 and 197.7 feet above msl. Interestingly, these heads correspond with wells having the lowest (AAF226) and highest (AAF353) wellheads and well intake elevations in the Vashon aquifer. This emphasizes the relationship between land-surface elevation and heads in the Vashon aquifer. Head patterns tend to be a subdued reflection of topography.

Heads in the Sea Level aquifer ranged between 26.8 feet above msl (ABM985) and 9.7 feet below msl (ACN797). Higher heads tend to occur inland.

The head data were not sufficient to allow construction of *potentiometric surface* maps for either aquifer. However, heads were plotted on surface maps for both the Vashon (Figure 16) and Sea Level (Figure 17) aquifers. The fact that heads in the Vashon aquifer are much higher than in the Sea Level aquifer indicates that there is a strong downward *hydraulic gradient* with respect to ground-water flow.

Hydrographs were developed for wells that were measured monthly – four in the Vashon aquifer (Figure 18) and 10 in the Sea Level aquifer (Figure 19). Vashon aquifer wells show seasonal fluctuation, with the lowest water levels occurring in the fall and early winter and the highest occurring in the late winter and spring due to recharge from precipitation. For wells completed in the Sea Level aquifer, the pattern is not as clear, although it is similar to that in the Vashon aquifer. Distortion of the pattern could be due to tidal influence in these wells (discussed below).

Seasonal variation of heads range from less than 1 foot to approximately 9 feet.

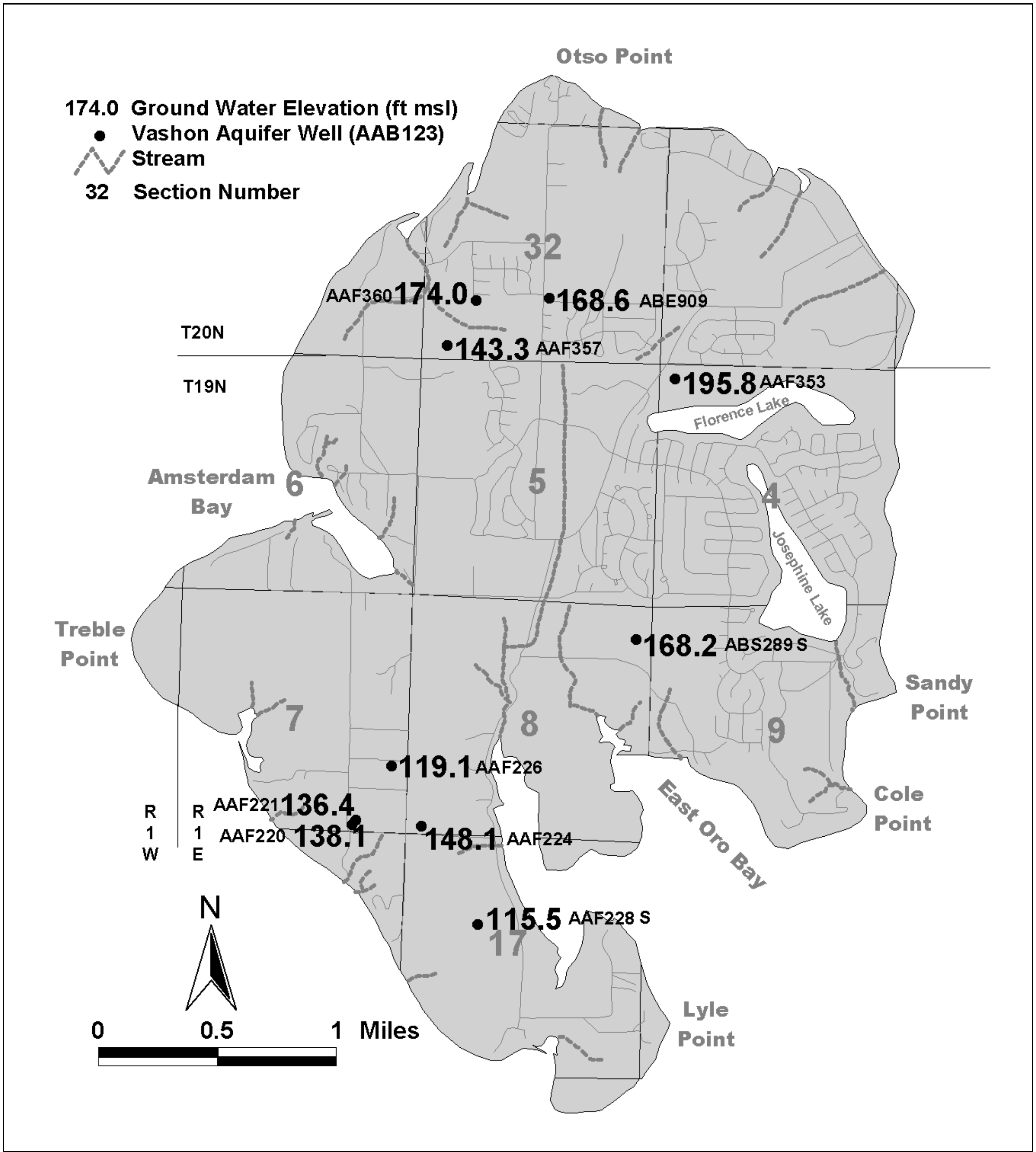


Figure 16. Ground-water heads in the Vashon aquifer, in feet relative to mean sea level. All measurements from 09/97.

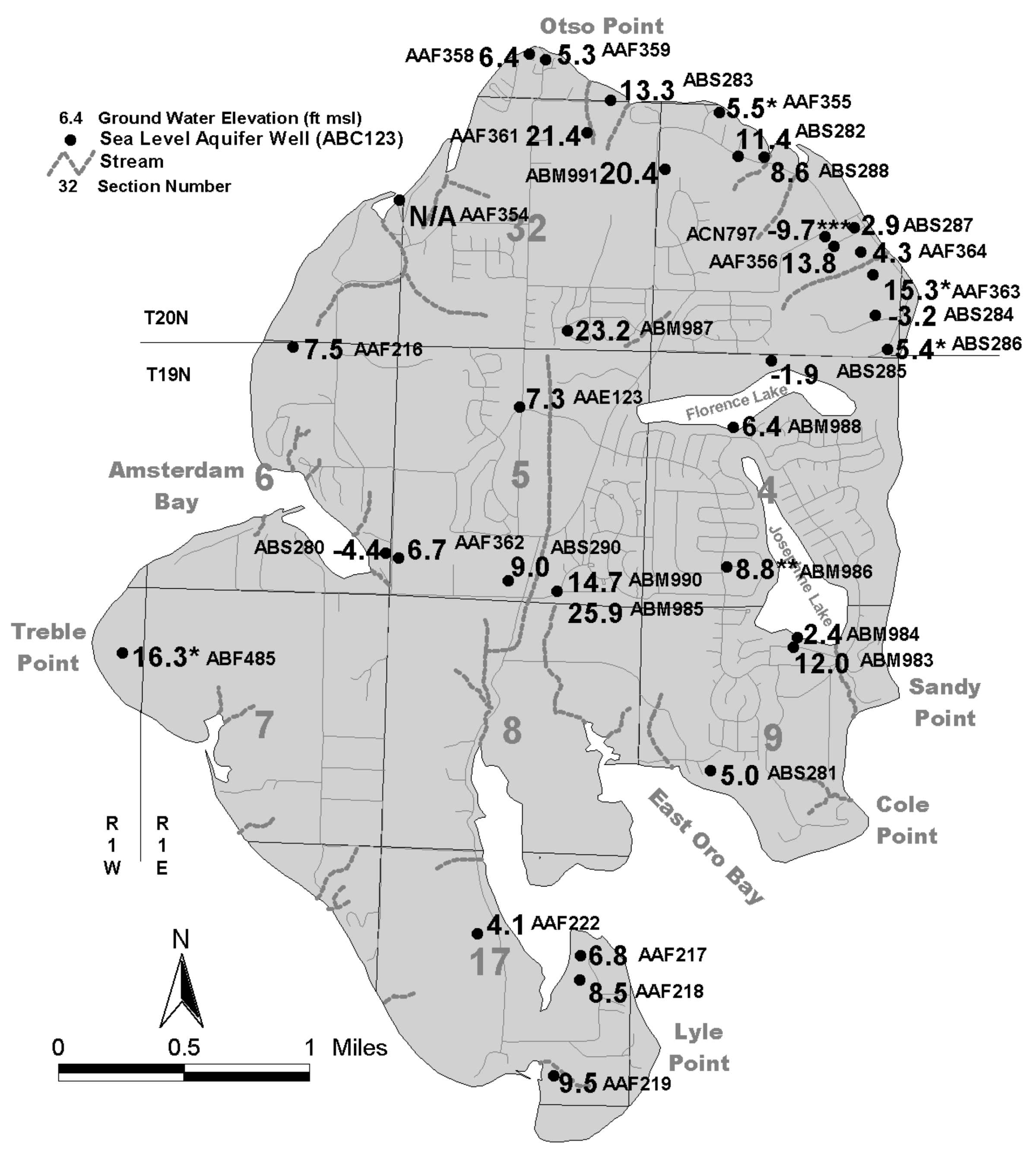


Figure 17. Ground-water heads in the Sea Level aquifer, in feet relative to mean sea level. All measurements from 09/97, with the following exceptions: * 06/97, ** 12/97, *** 03/98.

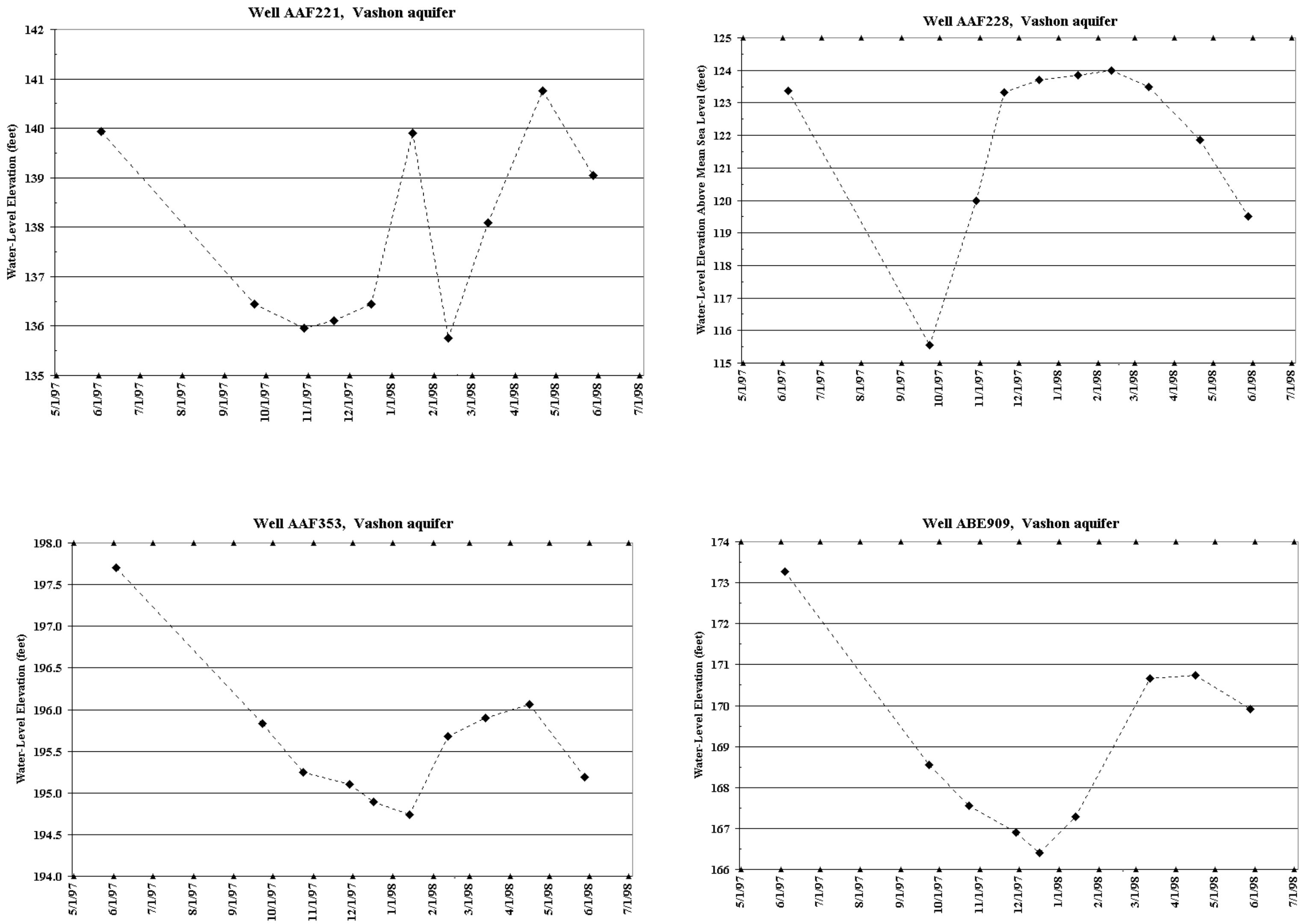
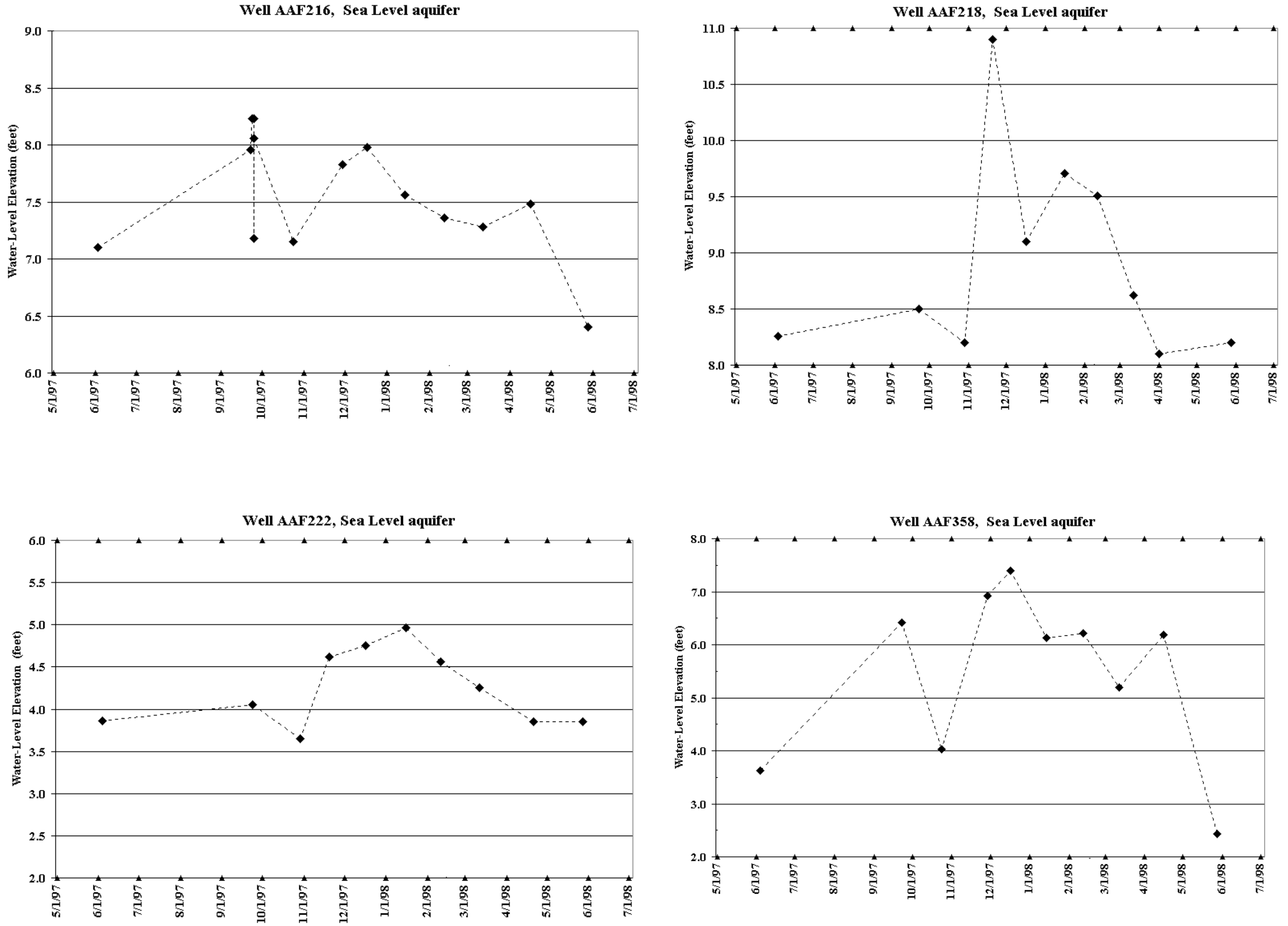


Figure 18. Hydrographs for selected Vashon aquifer monitoring wells (05/97 through 07/98).



Well AAF216, Sea Level aquifer

Well AAF218, Sea Level aquifer

Well AAF222, Sea Level aquifer

Well AAF358, Sea Level aquifer

Figure 19. Hydrographs for selected Sea Level aquifer monitoring wells (05/97 through 07/98).

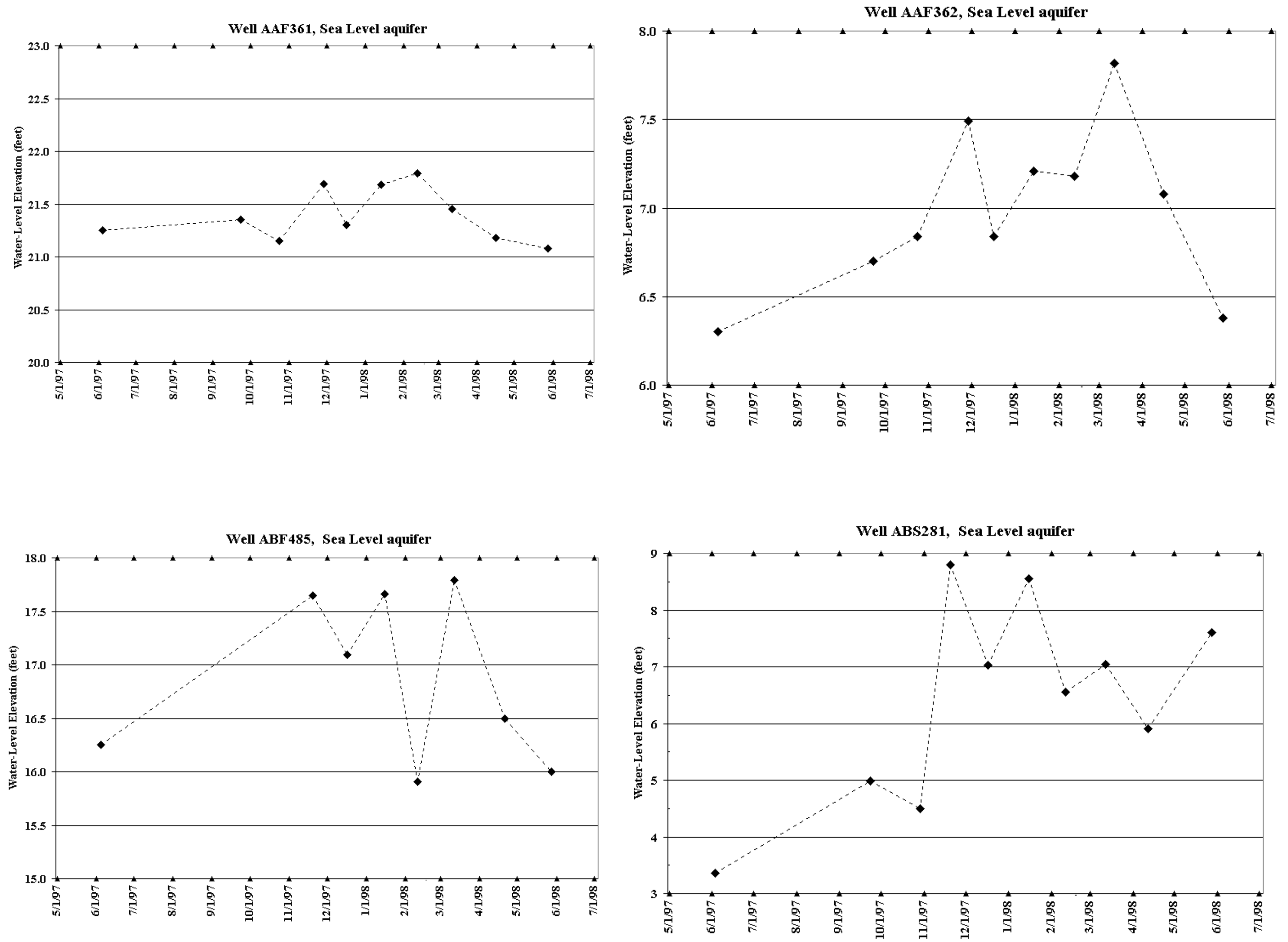


Figure 19. (continued) Hydrographs for selected Sea Level aquifer monitoring wells (05/97 through 07/98).

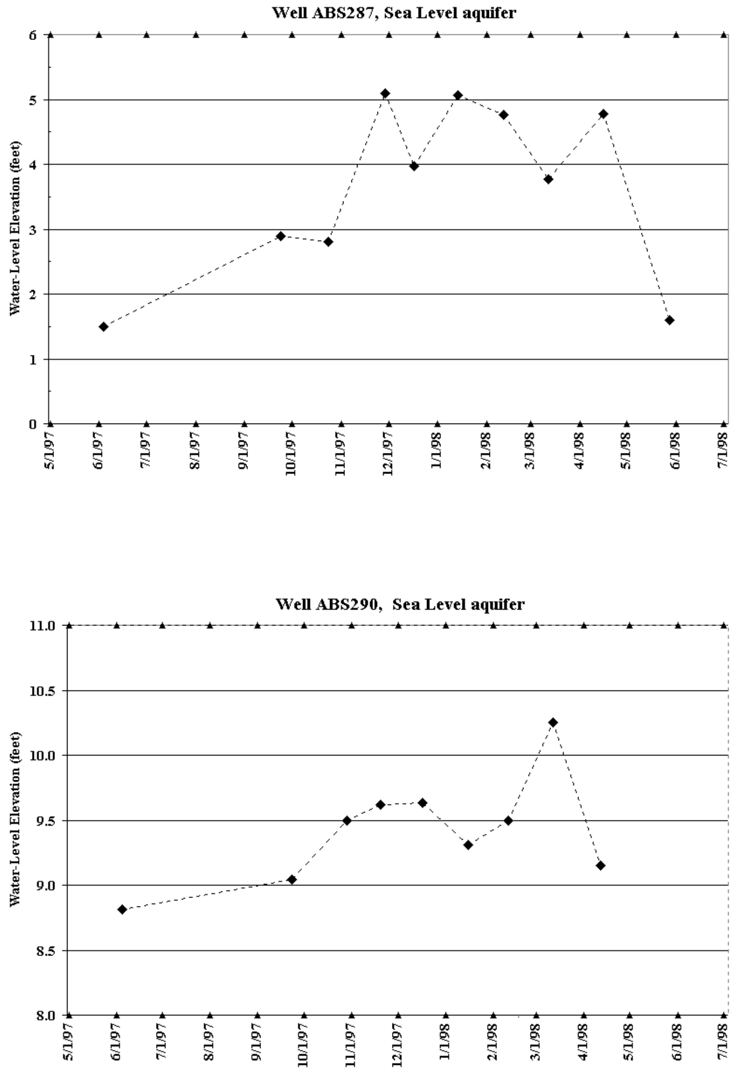


Figure 19. (continued) Hydrographs for selected Sea Level aquifer monitoring wells (05/97 through 07/98).

Tidal Effects

Aquifers that are hydraulically connected to seawater bodies are influenced by tidal cycles. Heads in these aquifers are higher during high tide and lower during low tide. There is typically a lag time between high or low tide and corresponding high or low water level in a well, respectively. Lag time is dependent on distance of the well from the shore and *transmissivity* of the aquifer. It is useful to know the extent of tidal effects in an aquifer so that these effects can be filtered out of any water-level data collected.

Tidal cycle monitoring was conducted in three wells on Anderson Island to estimate the degree of tidal effects from Puget Sound, particularly in the Sea Level aquifer (Figure 20). The wells were continuously monitored for a period of 24 or more hours each. This time interval was chosen to encompass at least one tidal cycle.

Two wells in the Sea Level aquifer were monitored for tidal influence. One well in the Vashon aquifer was monitored as a control well. No tidal influence was expected in this well since the Vashon aquifer is located above sea level and is isolated by the Olympia silt. These measurements were compared to the nearest verified tidal data, gage 9446484 at Commencement Bay, Tacoma. This tidal data is for a location too far north of Anderson Island to calculate accurate lag times between tidal cycles and water-level fluctuations. However, the general association between tidal cycles and water levels is evident.

As expected, tidal influence was evident in the two Sea Level aquifer wells. Well AAF216 is located on the western shore of the Island about 600 feet from Puget Sound. Its completion depth is 45 feet below mean sea level. In a 24-hour monitoring period, 0.53 foot of change was noted due to tidal influence (Figures 21A&B). Well AAF218 is located on the northwestern portion of Lyle Point peninsula about 300 feet from Oro Bay. Its completion depth is 5 feet above mean sea level. It was also monitored for 24 hours. There was some pumping interference in the data, but tidal effects were still discernable. Roughly 0.3 foot of change was noted due to tidal influence (Figures 22A&B).

Well ABE909 was monitored as a control well. It is located on the north-central portion of the Island, 3000 feet from Puget Sound. Well ABE909 is completed 131 feet above mean sea level in the Vashon aquifer. It was monitored for four days. Although not expected, minimal tidal effects were observed in this well. Pumping interference was heavy, but 0.1 to 0.2 foot of water level-fluctuation did seem to correspond with tidal cycles (Figure 23A&B). Analyses of well logs indicate that the Olympia aquitard, which separates these two aquifers, is very thin in the Otso Point area north of well ABE909. The Olympia aquitard might flex slightly in response to tidal effects in the underlying Sea Level aquifer, translating these effects to the Vashon aquifer. Additionally, the bottom of the Vashon aquifer appears to extend slightly below mean sea level in the area north of well ABE909. Therefore, there could be a minor direct response to tidal cycles in this portion of the Vashon aquifer.

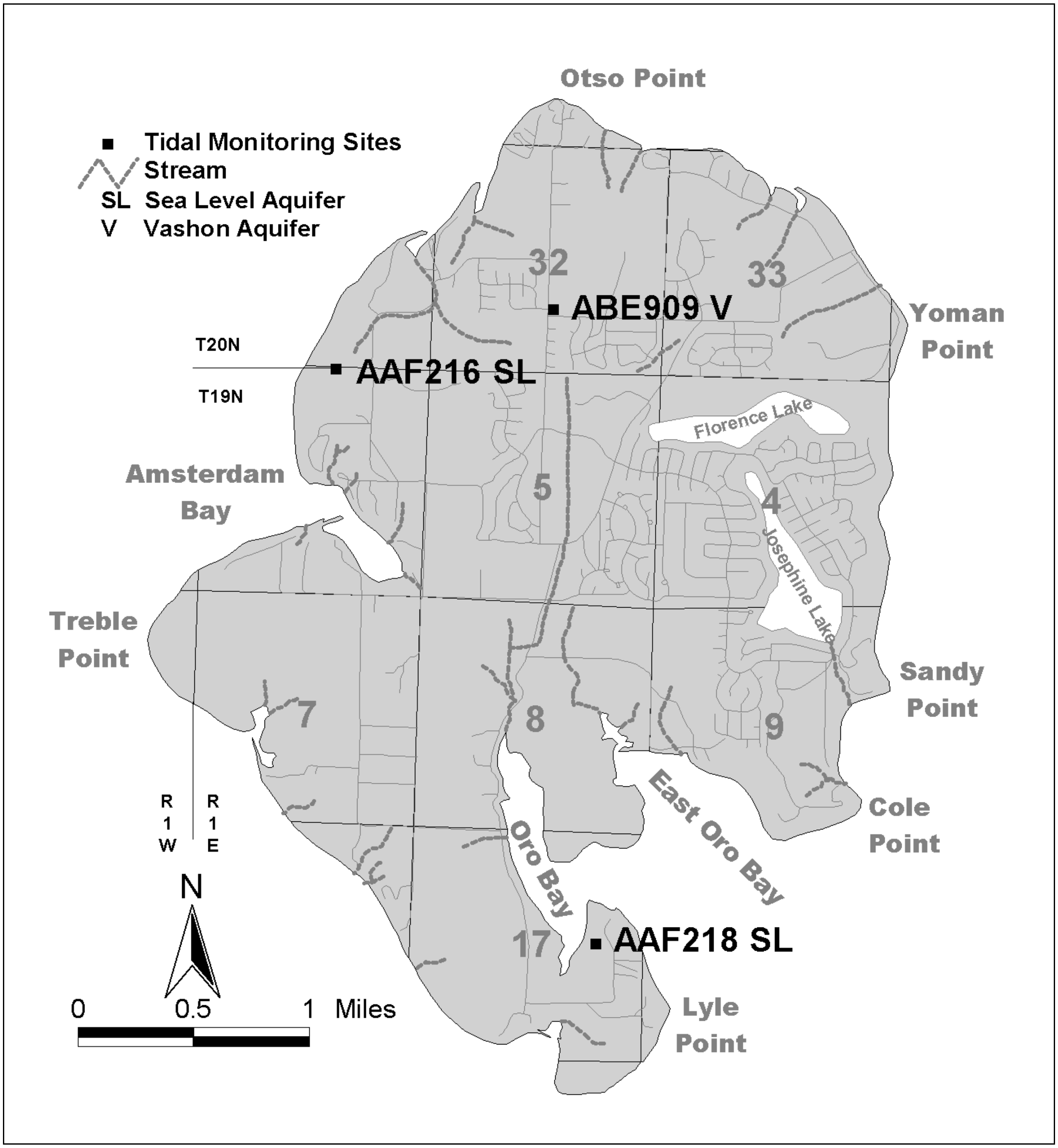


Figure 20. Location of wells used for tidal monitoring effects.

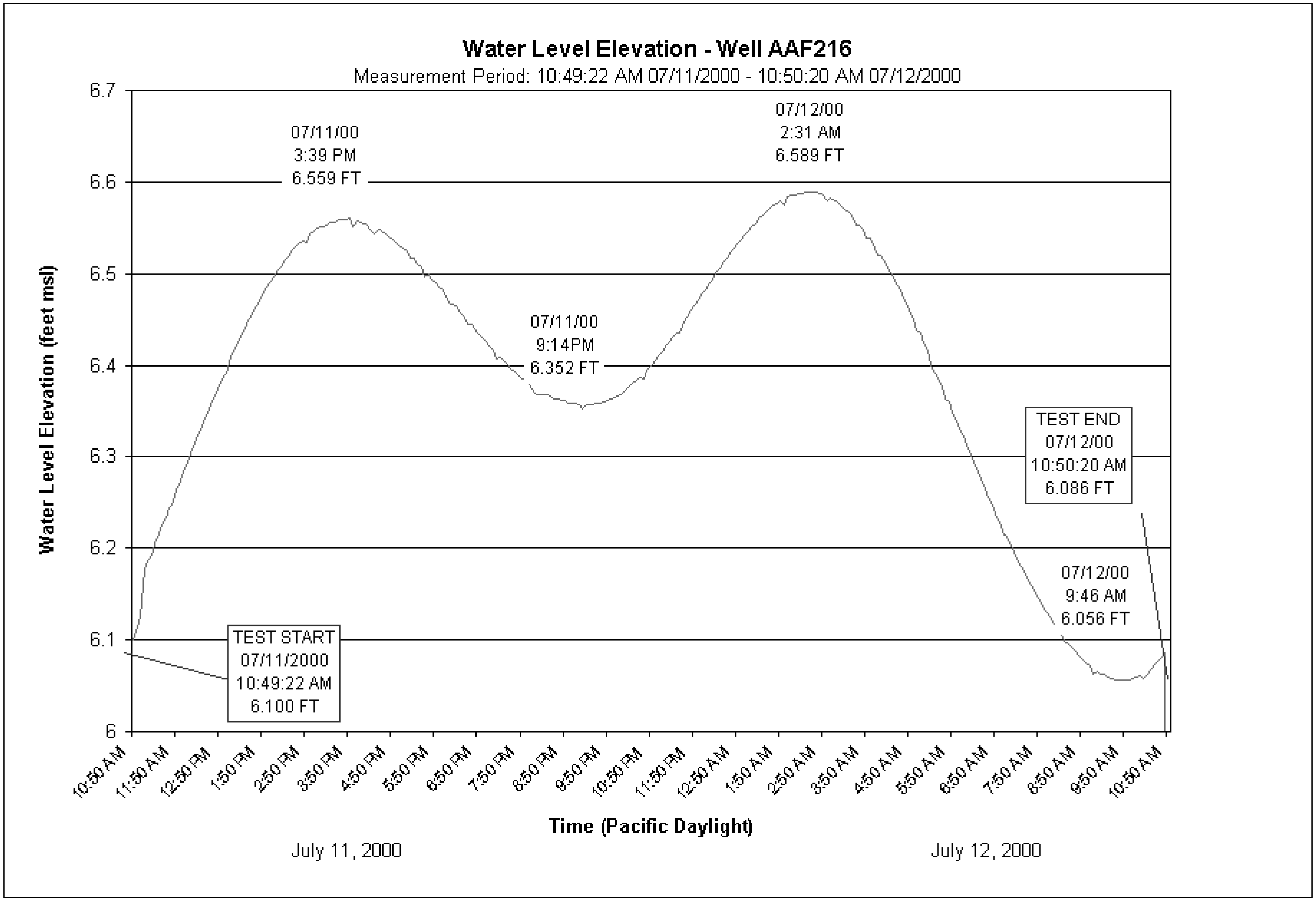


Figure 21 A. 24-hour tidal cycle hydrograph for Sea Level aquifer well AAF216, in feet relative to mean sea level. Uses an exaggerated scale to show the tidal cycle in the well. This well was not pumped for the duration of the test. The blips in the graph are probably due to interference from pumping of nearby wells.

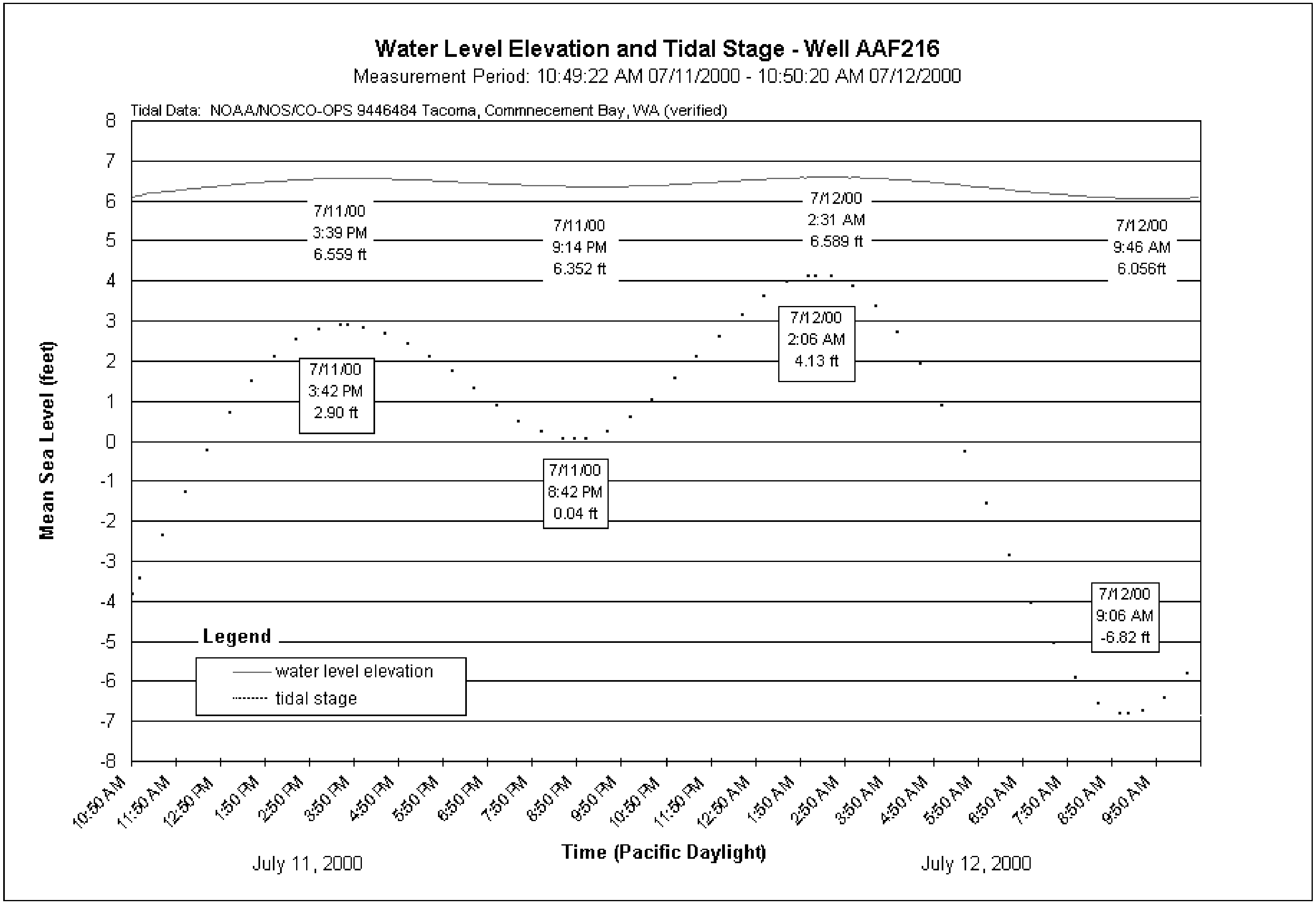


Figure 21 B. Sea Level aquifer well AAF126 water level elevation (top) superimposed with tidal stage (bottom). A slight lag effect between min/max tidal stage and well water level elevation is evident.

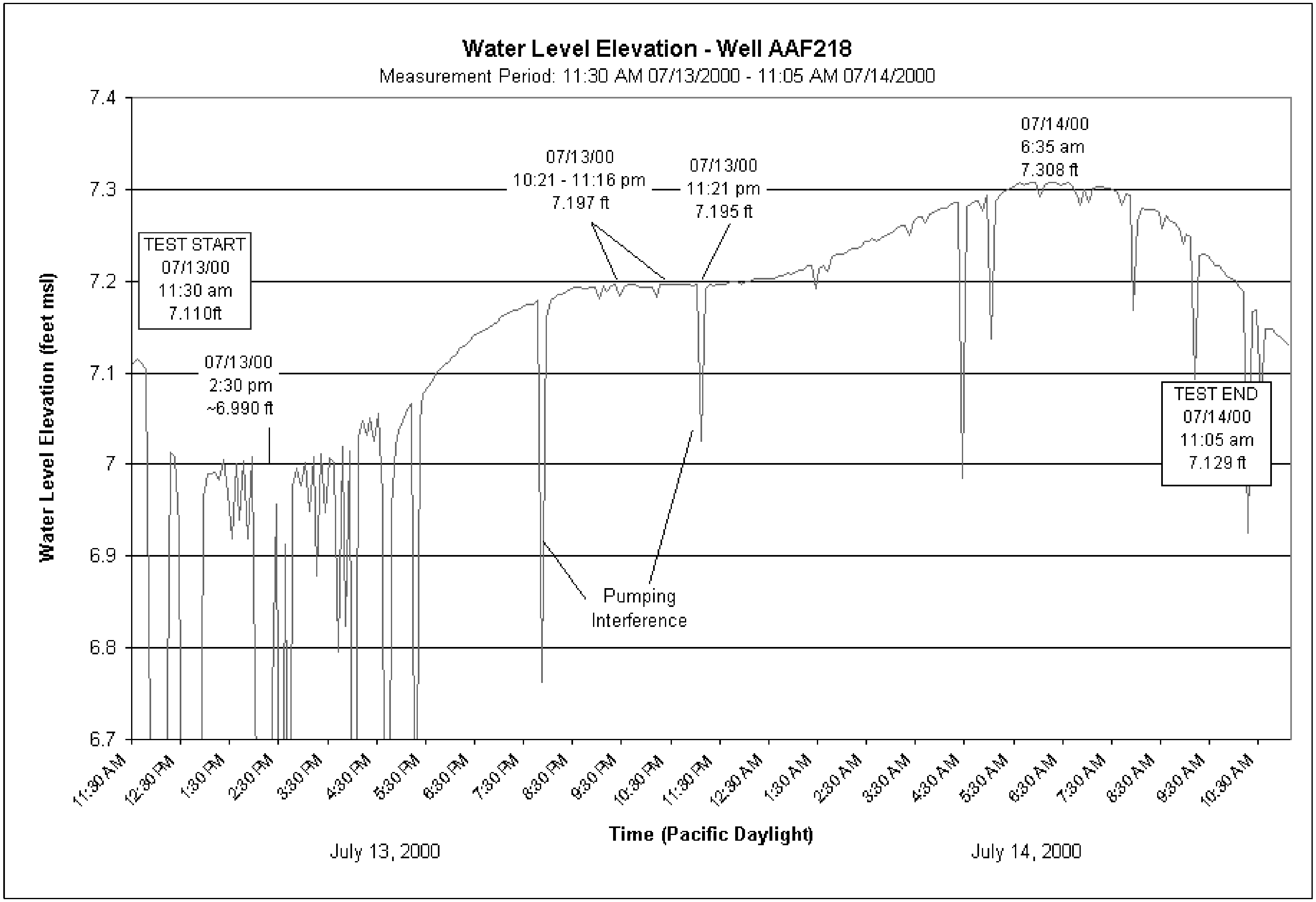


Figure 22 A. 24-hour tidal cycle hydrograph for Sea Level aquifer well AAF218, in feet relative to mean sea level. Uses an exaggerated scale to show the tidal cycle in the well. This well was pumped during the test and pumping interference is pronounced.

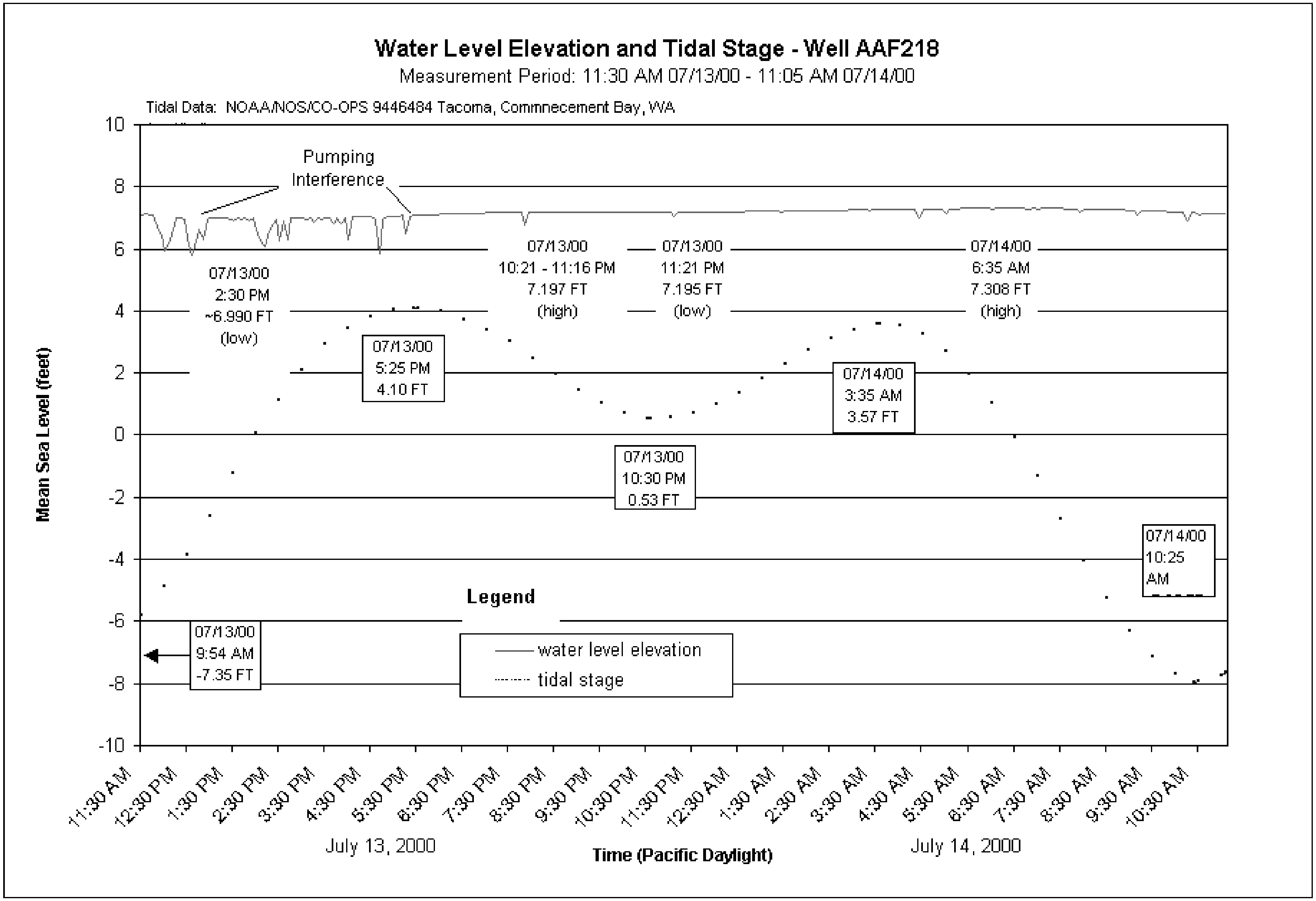


Figure 22 B. Sea Level aquifer well AAF128 water level elevation (top) superimposed with tidal stage (bottom). A slight lag effect between min/max tidal stage and well water level elevation is evident.

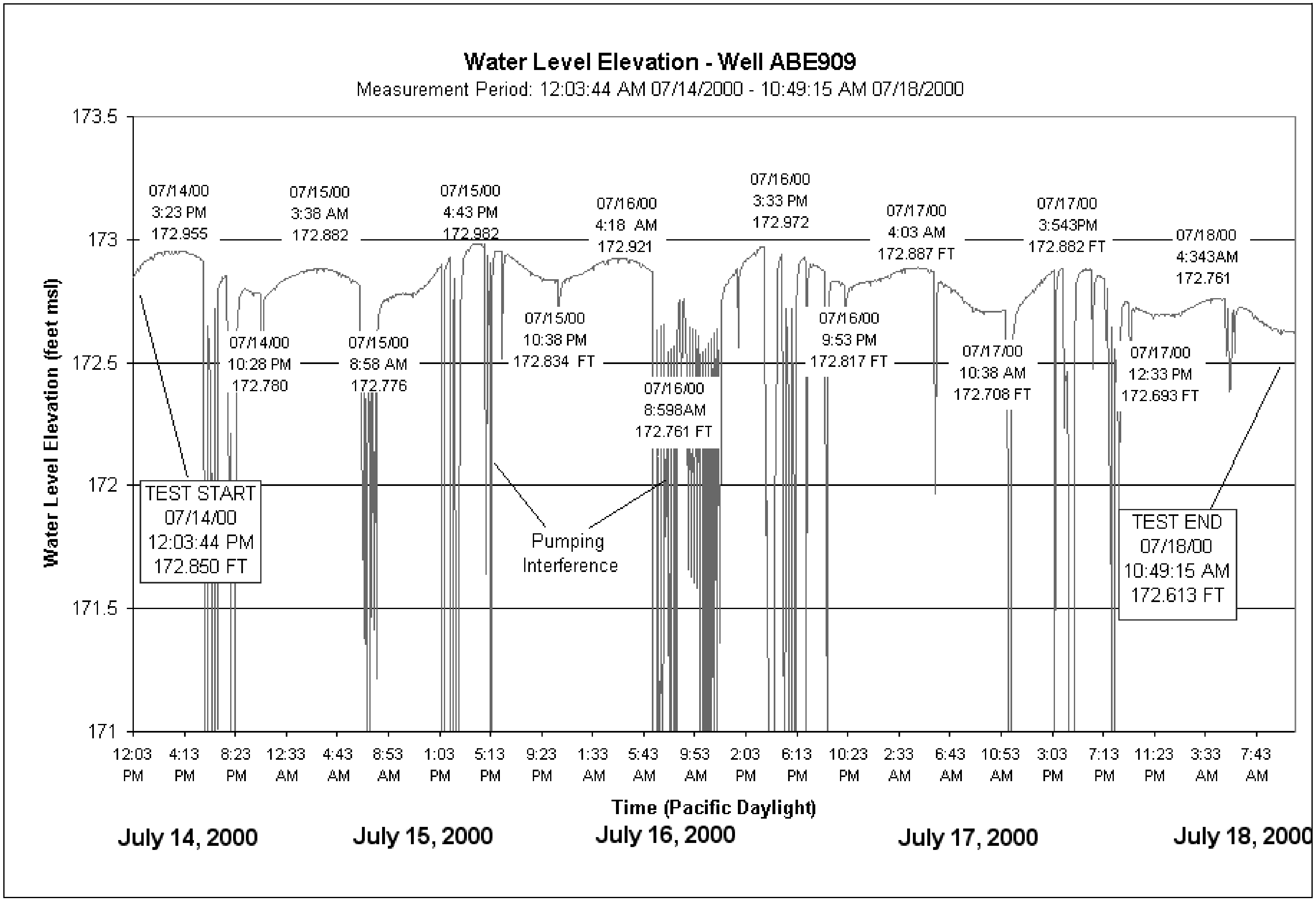


Figure 23 A. 95-hour (4 day) tidal cycle hydrograph for Vashon aquifer well ABE909, in feet relative to mean sea level. Tidal effects were not expected, but are visible with this exaggerated scale (~0.2 foot change). This well was pumped during the test and pumping interference is pronounced.

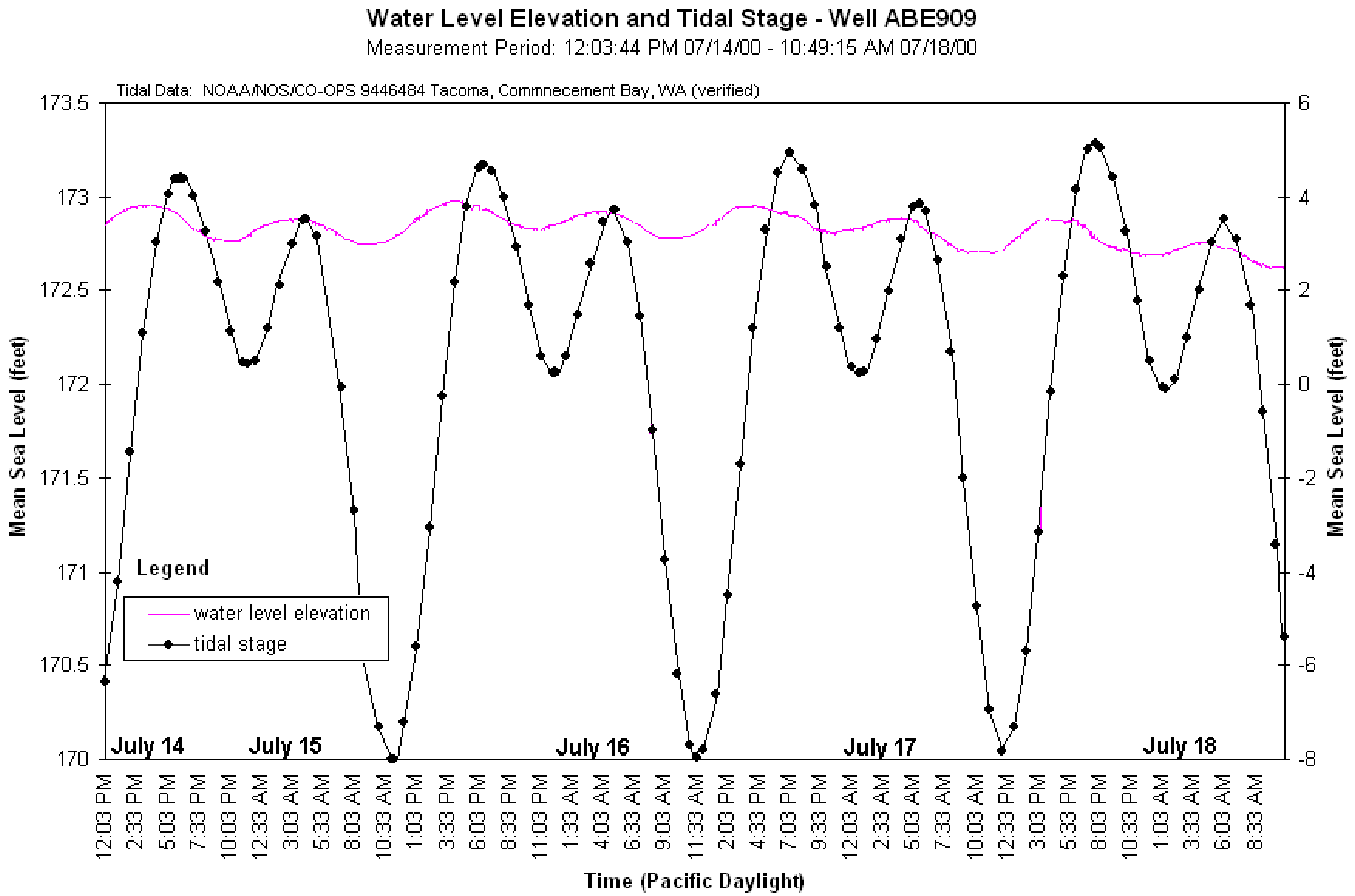


Figure 23 B. Vashon aquifer ABE909 water level elevation superimposed with tidal stage. Effects of pumping interference have been filtered out.

Surface Water

Springs

Springs form the headwaters of all the streams on Anderson Island. Numerous small springs also emerge from various points along the sea bluffs, wherein the discharge runs down the cliff face to the beach. These springs often emerge at the interface between the relatively impermeable Olympia silt and the overlying Vashon advance outwash.

In general, spring locations are associated with landslides and slumps on many of the Island's bluffs. Directly east of Florence Lake, a spring emerges from the sea bluff at the interface between the Vashon advance outwash and underlying Olympia silt. Flow from the spring has eroded a steep, narrow ravine into the bluff. Logan, et al. (2001) and the Coastal Zone Atlas of Washington (Department of Ecology, 1979) have identified a small slump near the spring (Figure 11). Additionally, wave action is slowly undermining the base of the bluff. The combined wave and spring-induced erosion could eventually cut the bluff so far inland that Florence Lake will drain, perhaps catastrophically. This process will likely take thousands of years.

Information on protecting beach and bluff property is available by contacting the Shorelands Program at the Department of Ecology. Their Website is a very good resource, located at http://www.ecy.wa.gov/programs/sea/shorelan.html.

Streams

Garling, et al. (1965) identified, mapped, and estimated low flows in 23 small streams on Anderson Island (Figure 24; Table 4). Only two streams, Schoolhouse Creek and Josephine Lake Outlet, are named. All streams, however, were assigned a number by Garling, et al. (1965). Most are so small that they are not represented on the McNeil Island 7.5 minute quadrangle.

For the current study, the existence and location of each stream was verified. Field reconnaissance indicates a change to the way in which School House Creek is represented on the McNeil Island 7.5 minute quadrangle. In the creek's upper watershed, an upper reach was added. This extends the creek northward, to the central portion of the Island (Figure 24).

Flows were measured in three streams for comparison to the low-flow estimates of Garling et al. (1965). Measurements were taken in Schoolhouse Creek (Stream 570), Stream 569, and Stream 582 (Figure 24; Table 4). Flows were 0.56, 0.04, and 0.97 cfs, respectively. The estimates of Garling, et al., (1965) were 0.40, 0.01, and 0.25 cfs, respectively. There is relatively good agreement between the measured data and the original estimates. Data for the current study was collected in late July (1997), whereas the Garling, et al. (1965) estimates were made for mid-September (1961). Flows are normally lower in September than in July. The flow in Stream 582 was higher than expected, possibly due to drainage of *bank storage* accumulated during high tide. Estimates of flows in several other streams were also made as part of this study. The estimates from this study are similar to those made by Garling, et al. (1965). This data is presented in Table 4.

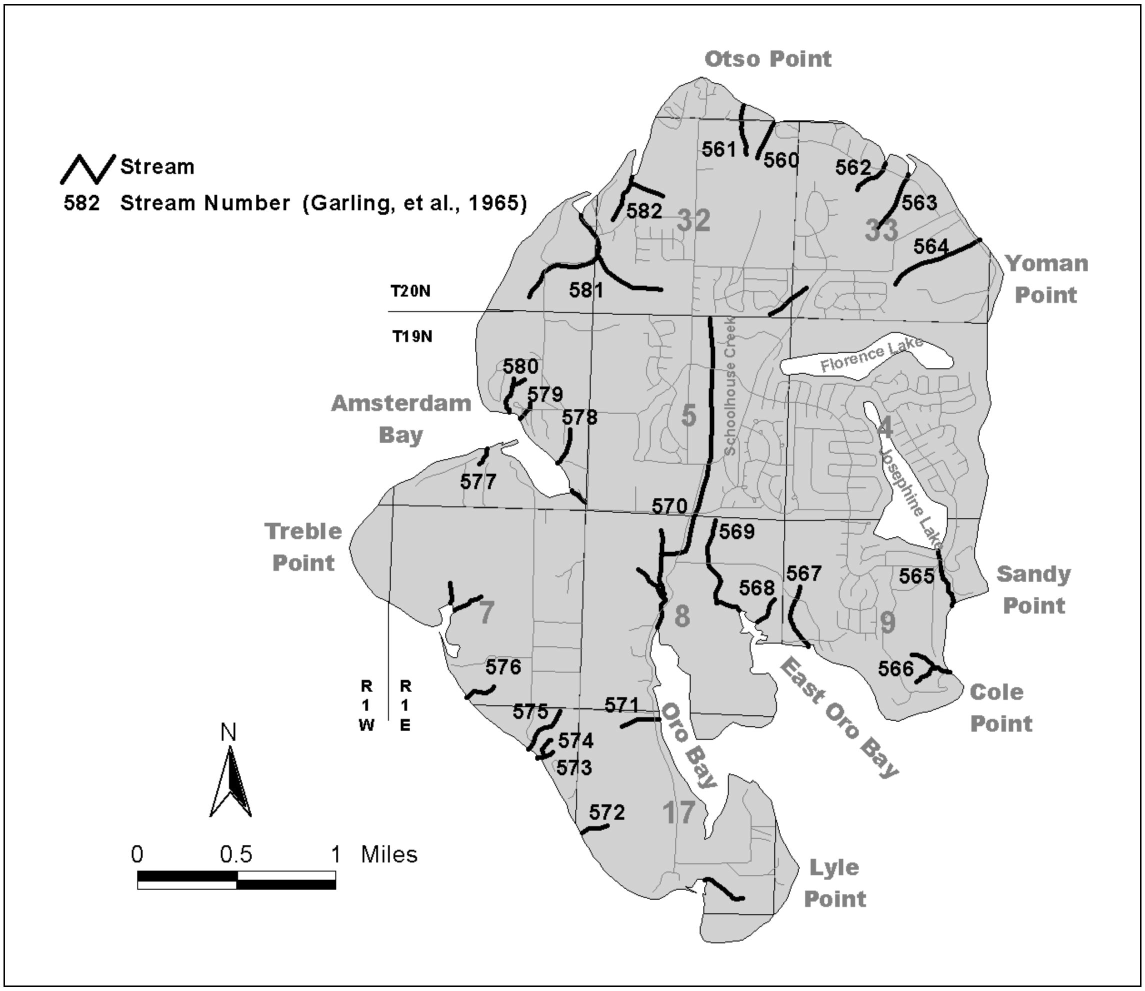


Figure 24. Stream locations on Anderson Island. Data from Garling, et al., 1965 and this study.

Streams on Anderson Island have cut deep ravines in Island margins with steeper slopes, but not on those with more gentle slopes. All streams have relatively low flows, less than a few cubic feet per second (cfs). Most of the streams might better be referred to as *brooks* because of their small size and origin from springs. Only one stream, Schoolhouse Creek, contains sufficient flow and habitat for small anadromous fish, such as cutthroat trout. None of the other streams on Anderson Island is listed by Department of Fish and Wildlife (Washington Department of Fisheries, 1975) as supporting salmon or steelhead runs.

The continued existence of all the small streams mapped by Garling, et al. (1965) constitutes additional proof that the ground-water supply on Anderson Island is relatively steady and not significantly diminished by development.

Table 4. Anderson Island stream data.

stream number, drainage area, and 9/11/61 flow estimates from Garling, et al., 1965;
* = higher than expected flow may be due to rapid drainage of bank storage accumulated during high tide

Stream Number	Stream Name	Surface Drainage Area (sq miles)	Date Measured	Estimated Discharge (cfs)	Measured Discharge (gpm)	Measured Discharge (cfs)	Method of Measurement or Estimate
560	Unnamed	0.03	9/11/1961	0.05			
			7/21/1997	trickle			visual
561	Unnamed	0.23	9/11/1961	0.02			
562	Unnamed	0.04	9/11/1961	dry			
563	Unnamed	0.22	9/11/1961	0.08			
			7/21/1997	0.07			visual
564	Unnamed	0.11	9/11/1961	0.01			
565	Josephine Lake Outlet	1.03	9/11/1961	not estimated			
566	Unnamed	0.14	9/11/1961	0.03			
567	Unnamed	0.17	9/11/1961	0.15			
568	Unnamed	0.09	9/11/1961	0.08			
569	Unnamed	0.17	9/11/1961	0.01			
			6/5/1997		50	0.11	bucket &
			7/17/1997		16	0.04	stopwatch
570	Schoolhouse Creek	1.28	9/11/1961	0.4			
			7/17/1997		251	0.56	wading rod & flow meter
571	Unnamed	0.05	9/11/1961	0.01			
572	Unnamed	0.03	9/11/1961	0.04			
573	Unnamed	0.01	9/11/1961	0.04			
574	Unnamed	0.03	9/11/1961	0.03			
575	Unnamed	0.1	9/11/1961	0.01			
576	Unnamed	0.04	9/11/1961	0.01			
577	Unnamed	0.12	9/11/1961	0.01			
			12/29/1997	0.02			visual
578	Unnamed	0.13	9/11/1961	0.1			
			7/17/1997	0.07			visual
579	Unnamed	0.03	9/11/1961	0.03			
580	Unnamed	0.11	9/11/1961	0.05			
581	Unnamed	0.16	9/11/1961	0.03			
582	Unnamed	0.72	9/11/1961	0.25			
			6/5/1997		435	0.97*	portable flume

Lakes

There are two large lakes on Anderson Island, Florence Lake and Josephine Lake (Figure 1). Florence Lake is roughly 63 acres in size, while Josephine Lake is 73 acres (RH2 Engineering, 1996). The lakes fill relatively shallow depressions in the surface of Anderson Island. Water is retained by an underlying silt layer of low permeability. This silt unit is exposed in nearby bluffs and is interpreted to be Olympia silt. Recharge to the lakes occurs by infiltration of shallow ground water, surface-water runoff, and direct precipitation. The surface elevations of Florence Lake and Josephine Lake are 197 and 196 feet above mean sea level, respectively. Both are less than 30 feet deep (Bortleson, et al., 1976). They are located only 600 and 300 feet, respectively, from the very steep bluff on the eastern margin of Anderson Island.

Florence and Josephine Lakes provide water for irrigation amounting to roughly 19 acre-feet per year. They have experienced annual variations in stage (water level) of several feet but are not progressively declining.

Florence Lake drains into Josephine Lake through a shallow channel and culvert, but only during periods of very high water. The winter of 1998-1999 was the wettest on record and the lakes were correspondingly bankfull in the spring. Flow from Florence Lake into Josephine Lake continued through early June 1999. Florence Lake has no other outlets.

Josephine Lake has a natural surface-water outlet at the south end (Josephine Lake Outlet). A control structure was built at the outlet in the mid-1900s to maintain constant lake levels. The upper 200 feet of the natural outlet channel was filled and replaced by a culvert. Discharge from the culvert has accelerated erosion at the head of the remaining natural channel. Consequently, the culvert is now perched roughly 20 feet above the natural channel on a cliff composed of Vashon advance outwash and Olympia silt - the same silt unit that underlies the lakes. Several feet of the culvert extend unsupported beyond this cliff. Anadromous fish do not currently inhabit the channel. It is not known if they ever did, but the lower end of the channel is very steep, potentially preventing its use by fish.

Water Quality

Nitrate

Nitrogen-based compounds, including *nitrate* (NO^-_3), are important plant and bacteria nutrients. Nitrate concentrations are measured in milligrams of nitrate per liter of water (mg/L), which is equivalent to parts per million (ppm). Natural background concentrations of nitrate in ground water tend to be low, usually less than 1 mg/L. Elevated concentrations of nitrate in ground water can indicate contamination by sewage, animal waste, industrial waste, or nitrogen-rich fertilizers. Nitrate concentrations exceeding the drinking water standard (10 mg/L), also known as the *maximum contaminant level* (MCL), can reduce the oxygen-carrying capacity of the blood, causing *methemoglobinemia*. This is a particular problem in infants, where methemoglobinemia is known as "blue baby syndrome."

Sampling of 35 wells, three springs, and one infiltration trench produced no indication of nitrate contamination (Appendix B, Table B1). The highest measured concentration was 0.19 mg/L in well ABS281, located west of Cole Point on East Oro Bay. This concentration is considerably below the 10 mg/L MCL. The next two highest concentrations were 0.12 and 0.05 mg/L. Of 39 samples, 23 were below the field detection limit of 0.01 mg/L.

pH

pH is a measure of hydrogen ion concentration and indicates whether a solution is acidic or alkaline (basic). pH is measured on a logarithmic scale from 0 to 14, with 7 being neutral. Values less than pH 7 are acidic, whereas those greater than pH 7 are alkaline. The drinking water standard for pH is between 6.5 and 8.5.

pH values in the Vashon aquifer ranged from 5.7 to 7.9 (Appendix B, Table B2). The median value was pH 6.9. The value of pH 5.7 is below the drinking water standard of pH 6.5. This result occurred in a sample from the collector trench of spring AAF228S (06/05/97). This low value could have been caused by acidic tannins associated with forest duff and soils in contact with water in the collector trench. Two more springs produced pH values slightly below the drinking water standard, those sources being AAF229S (pH 6.2; 06/05/97) and ABS283S (pH 6.4; 06/04/97). These values are not way out of range and are not considered a health risk.

pH values in the Sea Level aquifer ranged from 6.3 to 7.9 (Appendix B, Table B3). The median value was pH 7.0. The value of pH 6.3 is slightly below the drinking water standard of pH 6.5. This result was produced from samples from two wells, AAF363 (06/05/97) and AAF364 (06/05/97). Although well AAF363 was not sampled a second time, well AAF364 was sampled on 09/23/97 with markedly different results – pH 7.7. This lends suspicion to the 06/05/97 results. Even so, there is no inherent health risk associated with these levels.

Chloride

Chloride (Cl^-) is one of the major inorganic *ions* in water. Like nitrate, chloride concentrations are measured in milligrams of chloride per liter of water (mg/L). Chloride in ground water can come from contamination by seawater, brines, leaching of marine sedimentary deposits, and domestic, agricultural, or industrial pollution.

Pure seawater contains about 35,000 mg/L of dissolved solids. Roughly 19,000 mg/L of that is chloride (Hem, 1985). Chloride concentrations in Puget Sound are slightly less due to dilution by freshwater inflow. In northern Puget Sound, the concentration of chloride in seawater has been measured between 14,000 mg/L (Sapik, et al., 1988) and 17,600 mg/L (Culhane, 1993). Southern Puget Sound probably contains slightly less chloride because it is farther from the Pacific Ocean and is more subject to the influence of freshwater inflow. No actual measurements of chloride concentrations in southern Puget Sound were available. Fresh ground water typically contains less than 30 mg/L chloride.

The water quality standard for chloride is 250 mg/L. This is a secondary drinking water standard, based primarily on aesthetics (taste) and other factors as opposed to human health risks. Chloride concentrations above the 250 mg/L MCL begin to make water taste salty and the related sodium can be a health hazard to people requiring a low salt diet. Elevated chloride concentrations can also corrode metallic pipes and cause salt damage to plants. In coastal areas, a chloride concentration of 100 mg/L or greater in ground water is considered to be a red flag with respect to seawater intrusion.

Background levels for chloride concentrations in ground water on Anderson Island were determined by sampling wells completed in the Vashon aquifer, the base of which lies above sea level. Aquifers located above sea level are usually not susceptible to seawater intrusion. Ten wells and three springs in the Vashon aquifer were sampled for chloride. Laboratory analyses indicate chloride concentrations ranging from 3 to 17 mg/L, with a median value of 4 mg/L (Appendix B, Table B2). Based on these results, a conservative background concentration of 25 mg/L was assigned for chloride.

Aquifers located at or below sea level are susceptible to seawater intrusion. This would be true of the Sea Level aquifer on Anderson Island. Thirty-six wells in the Sea Level aquifer were sampled for chloride (Appendix B, Table B3). Chloride concentrations ranged from 3 to 347 mg/L, with a median of 5 mg/L. Of the thirty-six wells sampled, six had chloride concentrations consistently equaling or exceeding the assumed background concentration of 25 mg/L (Table 5). These wells were located on Lyle Point peninsula, near the southwest shore of Oro Bay, near Miller Cove, and near Otso Point (Figure 25). Chloride concentrations in four of these wells often exceeded 100 mg/L. These wells were AAF217, AAF354, AAF359, and ABS283 (Table 5). The chloride concentration in well AAF217 exceeded the MCL of 250 mg/L on one occasion (Table 5).

Unfortunately, none of the wells originally sampled by Walters (1971) and Dion and Sumioka (1984) were available for sampling during this study. However, three of the elevated chloride wells from this study are in close proximity to areas where Walters (1971) and Dion and Sumioka (1984) found elevated chloride concentrations in Sea Level aquifer wells. These include well AAF217 on Lyle Point peninsula and wells AAF359 and ABS283 near Otso Point. Historical and current elevated chloride concentrations are summarized in figure 25. Well depths and chloride concentrations in both the historical wells and the current wells are similar.

None of the wells with elevated chloride concentrations have histories of large water withdrawals. Therefore, these elevated chloride concentrations could be attributable to the close proximity of the well intakes to the natural zone of diffusion, rather than significant landward migration of the zone of diffusion.

Table 5. Monitoring wells with elevated chloride concentrations - exceeding background (25 mg/L) and/or seawater intrusion threshold (100 mg/L).

* = exceeds maximum contaminant level for chloride (250 mg/L)

Unique Well ID	Date Sampled	Chloride Concentration (mg/L)
AAF217	6/3/1997	347*
	09//23/97	216
	12/17/1997	235
	3/12/1998	164
AAF222	6/4/1997	68
	9/23/1997	57
	12/22/1997	123
	3/12/1998	35
AAF265	9/23/1997	79
	3/13/1998	87
	3/27/1998	100
AAF354	6/3/1997	209
	9/23/1997	207
	12/17/1997	207
	3/12/1998	198
AAF359	6/4/1997	160
	9/23/1997	174
	12/17/1997	177
ABS283	6/5/1997	186
	9/25/1997	185
	12/18/1997	196

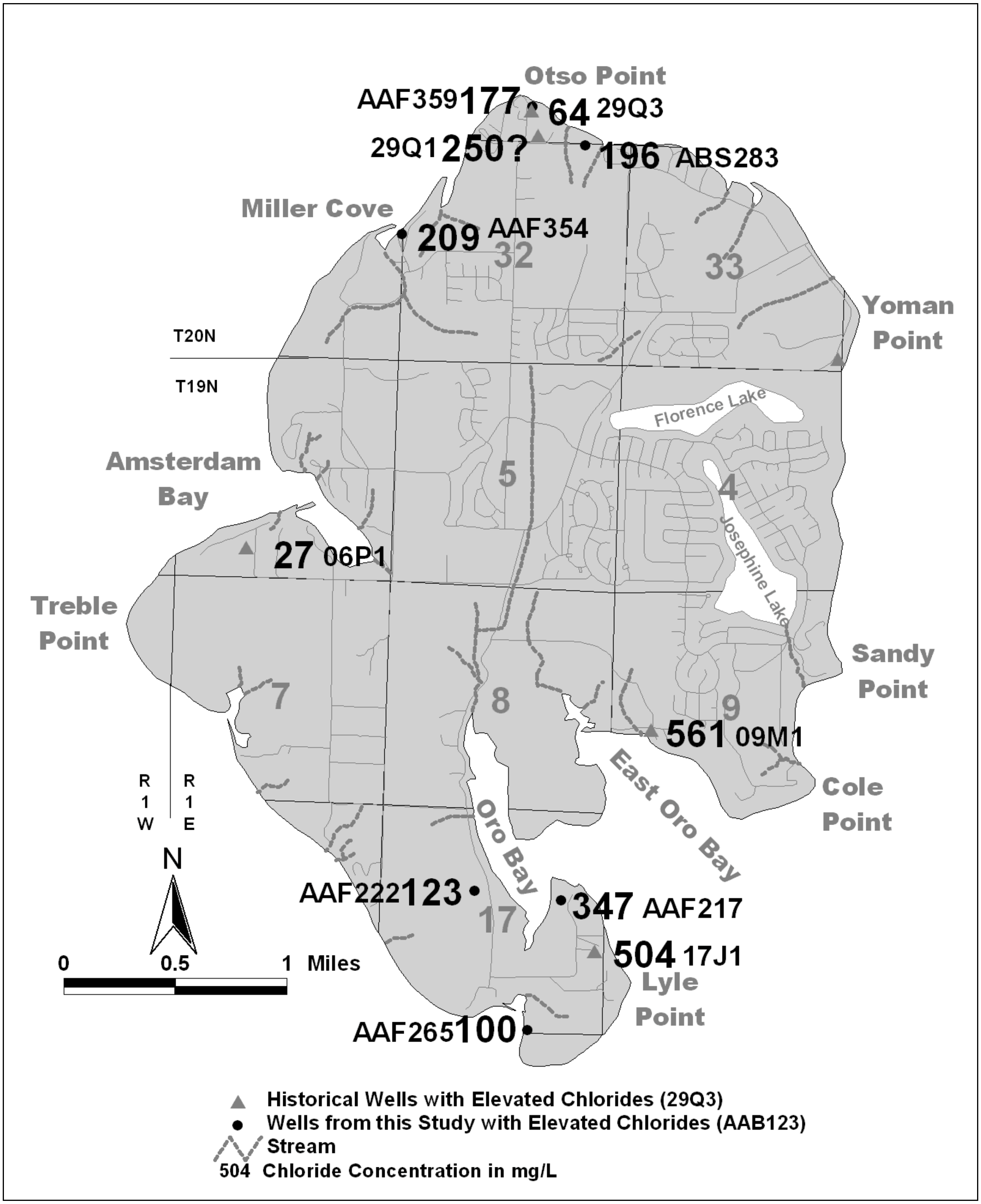


Figure 25. Historical and current chloride concentrations in Sea Level aquifer wells. For wells in which assumed background concentration (25 mg/L) was exceeded. Data represent maximum concentrations and therefore were not collected on the same date. Historical data is from Walters (1971) and Dion and Sumioka (1984).

Specific Conductance

Specific conductance is a measure of the ability of water to conduct electricity. Specific conductance is proportional to the concentration of dissolved solids in water. It is measured in microsiemens (µS) or micromhos (µmho) per square centimeter (cm^2). Specific conductance is a secondary (aesthetic) contaminant. The drinking water standard for specific conductance is 700 µmho/cm^2.

In the case of seawater, dissolved solids include salts such as sodium chloride, magnesium chloride, or potassium chloride. Seawater contains roughly 35,000 mg/L of dissolved solids. The specific conductance of pure seawater is roughly 50,000 µmho/cm^2. Specific conductance measurements can facilitate determining whether elevated chloride concentrations in ground water are due to seawater intrusion or other causes, such as *connate water*. Generally, higher specific conductance readings are indicative of seawater intrusion.

There is often a roughly linear relationship between chloride concentration and specific conductance such that the higher the chloride concentration, the higher the specific conductance value. By plotting chloride concentration against specific conductance data from a particular geographic area, a correlation coefficient (R^2) can be derived. The higher the correlation coefficient, the more reliable the relationship between chloride concentration and specific conductance. Dion and Sumioka (1984) found correlation coefficients ranging from 0.45 (poor) to 0.97 (excellent) in Washington coastal counties during their investigation of seawater intrusion. Data from the current study produced a correlation coefficient of 0.89 (Figure 26), which is considered good.

Specific conductance in the Vashon aquifer ranged from 60 to 294 µmho, with a median value of 130 µmho (Appendix B, Table B2). These values are well within range of the MCL (700 µmho/cm^2).

In the Sea Level aquifer, specific conductance ranged from 80 to 1302 µmho/cm^2, with a median value of 181 µmho/cm^2 (Appendix B, Table B3). Four wells consistently exceeded the MCL for specific conductance – AAF217 on Lyle Point peninsula, AAF354 near Miller Cove, and AAF359 and ABS283 near Otso Point (Figure 27). These wells also produced elevated chloride concentrations.

Using the relationship between chloride and specific conductance, elevated chloride levels are suspected in a well that was not sampled for chloride during this study. Because the owner elected not to be part of the official study, the well was not tagged with a unique well ID. The well is located in T19N/R1E-9, east of the main access road south of Josephine Lake, on the Cole Point peninsula. A specific conductance of 920 µmho was measured in July 1998. Inserting this value into the regression equation in Figure 16 indicates that the well has a chloride concentration of 190 ±30 mg/L. This well is in the general proximity of a well (09M1) sampled by Walters (1971) that produced high chloride concentrations (Table 1, Figures 3&25).

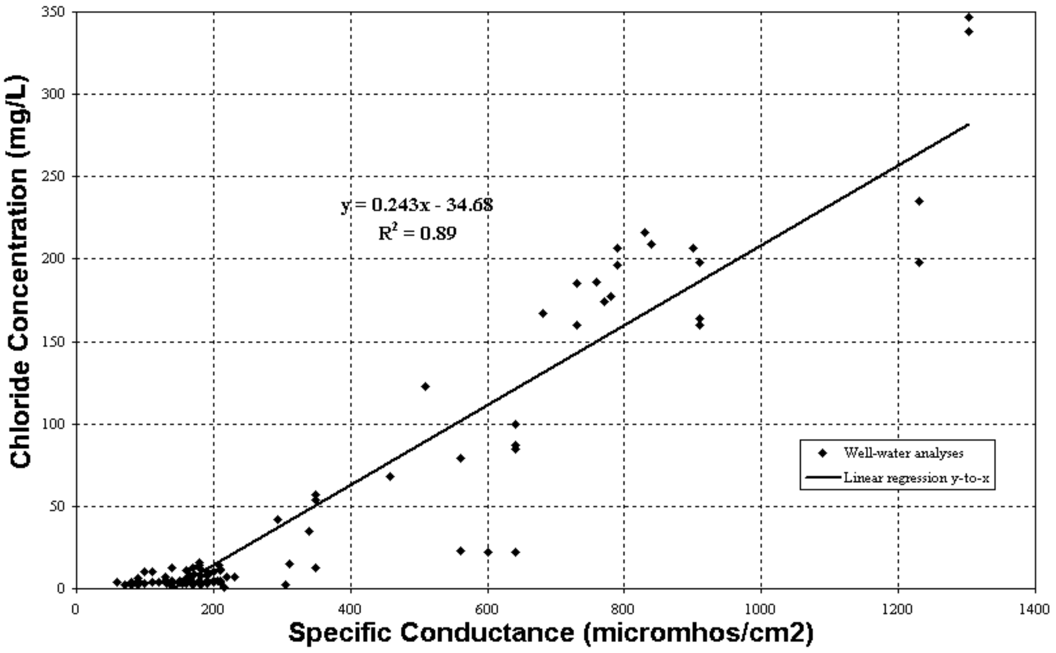


Figure 26. Linear regression between chloride concentration and specific conductance, Sea Level aquifer.

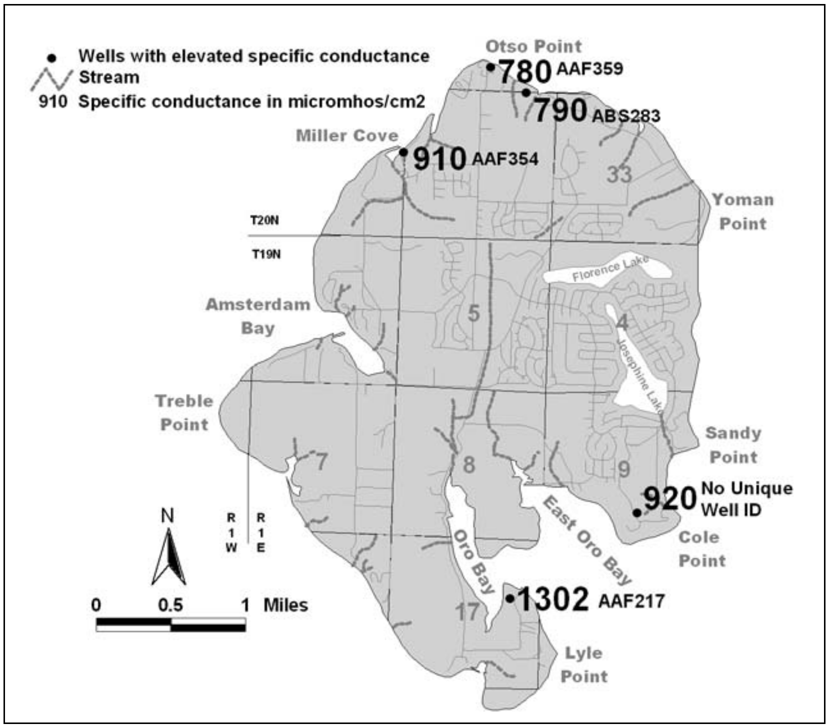


Figure 27. Specific conductance values in Sea Level aquifer wells where the water-quality standard (700 µmho) was exceeded. Data represent maximum values and therefore were not collected on the same date.

Water Rights and Claims

Water Rights

The waters of Washington State collectively belong to the public and cannot be owned by any one individual or group. Instead, individuals or groups may be granted rights to use them. A water right is a legal authorization to use a predefined quantity of public water for a designated purpose. This purpose must qualify as a "beneficial use." Beneficial use involves the application of a reasonable quantity of water to a non-wasteful use, such as irrigation, domestic water supply, or power generation, to name a few. An average household uses about 300 gallons per day (gpd) of water.

Washington State law requires certain users of public waters to receive approval from the state prior to use of the water – in the form of a water right permit or certificate. Any use of surface of water (lakes, ponds, rivers, streams, or springs) from 1917 onward requires a water-right permit or certificate. Likewise, ground-water withdrawals from 1945 onward require a water-right permit or certificate, with the following exceptions:

Use of 5000 gallons a day or less for:

- Stock watering;
- Single domestic purposes ;
- Industrial purposes; or
- Watering a lawn or noncommercial garden that is one-half acre or less.

These uses of ground water are "exempt" from the need to obtain a water right permit or certificate, but are still considered water rights. They are referred to as "exempt ground-water withdrawals."

Water use of any sort is subject to the "first in time, first in right" clause, originally established in historical water law and now part of Washington State law. This means that a senior right cannot be impaired by a junior right. Seniority is established by "priority date" – the date an application was filed for a permitted or certificated water right – or the date that water was first put to beneficial use in the case of claims (discussed below) and exempt ground-water withdrawals.

A break in use of five or more consecutive years may invalidate a permitted or certificated water right.

Presently, Islanders hold 15 ground-water rights and 16 surface-water rights. These rights are summarized in Appendix C, Table C1. One application for a ground-water permit is pending review.

Claims

In the 1960's, the Washington State legislature realized the need to document water rights established prior to 1917 for surface water and 1945 for ground water. These water rights are "vested rights." A vested right is a water right established through beneficial use of water. A water right claim is a statement of beneficial use of water that began prior to 1917 for surface water and 1945 for ground water. In 1967, the Claims Registration Act was passed to record the amount and location of these vested water rights (Ecology, 1998).

The Claims Registration Act set a specific time window for water users to file their water right claims with the state. Users of exempt ground-water withdrawals were also encouraged to file claims so that they could establish priority dates for their rights. Some users were not required to file a claim, including:

- Individuals served water through a company, district, public or municipal corporation (the water supplier should have filed claims for its users);
- Persons with a valid Water Right Permit or recorded Certificate;
- Individuals with a water right determined by Court Decree and recorded through issuance of a Certificate of Water Right by Ecology or one of its predecessor agencies;
- Nonconsumptive water uses, like boating, swimming, or other recreational and aesthetic uses, with no physical diversion or artificial impoundment of water; or
- Owners of livestock that drank directly from a surface-water source.

The initial statewide opening of the Claims Registry ended June 30, 1974. The legislature has subsequently re-opened the Claims Registry three times. The most recent opening occurred from September 1997 to June 1998. Statewide, there are roughly 169,000 water-right claims on record.

Islanders have filed 18 surface-water claims and 101 ground-water claims (Appendix C, Table C2). These claims will remain valid until such time that an *adjudication* occurs, whereby the validly of the claims must be proven before a court of law. Adjudication can be initiated by several means, but normally will not occur unless there are significant problems with water availability in an area. During adjudication, claimants are required to prove that water has been in constant beneficial use prior to 1917 for surface water or 1945 for ground water. As with a water right, any break in use of five or more consecutive years invalidates a claim.

Information on water rights and claims is available by contacting the Water Resources Program at the Department of Ecology or by visiting their Website at: http://www.ecy.wa.gov/programs/wr/wrhome.html.

Summary and Conclusions

Water Supply

The water supplies on Anderson Island appear to be ample to meet current demands, with the exception of the areas outlined below. Although historical data is relatively sparse, ground-water withdrawals do not appear to have caused noticeable declines in ground-water heads over the past ten years.

Surface waters are little used, judging by records of water rights and claims on file at the Department of Ecology. Exceptions are Florence and Josephine Lakes, the waters of which are used for irrigation. The streams that drain Anderson Island are all very small and would be noticeably diminished by almost any diversion.

Water Quality

The quality of the ground water on Anderson Island generally appears to be excellent, with a few exceptions.

Nitrate concentrations are well within acceptable standards, indicating no present contamination problems from septic systems or agricultural sources. Prudence with respect to the use of agricultural chemicals, management of animal wastes, and septic system maintenance is necessary to keep these levels low.

pH is within acceptable limits, with the exception of three springs. It is suspected that the slightly low pH levels in these springs are the result of water being exposed to acid soils and forest duff. The levels are not considered a health hazard.

Chloride concentrations are within acceptable limits in most wells on Anderson Island, with the exception of three areas in the Sea Level aquifer – the Otso Point vicinity, the Lyle Point peninsula and vicinity, and the Cole Point peninsula (Figure 24). There was also one well near Miller Cove that displayed elevated chloride concentrations. It is not known whether the withdrawal of water from these wells has induced seawater intrusion or if they were originally drilled near the natural zone of diffusion. Chloride monitoring for any new wells installed in these areas is recommended. Owners of older wells have some legal recourse should newer wells exacerbate or initiate a seawater intrusion problem. Older withdrawals have senior rights and therefore cannot be impaired by newer withdrawals.

There is a roughly linear relationship between specific conductivity and chloride concentrations in wells on Anderson Island. Specific conductivity levels are above acceptable limits in the same wells where chloride concentrations exceed acceptable limits. Additionally, one well on the Cole Point peninsula measured only for specific conductivity had levels high enough to indicate a seawater intrusion problem.

Monitoring Recommendations

Periodic monitoring of ground-water levels and chloride concentrations in wells should be continued. This will assist Islanders in determining whether ground-water heads are remaining at safe, sustainable levels and whether seawater intrusion is increasing. Ecology recommends measuring water levels in four wells – three in the Sea Level aquifer and one in the Vashon aquifer - on a yearly basis. Additionally, chloride concentrations and specific conductance should be monitored in the three Sea Level aquifer wells every other year. Monitoring should occur in late summer or early fall, when water levels are usually lowest and the manifestation of seawater intrusion is usually greatest. Tacoma-Pierce County Health Department has agreed to conduct these chloride analyses.

Selected References

Berris, S.N., 1995. Conceptualization and simulation of runoff generation from three basins in Thurston County, Washington. U.S. Geological Survey Water-Resource Investigation Report 94-4038, 149 p.

Blunt, D.J., Easterbrook. D.J., and Rutter, N.W., 1987. Chronology of Pleistocene sediments in the Puget Lowland, Washington. Washington State Department of Natural Resources, Division of Geology and Earth Resources Bulletin 77, p. 321-353.

Bortleson, G.C., Dion, N.P., McConnell, J. B., and Nelson, L. M., 1976. Reconnaissance data on lakes in Washington, Vol. 3, Kitsap, Mason, and Pierce Counties. Washington State Department of Ecology, Water-Supply Bulletin no. 43, vol. 3, 259 p.

Booth, D., and Goldstein, 1994. Patterns and processes of landscape development by the Puget lobe ice sheet. IN: Lasmanis and Cheney (eds.), 1994. Regional Geology of Washington State. Washington Department of Natural Resources, Division of Geology and Earth Resources, Bulletin 80, 227p.

Bretz, J.H., 1913. Glaciation of the Puget Sound Region. Washington Geological Survey Bulletin 8, 244 p.

Brown and Caldwell Consultants, 1985. Clover/Chambers Creek geohydrologic study. Prepared for Tacoma-Pierce County Health District, 197 p.

Calvin, W.H., 2000. The ascent of mind - ice age climates and the evolution of intelligence. iUniverse.com Inc. 324 p.

Cammon, B.J., 1987. Island memoir, a personal history of Anderson and McNeil Islands. Anderson Island Historical Society, 228 p.

Culhane, Tom, 1993. High chloride concentrations in ground water withdrawn from above sea level aquifers, Whidbey Island, Washington. Washington State Department of Ecology Open-File Technical Report 93-07, 35 p.

Dion, N.P. and Sumioka, S.S., 1984. Seawater intrusion into coastal aquifers in Washington. Washington State Department of Ecology, Water-Supply Bulletin no. 56, 13 p., 14 plates.

Driscoll, F.G., 1986. Groundwater and wells, second edition. U.S. Filter, Johnson Screens, St. Paul, Minnesota, 1089 p.

Heckman, H., 1967. Island in the Sound. University of Washington Press. 284 p.

Hem, J.D., 1985. Study and interpretation of the chemical characteristics of natural water (Third Edition). U.S. Geological Survey Water-Supply Paper 2254, 263 p.

Horton, Gary A., 1999. Water words dictionary. Nevada Division of Water Planning, Department of Conservation and Natural Resources, Eighth Edition, Second Update, August 1999, (URL: http://www.state.nv.us/cnr/ndwp/dict-1/waterwds.htm).

Jones, M.A., 1999. Geologic framework for the Puget Sound aquifer system, Washington and British Columbia. U.S. Geological Survey Professional Paper 1424-C, 31 p.

Fetter, C.W., 1994. Applied hydrogeology, third edition. Prentice Hall, Inc., a Simon & Schuster Company, Upper Saddle River, New Jersey, 691 p.

Flint, R.F., 1971. Glacial and quaternary geology. John Wiley and Sons, Inc., New York, 892 p.

Garling, M.E., Molenaar, D., Bailey, E.G., VanDenburgh, A.S., and Fiedler, G.H., 1965. Water resources and geology of the Kitsap Peninsula and certain adjacent islands. Washington State Department of Conservation, Division of Water Resources, Water Supply Bulletin no. 18.

Garrigues, R.A., 1997. Anderson Island monitoring quality assurance plan. Unpublished memorandum, Washington State Department of Ecology.

Gary, M., McAfee, R. Jr., and Wold, C.L. (eds.), 1974. Glossary of geology. American Geologic Institute (AGI), Washington D.C., 805 p.

Logan, R., Walsh, T., and Polenz, M., 2001 (draft). Geologic maps of McNeil Island and Longbranch 7.5' minute quadrangles, Washington—preliminary geologic maps. Washington State Department of Natural Resources, Division of Geology and Earth Resources, geologic maps with text (14 p.), scale 1:24,000.

Logan, R.L., Walsh, T.J., and Gerstel, W.J., 2000. A revision of Quaternary stratigraphy in the southern Puget Lowland, Washington [abstract]. Geological Society of America Abstracts with Programs, v. 32, no. 6, p. A25.

Miller, J.F., et al., 1973. Precipitation-frequency atlas of the United States, vol. ix, Washington. U.S. Department of Commerce and National Oceanographic and Atmospheric Administration, 1:2,000,000 scale, digitized 1991 by Washington State Department of Natural Resources.

Noble, J.B., 1990. Proposed revision of nomenclature for the Pleistocene stratigraphy of coastal Pierce County, Washington. Washington State Department of Natural Resources, Division of Geology and Earth Resources, Open-File Report 90-4, 54 p.

Orr, Laura, 2000. Is seawater intrusion affecting ground water on Lopez Island, Washington? U.S. Geological Survey Fact Sheet FS-057-00, 8p.

RH2 Engineering, 1996. Riviera Community Club comprehensive water plan. Fall 1996, Redmond, Washington.

Sapik, D.B., Bortleson, G.C., Drost, B.W., Jones, M.A., and Prych, E.A., 1988. Ground-water resources and simulation of flow in aquifers containing freshwater and seawater, Island County, Washington. U.S. Geological Survey Water-Resources Investigations Report 87-4182, 67 p., 4 plates.

Sinclair, K.A. and Garrigues, R.S., 1994. Geology, water resources, and seawater intrusion assessment of Marrowstone Island, Jefferson County, Washington. Washington State Department of Ecology, Water Supply Bulletin no. 59, 83 p., Appendices, 7 plates.

Sonnichsen, A., 1999. Hydrologic and geologic conditions of Anderson Island. Pacific Lutheran University, unpublished senior capstone report, Earth Science Department.

Toth, J., 1970. A conceptual model of the groundwater regime and the hydrogeologic environment. Journal of Hydrology, vol. 10, p. 164-176.

Troost, K.G., 1999. The Olympia nonglacial interval in the southcentral Puget Lowland, Washington. University of Washington Master of Science thesis, 123 p.

Vaccaro, J.J., Hansen, A.J., Jr., and Jones, M. A., 1998. Hydrogeologic framework of the Puget Sound aquifer system, Washington and British Columbia. U.S. Geological Survey Professional Paper 1424-D, 77 p.

U.S. Geological Survey, 1999. The geologic time scale. U.S. Geological Survey, 926 National Center, Reston, VA, 20192 (URL: http://geology.er.usgs.gov/paleo/geotime.shtml).

Walsh, T.J., 1987. Geologic map of the south half of the Tacoma quadrangle, Washington. Washington State Department of Natural Resources, Division of Geology and Earth Resources, Open File Report 87-3, 1 sheet, scale 1:1000,000, 10 p. text.

Walsh, T.J., Korosec, M.A., Phillips, W.M., Logan, R.L., and Schasse, H.W., 1987. Geologic map of Washington—Southwest quadrant. Washington State Department of Natural Resources, Division of Geology and Earth Resources, Geologic Map 34, scale 1:250,000, 28 p. text.

Walters, K.L., 1971. Reconnaissance of seawater intrusion along coastal Washington, 1966-68. Washington State Department of Ecology, prepared in cooperation with U.S. Geological Survey, Water Resources Division, Water-Supply Bulletin no. 32, 208 p.

Washington State Department of Ecology, 1998. Washington State water law - a primer. Publication no. WR-98-152.

Washington State Department of Ecology, 1997. Water right claims - questions and answers. Publication no. 97-2022-S&WR.

Washington State Department of Ecology, 1996. Water rights in Washington - questions and answers. Publication no. 96-1804-S&WR.

Washington State Department of Ecology, 1979. Coastal zone atlas of Washington. Vol. 7, Pierce County. Washington State Department of Ecology, maps, scale 1:24,000.

Washington State Department of Fisheries, 1975. A catalog of Washington streams and salmon utilization. Vol. 1, Puget Sound.

Wolcott, E.E., 1961. Lakes of Washington, Vol. 1, Western Washington. Department of Conservation, Water Supply Bulletin no. 14.

Zulauf, A., 1979. Soil survey of Pierce County area, Washington. U.S. Department of Agriculture, Soil Conservation Service, 131 p., 55 plates.

Glossary

7.5 minute quadrangle: Term for the commonly used map *scale* of 1:24,000, which covers an area measuring 7.5 minutes of latitude and 7.5 minutes of longitude.

Accuracy: How close a measured value is to a "true" value or standard.

Acre-foot: A unit commonly used for measuring volume of water, especially total water usage per year. The quantity of water required to cover one acre (43,560 square feet) to a depth of 1 foot. Equal to 43,560 cubic feet or 325,851 gallons (after Horton, 1999).

Advance outwash: Sediments deposited by meltwater streams in front of and along the margins of a *glacier* as it advances. Also see *outwash*.

Adjudication: With respect to water rights, a legal process conducted in local Superior Court to verify the validity and extent of water rights in a certain area. If a right is confirmed, the holder will receive a certificate issued by the state. Each confirmed right includes a priority date, quantity, point of diversion, and place of use. Ecology will protect and enforce the elements of a right as stated on the certificate once a vested right is confirmed and a certificate is issued.

Anion: A negatively charged *ion*.

Aquifer: The water-saturated portion of a geologic *formation*, group of formations, or portion of a formation that is capable of yielding water to wells or springs in useful quantities. An aquifer is a *hydrostratigraphic unit*. Also, see *confined aquifer*, *semi-confined aquifer*, and *unconfined aquifer*.

Aquifer test: A test designed to determine the hydraulic characteristics of an *aquifer*. This is usually performed by pumping a well and monitoring the resultant water level drawdown and recovery with respect to time. Drawdown and recovery are measured in the pumping well and nearby *observation well*(s).

Aquitard: A geologic *formation*, group of formations, or portion of a formation of lower permeability than adjacent aquifers. Aquitards may or may not be saturated and tend to reduce the movement of water between *aquifers*. An aquitard is a *hydrostratigraphic unit*. Synonyms: *confining layer* or unit.

Artesian aquifer: An *aquifer* contained between two *confining units* or *aquitards*. Since the ground water in an artesian aquifer is usually under greater pressure than the atmosphere, the water level in a well completed in an artesian aquifer usually rises above the top of that aquifer. Synonym: *confined aquifer*.

Artesian well: A well completed in a *confined* or *artesian aquifer*. Also see *flowing well*.

Bank storage: The water absorbed into banks of a stream, lake, or reservoir when the stage rises above the *water table*, then returns to the channel as effluent seepage when the stage falls below the water table (after Horton, 1999).

Baseflow: That component of water contributed to a river or stream by groundwater.

Brook: A natural stream of water, smaller than a river or a creek. Especially a small stream or rivulet that breaks directly out of the ground, as from a *spring* or a *ground-water seep* (Horton, 1999).

Cation: A positively charged *ion*.

Chloride: Chlorine *anion*, Cl-, found naturally in some surface waters and ground waters and in high concentrations in seawater. Chloride concentrations exceeding 100 mg/L in coastal aquifers are a red flag with respect to *seawater intrusion*. The *maximum contaminant level* (MCL) for chloride is 250 mg/L.

Colluvium: A loose mixture of materials derived from upslope erosion.

Confined aquifer: An aquifer contained between two *confining units* or *aquitards*. Since the ground water in a confined aquifer is usually under greater pressure than the atmosphere, the water level in a well completed in a confined aquifer usually rises above the top of that aquifer. Synonym: *artesian aquifer*.

Confining unit or layer: A geologic *formation*, group of formations, or portion of a formation of lower permeability than adjacent aquifers. Confining units may or may not be saturated and tend to reduce the movement of water between aquifers. Synonym: *aquitard*.

Connate water: Water that was trapped in the interstices of a sedimentary or extrusive igneous rock at the time of deposition. It is usually highly mineralized and frequently saline (Horton, 1999).

Contour interval: Distance between *contour lines* on a *topographic* or *contour map*. Usually measured in feet or meters.

Contour line: Lines connecting points of equal elevation on a *topographic* or *contour map.*

Contour map: See *topographic map*.

Current meter: An instrument used to measure flow velocity in a stream or channel. The flowing water rotates a propeller or series of cups, which is then translated into a velocity.

Discharge zone or area: An area in which there are upward components of *hydraulic head* in the *aquifer*. Ground water is flowing toward the surface in a discharge area and may escape as a *spring*, *ground-water seep*, or *baseflow*, or by *evaporation* and *transpiration* (Fetter, 1980).

Drawdown: In a well, the water-level decline induced by pumping. It is measured by subtracting the pumping water level from the static (pre-pumping) water level.

Drift: See glacial drift.

Duff: A general term referring to the organic layer on top of mineral soil, consisting of fallen vegetative matter in the process of decomposition. Includes everything from litter on the surface to pure humus (after Horton, 1999).

Evaporation: The process by which water is changed from a liquid to a vapor. In hydrology, evaporation is vaporization that occurs at a temperature below the boiling point (Horton, 1999).

Evapotranspiration: Loss of water from a land area through *transpiration* from plants and *evaporation* from the soil and surface waters (Driscoll, 1986).

Flowing well: An *artesian well* were the *head* (pressure) of the *confined aquifer* in which it is completed is so great that the water level in the well rises above the land surface. In the case of a flowing well, the *potentiometric surface* of the *confined aquifer* lies above the land surface.

Flume: An open artificial chute used to channel water in a stream such that it can be measured.

Formation: A body of rock or soil of considerable thickness that has characteristics making it distinguishable from adjacent geologic structures (Horton, 1999).

Glacial drift: A general term applied to glacially transported and deposited rock material (clay, silt, sand, gravel, cobbles and/or boulders). It is deposited by or from glacial ice and/or by water emanating from a glacier (Gary & Others, 1974).

Glacier: A large ice mass formed on land by the compaction and recrystallization of snow, that moves very slowly downslope or outward under its own weight (Horton, 1999).

Glaciolacustrine: A term which refers to suspended material carried by meltwater streams that is eventually deposited as sediment in glacial lakes (Gary & Others, 1974).

Global Positioning System (GPS): System that determines latitude and longitude of a location on the ground by using a computerized receiver and a system of satellites.

Ground-water discharge: The flow of water from the *saturated zone* – usually to the ground surface or a surface water body in the form of a *spring* or a *ground-water seep*.

Ground-water recharge: Inflow of water from the surface into the *saturated zone*. Infiltration of precipitation and its movement to the water table is one form of natural recharge (after Horton, 1999). Also see *ground-water discharge*.

Ground-water seep: A place where ground water oozes or trickles from the ground. Similar to a *spring*, but not as prolific.

Head: See hydraulic head.

Heterogeneous: In the context of this study, a *hydrostratigraphic unit* where the properties (i.e. porosity, *hydraulic conductivity*, etc.) are not uniformly distributed throughout the entire unit.

Hydraulic conductivity: The ability of an aquifer to transmit water. Hydraulic conductivity is expressed as the volume of water at the prevailing kinematic viscosity, that will move through a unit area of aquifer at right angles to the flow direction, per unit hydraulic gradient, per unit time.

Hydraulic gradient: The change in total *hydraulic head* in an aquifer over a horizontal distance. Expressed as h/d where h is the difference in total measured hydraulic head between two points in an aquifer that are separated by horizontal distance, d. Gradient is slope. In simple terms, water always runs downhill.

Hydraulic head (total): The sum of the elevation head, pressure head, and velocity head at any given point in an aquifer. In an *unconfined aquifer*, it is represented by the elevation of the water table. In a confined aquifer, it is represented by the elevation of the water in a well. Often simply referred to as *head*.

Hydrograph: A graphical plot of stream discharge data or ground-water heads with respect to time.

Hydrostratigraphic unit: A *formation*, group of formations, or part of a formation that can be grouped into aquifers or aquitards/confining layers based on hydrologic similarities.

Ion: An electrically charged atom or group of atoms. An *anion* has a negative charge while a *cation* has a positive charge.

Interglacial: Occurring between major glacial advances. An interglacial period is characterized by warmer temperatures and non-glacial deposition. We are currently in an interglacial period.

Lacustrine deposits: Sediments deposited in a lake. Commonly include laminated silt due to seasonal variations the “quiet water” environment.

Leaky aquifer: An aquifer that gains or looses water through an overlying or underlying semi-permeable or discontinuous *aquitard* or *confining unit*.

Lithology: A term used to describe rocks or sediments with regard to their color, texture, mineral composition, structure, or grain size.

Maximum contaminant level (MCL): The maximum permissible level of a contaminant in water that is delivered to any user of a public water system. Primary MCLs are human health-based standards. Secondary MCLs are aesthetic standards, relating to taste, odor, and color. MCL's are enforceable standards established by the U.S. Environmental Protection Agency (EPA) and adopted by the states.

Methemoglobinemia: Acquired (as opposed to hereditary) methemoglobinemia can occur from the ingestion of certain drugs and chemicals that produce an overabundance of oxidized compounds in the bloodstream. These compounds reduce the ability of the blood to carry oxygen, resulting in symptoms ranging from a bluish discoloration of the skin and mucous membrane to weakness, difficulty in breathing, and dizziness in more severe cases. In elevated concentrations, *nitrate* is one of these compounds. In the gastrointestinal tract, nitrate is converted to nitrite through reactions with bacteria. Nitrite subsequently reacts with hemoglobin to form methemoglobin, which cannot carry oxygen. If more than 10% of hemoglobin is replaced by methemoglobin, the above symptoms result. Infants are particularly susceptible to nitrate-induced methemoglobinemia. It is also know as "blue baby syndrome." Methemoglobinemia is a particular problem in rural areas, due to the abundance of nitrate sources such as septic systems, fertilizers, and animal wastes. Boiling increases the concentration of nitrate in water.

Nitrates: Nitrates represent a class of chemical compounds having the formula NO_3-. Nitrate salts are used as fertilizers to supply nitrogen for plant growth. Nitrate additions to surface waters can lead to excessive growth of aquatic plants (like algae). The presence of nitrates in ground water occurs from the conversion of nitrogenous matter into nitrates. For example, ammonia in septic system discharge is oxidized by bacterial or chemical reactions, first into nitrite and then into nitrate. Elevated ground-water nitrate concentrations can cause *methemoglobinemia*, otherwise known as "blue baby syndrome" in infants. The *maximum contaminant level* (MCL) for nitrate is 10 mg/L (after Horton, 1999).

Observation well: A non-pumping well used to measure *hydraulic head* changes in the *water table* or *potentiometric surface* resulting from seasonal water level fluctuations or ground-water withdrawal at a nearby pumping well.

Outwash: Stratified deposits of sand, gravel, and larger particles formed by streams of meltwater flowing from a glacier. Outwash deposited during glacial advances is called *advance outwash*, while outwash deposited during glacial retreats is referred to as *recessional outwash*. Coarser material is deposited closer to the ice while finer material is deposited farther from the ice (after Horton, 1999, Driscoll, 1986, and Gary & Others, 1974).

pH (potential of hydrogen or hydrogen *ion* concentration): A method for expressing the acidity or alkalinity of a solution in terms of the negative logarithm of the hydrogen ion concentration. The pH scale runs from 0 to 14. A pH value of 7.0 indicates a neutral solution. Values above 7.0 indicate alkalinity; those below 7.0 indicate acidity. Natural waters usually have a pH between 6.5 and 8.5. Because the units are derived from common logarithms, a difference of one pH unit indicates a tenfold (10^1) difference in acidity or alkalinity. Similarly, a difference of two pH units indicates a hundred-fold (10^2) difference in acidity or alkalinity (after Horton, 1999).

Permeability: The capacity of soil, sediment, or fractured/porous rock to transmit water. Permeability is equal to velocity of flow divided by the *hydraulic gradient* (after Horton, 1999).

Porosity: The percentage of void space in a porous medium relative to the total volume of porous medium. *Primary porosity* refers to the spaces between mineral grains or rock fragments in a rock matrix. *Secondary porosity* refers to void space created by the fracturing or dissolution of rocks after their initial deposition or emplacement.

Potentiometric surface: A surface that represents the static *hydraulic head* of ground water in tightly cased wells that tap a *confined aquifer*. It is defined by the levels to which water will rise in the well casings. The *water table* is the potentiometric surface of an *unconfined aquifer* (after Horton, 1999).

Precision: How close a group of measurements are to each other. A measuring device or method can produce precise results that are not necessarily accurate. An example would be a cluster of marks near the edge of a target - instead of near the center.

Proglacial lake: A lake formed at the terminus of a *glacie*r by damming from glacial ice and/or glacial sediments.

Quaternary Period: A period consisting of approximately the last 2 million years of earth history, encompassing both the Pleistocene and Holocene epochs (Horton, 1999).

Recharge zone or area: Those areas of an *aquifer* where there are vertical components of *hydraulic head* in a downward direction. Water moves downward into deeper parts of an aquifer in a recharge area.

Recovery: The rise of water levels in a pumping or observation well that occurs after pumping ceases.

Recessional outwash: Glacial sediments deposited by meltwater streams in front of and along the margins of a glacier as it retreats. Also see *outwash*.

Saturated zone: That portion of the subsurface where all interconnected voids are filled with water.

Scale: With respect to maps, the relationship between the distance on the map and the distance on the ground. Often expressed as a ratio, such as 1:24,000, which means that one unit on the map equals 24,000 of the same units on the ground. Small-scale maps include more area, meaning the features on them are smaller and therefore more general. Large-scale maps include less area, meaning the features on them are larger and they can include information that is more detailed. 1:24,000 is a larger scale commonly used for mapping topography and geology in Washington. It is also know as a *7.5 minute quadrangle*.

Seawater intrusion: The invasion of a body of freshwater by a body of salt water, due to its greater density. It can occur either in surface or ground-water bodies. The term is applied to the flooding of freshwater marshes by seawater, the migration of seawater up rivers and navigation channels, and the movement of seawater into freshwater aquifers along coastal regions (after Horton, 1999).

Semi-confined aquifer: An *aquifer* which exhibits properties of a *confined aquifer* during short-term *aquifer tests*, but which over a long-term test will begin to exhibit properties common to an *unconfined aquifer*. Semi-confined conditions are often caused by a discontinuous overlying *aquitard*.

Soil moisture (or soil water): Water diffused in the upper part of the *unsaturated zone* of the soil, from which water is discharged by the *transpiration* of plants, by *evaporation*, or by *interflow*. Also referred to as "soil moisture content" or "available water content" (Horton, 1999).

Soil-moisture deficit: The difference between the *soil-moisture holding capacity* and the instantaneous *soil moisture* (Horton, 1999)

Soil-moisture holding capacity: The maximum amount of water that the *unsaturated zone* of a soil can hold under the influence of gravity.

Specific capacity: A measure of a wells production capacity defined as the yield per unit drawdown. Specific capacity is usually expressed in units of gallons per minute per foot of drawdown (gpm/ft).

Specific conductance or conductivity: A measure of the ability of a solution at 25 ºC to conduct an electrical current as measured within a square centimeter. In solution, electrical current flows by *ion* transport. The more ions in solution, the higher the specific conductance. Specific conductance is expressed in units of electrical conductance, usually micromhos (µmhos ; pronounced "micomoze") or microsiemens (µS) per centimeter. It can be used for approximating the total dissolved solids (TDS) content of water.

Specific yield: The ratio of the volume of water that will drain from a porous medium under the influence of gravity, relative to the total volume of material.

Spring: (1) A concentrated discharge of ground water emerging at the surface as flowing water. (2) A place where ground water flows from rock or soil to the land surface or into a body of surface water. Its occurrence depends on the nature and relationship of the rocks and/or soil, especially the permeability. It also depends on the position of the *water table* (*saturated zone*) and on the *topography* (after Horton, 1999).

Stade: A climatic episode within a glacial stage during which a secondary advance of glaciers occurred (Gary & Others, 1974).

Static water level: The water level in a well that is not being affected by withdrawal of ground water (Driscoll, 1986).

Storativity: The volume of water released from or taken up by an aquifer, per unit area of aquifer, per unit change in head.

Sub-basin: A portion of a *watershed* or basin drained by a single stream or group of minor streams (after Horton, 1999).

Tectonic: Relating to the structure of rocks that result from movement and subsequent deformation in the crust of the earth.

Theodolite: An optical surveying instrument for measuring horizontal and vertical angles. It consists of a small sighting telescope mounted on a tripod. It can be rotated in both the horizontal and vertical planes. A spirit level is used to indicate when the instrument is horizontal. Newer models are digital.

Till: A *heterogeneous* mixture (generally unsorted, unstratified, and unconsolidated) of clay, sand, gravel, cobbles and boulders deposited directly by and underneath a glacier without subsequent reworking by glacial meltwater.

Topographic map: Map with lines or contours connecting points of equal elevation. These maps depict surface relief (such as hills and valleys) and show surface features, including rivers, lakes; roads, and cities. The distance between *contour lines* is referred to as a *contour interval* and is measured in feet or meters. Also referred to as a *contour map*.

Topography: The general configuration of the land surface, including surface relief and position of the natural and man-made features (Horton, 1999).

Transmissivity: The rate that water is transmitted through a unit width of *aquifer* under a unit *hydraulic gradient* – essentially a measure of an aquifer's ability to transmit water. Transmissivity is equal to the aquifer *hydraulic conductivity* multiplied by aquifer thickness.

Transpiration: The movement of water from soil or ground water to the atmosphere via plants – primarily through the leaves (after Horton, 1999).

Unconfined aquifer: An *aquifer* that is not separated from land surface by an intervening *confining layer*. This type of aquifer is not under pressure like a *confined aquifer*. Consequently, the water level in a well completed in an unconfined aquifer is the same as the water table. Synonym: *water table aquifer*.

Underflow: Water that infiltrates into the soil and moves down slope as lateral, unsaturated flow in the soil zone. Also referred to as "throughflow".

Unsaturated zone: (1) The portion of the subsurface containing both air and water in the voids between soil particles. (2) The zone between the ground surface and the *water table* (or *saturated zone)* where some of the voids between soil particles are filled with air. Water in this zone cannot enter a well. Also referred to as the *vadose zone (after Horton, 1999)*.

Vadose zone: See *unsaturated zone*.

Wading rod: A rod to which a *current meter* is attached, used for wading into streams to take flow measurements.

Water budget: A conceptual evaluation of water input, output, and storage in a hydrogeologic unit or *watershed*.

Water-quality standard: A legally enforceable state-adopted and U.S. Environmental Protection Agency-approved ambient standard for water bodies. Standards include the use of the water body and the water-quality criteria that must be met to protect the designated use or uses.

Water Resource Inventory Area (WRIA): Following the Water Resources Management Act of 1971, Washington State was divided into 62 different areas for the purpose of water management. Each WRIA is a major *watershed* within which there are many *sub-basins*.

Watershed: A region or area bounded peripherally by major drainage divides, ultimately draining to a particular watercourse or body of water. Watersheds are divided into *sub-basins*. Synonyms: water basin or drainage basin (after Horton, 1999).

Water table: The top of the *saturated zone* in an *unconfined aquifer*. Here, aquifer pressure is equal to atmospheric pressure. Synonym: ground-water table.

Water table aquifer: See *unconfined aquifer*.

Water year: The 12-month period, October 1 through September 30. The water year is designated by the calendar year in which it ends. For example, the 2000 water year ends on September 30, 2000 (Horton, 1999).

Well (water): An excavation (pit, hole, tunnel), generally cylindrical in form and often walled in or cased, drilled, dug, driven, bored, or jetted into the ground to such a depth as to penetrate water-yielding geologic material and allow the water to flow or to be pumped to the surface (after Horton, 1999).

Well, fully penetrating: A well that is screened or perforated across the full, saturated thickness of an *aquifer*.

Well, partially penetrating: A well that is not screened or perforated across the full, saturated thickness of an *aquifer*.

Wellhead: The physical structure, facility, or device at the land surface from or through which ground water flows or is pumped from subsurface water-bearing *hydrostratigraphic units* (from Horton, 1999).

Wellhead elevation: The ground elevation at the base of the wellhead.

Well interference: A water level and/or discharge decline in a well resulting from pumping a neighboring well.

Zone of Diffusion: In coastal aquifers, the interface between freshwater and salt water. The zone of diffusion can migrate landward or seaward, depending on local conditions. Withdrawal of ground water from coastal aquifers can result in the landward migration of salt water, creating what is known as *seawater intrusion*. Also known as the "zone of transition" or the "freshwater-seawater interface."

Appendix A. Ground-Water-Level Data

Table A1. Vashon aquifer monitoring well and spring water-level data.

S* = spring/collector trench (very shallow well); P = pumping during sampling; R = recently pumped prior to sampling; T = recent pumping in nearby well; Z = other

Unique Well ID	Date Measured	Land Surface Elevation (feet above msl)	Water Level Elevation (feet above msl)	Depth Below Land Surface (feet)	Depth Below Measuring Point (feet)	Comment
AAF220	6/3/97	175	141.6	33.4	34	
	9/24/97	175	138.1	36.9	37.5	
	12/17/97	175	138.2	36.8	36.8	
	3/12/98	175	143.5	31.9	32.5	
AAF221	6/3/97	172	139.9	32.1	33.2	
	9/23/97	172	136.4	35.6	36.7	
	10/29/97	172	136	36.1	37.2	Z
	11/20/97	172	136.1	35.9	37	Z
	12/17/97	172	136.5	35.6	36.7	Z
	1/16/98	172	139.9	32.1	33.2	Z
	2/11/98	172	135.8	36.2	37.4	Z
	3/12/98	172	138.1	33.9	35.1	
	4/21/98	172	140.8	31.3	32.4	Z
	5/28/98	172	139.1	33	34.1	Z
AAF224	6/4/97	177	148.8	28.2	29.7	
	9/23/97	177	148.1	28.9	30.4	
	12/17/97	177	147.3	29.7	31.2	
	3/12/98	177	149	28	29.5	
AAF226	6/4/97	159	120.8	38.3	39.5	
	9/24/97	159	119.1	40	41.2	
	12/17/97	159	117.8	41.2	42.4	
	3/12/98	159	118.9	40.1	41.3	
AAF228S*	6/5/97	125	123.4	1.6	2.4	
	9/23/97	125	115.5	9.5	10.3	
	10/29/97	125	120	5	5.8	R
	11/20/97	125	123.3	1.7	2.5	Z
	12/17/97	125	123.7	1.3	2.1	R
	1/16/98	125	123.9	1.2	2	Z
	2/11/98	125	124	1	1.8	R
	3/12/98	125	123.5	1.5	2.3	
	4/21/98	125	121.9	3.2	4	R
	5/28/98	125	119.5	5.5	6.3	R
AAF353	6/3/97	255	197.7	57.3	60.4	
	9/23/97	255	195.8	59.2	62.3	
	10/24/97	255	195.3	59.8	62.9	
	11/29/97	255	195.1	59.9	63	
	12/17/97	255	194.9	60.1	63.2	
	1/14/98	255	194.7	60.3	63.4	
	2/12/98	255	195.7	59.3	62.4	

Table A1. Vashon aquifer monitoring well and spring water-level data--Continued.

S* = spring/collector trench (very shallow well); P = pumping during sampling; R = recently pumped prior to sampling; T = recent pumping in nearby well; Z = other

Unique Well ID	Date Measured	Land Surface Elevation (feet above msl)	Water Level Elevation (feet above msl)	Depth Below Land Surface (feet)	Depth Below Measuring Point (feet)	Comment
AAF353	3/13/98	255	195.9	59.1	62.2	
cont.	4/16/98	255	196.1	58.9	62	
	5/28/98	255	195.2	59.8	62.9	
AAF357	6/3/97	183	146.2	36.8	37.2	
	9/23/97	183	143.3	39.7	40.1	
	12/17/97	183	143.2	39.8	40.2	
	3/12/98	183	145.3	37.7	38.1	
AAF360	6/4/97	179	177.9	1.1	2.4	
	9/23/97	179	174	5	6.4	
	12/17/97	179	173.8	5.2	6.6	
	3/12/98	179	177.3	1.7	3.1	
ABE909	6/4/97	228	173.3	54.7	56.5	
	9/23/97	228	168.6	59.4	61.2	
	10/24/97	228	167.6	60.5	62.3	
	11/29/97	228	166.9	61.1	62.9	
	12/17/97	228	166.4	61.6	63.4	
	1/14/98	228	167.3	60.7	62.5	
	2/12/98	228	169.7	58.3	60.1	
	3/12/98	228	170.7	57.3	59.1	
	4/16/98	228	170.7	57.3	59.1	
	5/28/98	228	169.9	58.1	59.9	
ABS289S*	6/4/97	170	168.2	1.8	2.2	

Table A2. Sea Level aquifer monitoring well water-level data.

P = pumping during sampling; R = recently pumped prior to sampling; T = recent pumping in nearby well; Z = other

Unique Well ID	Date Measured	Land Surface Elevation (feet above msl)	Water Level Elevation (feet above msl)	Depth Below Land Surface (feet)	Depth Below Measuring Point (feet)	Comment
AAE123	9/25/97	136	7.3	128.8	130.3	
	12/18/97	136	6.7	129.3	130.8	
AAF216	6/3/97	173	7.1	165.9	167.2	
	9/23/97	173	8	165	166.3	12:25
	9/24/97	173	8.2	164.8	166.1	13:18
	9/25/97	173	8.2	164.8	166.1	9:00
	9/25/97	173	7.2	165.8	167.1	12:20
	9/25/97	173	8.1	164.9	166.2	13:15
	10/24/97	173	7.2	165.9	167.2	
	11/29/97	173	7.8	165.2	166.5	
	12/17/97	173	8	165	166.3	
	1/14/98	173	7.6	165.4	166.7	
	2/12/98	173	7.4	165.6	166.9	
	3/12/98	173	7.3	165.7	167	
	4/16/98	173	7.5	165.5	166.8	
	5/28/98	173	6.4	166.6	167.9	
AAF217	6/3/97	34	6.2	27.8	29.7	R
	9/23/97	34	6.8	27.3	29.1	
	12/17/97	34	7.9	26.1	28	
	3/12/98	34	6.7	27.3	29.1	
AAF218	6/3/97	44	8.3	35.7	36.4	
	9/23/97	44	8.5	35.5	36.2	R
	10/29/97	44	8.2	35.8	36.5	R
	11/20/97	44	10.9	33.1	33.8	Z
	12/17/97	44	9.1	34.9	35.6	R
	1/16/98	44	9.7	34.3	35	R
	2/11/98	44	9.5	34.5	35.2	R
	3/12/98	44	8.6	35.4	36.1	
	4/1/98	44	8.1	35.9	36.6	R
	5/28/98	44	8.2	35.8	36.5	R
AAF219	6/3/97	33	9.3	23.8	24.7	
	9/23/97	33	9.5	23.6	24.5	
	12/17/97	33	10.7	22.3	23.2	R
	3/12/98	33	9.6	23.4	24.3	
AAF222	6/4/97	56	3.9	52.1	52.9	
	9/24/97	56	4.1	52	52.7	
	10/29/97	56	3.7	52.4	53.1	T
	11/20/97	56	4.6	51.4	52.1	Z
	12/17/97	56	4.8	51.3	52	R

Table A2. Sea Level aquifer monitoring well water-level data--Continued.

P = pumping during sampling; R = recently pumped prior to sampling; T = recent pumping in nearby well; Z = other

Unique Well ID	Date Measured	Land Surface Elevation (feet above msl)	Water Level Elevation (feet above msl)	Depth Below Land Surface (feet)	Depth Below Measuring Point (feet)	Comment
AAF222 cont.	1/16/98	56	5	51	51.8	R
	2/11/98	56	4.6	51.4	52.2	R
	3/12/98	56	4.3	51.8	52.5	
	4/21/98	56	3.9	52.2	52.9	Z
	5/28/98	56	3.9	52.2	52.9	Z
AAF355	6/3/97	35	5.5	29.5	30.2	
AAF356	6/3/97	92	14	78	78.9	
	9/23/97	92	13.8	78.2	79.1	
	12/17/97	92	13.9	78.1	79	
	3/12/98	92	14.2	77.8	78.7	
AAF358	6/4/97	42	3.6	38.4	38.8	
	9/23/97	42	6.4	35.6	36	
	10/24/97	42	4	38	38.4	
	11/29/97	42	6.9	35.1	35.5	
	12/17/97	42	7.4	34.6	35	
	1/14/98	42	6.1	35.9	36.3	
	2/12/98	42	6.2	35.8	36.2	
	3/12/98	42	5.2	36.8	37.2	
	4/16/98	42	6.2	35.8	36.2	
	5/28/98	42	2.4	39.6	40	
AAF359	6/4/97	47	2.6	44.4	44.5	
	9/23/97	47	5.3	41.7	41.8	
	12/17/97	47	6.1	40.9	41.1	
	3/12/98	47	4	43	43.1	
AAF361	6/4/97	133	21.3	111.8	113.3	
	9/23/97	133	21.4	111.7	113.2	
	10/24/97	133	21.2	111.9	113.4	
	11/29/97	133	21.7	111.3	112.9	
	12/17/97	133	21.3	111.7	113.3	
	1/14/98	133	21.7	111.3	112.9	
	2/12/98	133	21.8	111.2	112.8	
	3/12/98	133	21.5	111.6	113.1	
	4/16/98	133	21.2	111.8	113.4	
	5/28/98	133	21.1	111.9	113.5	
AAF362	6/5/97	96	6.3	89.7	90.2	
	9/23/97	96	6.7	89.3	89.8	
	10/24/97	96	6.8	89.2	89.6	
	11/29/97	96	7.5	88.5	89	

Table A2. Sea Level aquifer monitoring well water-level data--Continued.

P = pumping during sampling; R = recently pumped prior to sampling; T = recent pumping in nearby well; Z = other

Unique Well ID	Date Measured	Land Surface Elevation (feet above msl)	Water Level Elevation (feet above msl)	Depth Below Land Surface (feet)	Depth Below Measuring Point (feet)	Comment
AAF362	12/17/97	96	6.8	89.2	89.6	Z
cont.	1/14/98	96	7.2	88.8	89.2	
	2/12/98	96	7.2	88.8	89.3	
	3/12/98	96	7.8	88.2	88.6	
	4/16/98	96	7.1	88.9	89.4	
	5/28/98	96	6.4	89.6	90.1	
AAF363	6/5/97	35	15.3	19.7	20.7	P
AAF364	6/5/97	50	2.3	47.8	49.1	
	9/23/97	50	4.3	45.7	47	
	12/17/97	50	4.3	45.7	46.6	
	3/12/98	50	2.8	47.2	48.5	
ABF485	6/5/97	180	16.3	163.8	164.8	
	11/20/97	180	17.7	162.4	163.4	Z
	12/17/97	180	17.1	162.9	163.9	R
	1/16/98	180	17.7	162.3	163.3	Z
	2/11/98	180	15.9	164.1	165.1	Z
	3/12/98	180	17.8	162.2	163.2	
	4/21/98	180	16.5	163.5	164.5	Z
	5/28/98	180	16	164	165	Z
ABM983	9/25/97	198	12	186	187	
	12/18/97	198	12.5	185.5	186.5	
ABM984	9/25/97	193	2.4	190.6	191.7	
ABM985	9/25/97	111	25.9	85.1	87.1	
	3/12/98	111	26.8	84.2	86.2	Z
ABM986	12/18/97	254	8.8	245.2	246.1	
	3/12/98	254	19.3	234.7	235.5	R
ABM987	9/25/97	195	23.2	171.8	172.5	
	12/18/97	195	12.5	182.5	183.3	
ABM988	9/25/97	200	6.4	193.6	196	
	12/18/97	200	7.4	192.6	195	
ABM990	9/25/97	106	14.7	91.3	92.6	
	12/18/97	106	19.4	86.6	87.9	P
	3/12/98	106	15.4	90.6	91.9	

Table A2. Sea Level aquifer monitoring well water-level data--Continued.

P = pumping during sampling; R = recently pumped prior to sampling; T = recent pumping in nearby well; Z = other

Unique Well ID	Date Measured	Land Surface Elevation (feet above msl)	Water Level Elevation (feet above msl)	Depth Below Land Surface (feet)	Depth Below Measuring Point (feet)	Comment
ABM991	9/25/97	156	20.4	135.6	136.6	
	12/18/97	156	20.1	135.9	136.9	
ABS280	6/3/97	56	-4	60	60.4	
	9/23/97	56	-4.4	60.4	60.8	
	12/18/97	56	-3.4	59.4	59.8	
	3/13/98	56	-7.5	63.5	63.9	
ABS281	6/3/97	100	3.4	96.6	98.5	
	9/23/97	100	5	95	96.9	
	10/29/97	100	4.5	95.5	97.4	R
	11/20/97	100	8.8	91.2	93.1	Z
	12/17/97	100	7	93	94.9	R
	1/16/98	100	8.6	91.4	93.3	R
	2/11/98	100	6.6	93.4	95.3	R
	3/12/98	100	7.1	93	94.9	R
	4/12/98	100	5.9	94.1	96	
	5/28/98	100	7.6	92.4	94.3	
ABS282	6/3/97	34	11.6	22.4	22.7	
	9/23/97	34	11.4	22.6	22.9	
	12/17/97	34	12.1	21.9	22.3	
	3/12/98	34	12.1	21.9	22.2	
ABS283	6/3/97	97	13.2	83.8	84.1	
	9/24/97	97	13.3	83.8	84.1	
	12/18/97	97	13.5	83.5	83.8	Z
	3/13/98	97	12.2	84.8	84.1	
ABS284	6/4/97	125	-3.8	128.9	130.3	
	9/24/97	125	-3.2	128.2	129.6	
	12/17/97	125	-3.2	128.2	129.6	
	3/13/98	125	-3.5	128.5	129.9	
ABS285	6/4/97	210	3.9	206.1	206.5	
	9/25/97	210	-1.9	212	212.4	
ABS286	6/4/97	181	5.4	175.6	174.1	
ABS287	6/4/97	49	1.5	47.5	47.9	
	9/24/97	49	2.9	46.1	46.5	
	10/24/97	49	2.8	46.2	46.6	
	11/29/97	49	5.1	43.9	44.3	
	12/17/97	49	4	45	45.4	

Table A2. Sea Level aquifer monitoring well water-level data--Continued.

P = pumping during sampling; R = recently pumped prior to sampling; T = recent pumping in nearby well; Z = other

Unique Well ID	Date Measured	Land Surface Elevation (feet above msl)	Water Level Elevation (feet above msl)	Depth Below Land Surface (feet)	Depth Below Measuring Point (feet)	Comment
ABS287 cont.	1/14/98	49	5.1	43.9	44.3	
	2/12/98	49	4.8	44.2	44.6	
	3/12/98	49	3.8	45.2	45.6	
	4/16/98	49	4.8	44.2	44.6	
	5/28/98	49	1.6	47.4	47.8	
ABS288	6/4/97	65	8.3	56.7	57.4	
	9/24/97	65	8.6	56.4	57.1	
	12/17/97	65	8.6	56.4	57.1	
	3/12/98	65	8.9	56.1	56.8	
ABS290	6/5/97	72	8.8	63.2	63.7	
	9/23/97	72	9	63	63.5	
	10/29/97	72	9.5	62.5	63	Z
	11/20/97	72	9.6	62.4	62.9	Z
	12/17/97	72	9.6	62.4	62.9	Z
	1/16/98	72	9.3	62.7	63.2	Z
	2/11/98	72	9.5	62.5	63	Z
	3/12/98	72	10.3	61.8	62.3	
	4/12/98	72	9.2	62.9	63.4	Z
	5/28/98	72	9	63	63.5	Z
ACN797	3/13/98	60	-9.7	69.7	70.2	

Appendix B. Water-Quality Data

Table B1. Nitrate concentrations in monitoring wells and springs.

Hach Kit detection limit 0.01; W = well; S = spring; C = collector trench (very shallow well)

Unique Well ID	Source	Nitrate Concentration (mg/L as NO3)	Date Sampled
AAF216	W	< 0.01	6/3/97
AAF217	W	0.02	6/3/97
AAF218	W	< 0.01	6/3/97
AAF219	W	0.02	6/3/97
AAF220	W	< 0.01	6/3/97
AAF221	W	< 0.01	6/3/97
AAF222	W	0.05	6/4/97
AAF223	W	< 0.01	6/3/97
AAF224	W	< 0.01	6/3/97
AAF226	W	< 0.01	6/4/97
AAF227S	S	0.01	6/4/97
AAF228S	C	< 0.01	6/4/97
AAF229S	S	0.03	6/4/97
AAF230S	S	0.04	6/4/97
AAF353	W	< 0.01	6/3/97
AAF354	W	< 0.01	6/3/97
AAF355	W	0.02	6/3/97
AAF356	W	0.12	6/3/97
AAF357	W	< 0.01	6/3/97
AAF358	W	0.05	6/3/97
AAF359	W	< 0.01	6/4/97
AAF360	W	< 0.01	6/4/97
AAF362	W	< 0.01	6/5/97
AAF363	W	0.02	6/5/97
AAF364	W	< 0.01	6/5/97
ABE909	W	< 0.01	6/4/97
ABF485	W	< 0.01	6/5/97
ABS280	W	< 0.01	6/3/97
ABS281	W	0.19	6/3/97
ABS282	W	< 0.01	6/3/97
ABS283	W	< 0.01	6/3/97
ABS284	W	0.04	6/3/97
ABS285	W	< 0.01	6/3/97
ABS286	W	< 0.01	6/3/97
ABS287	W	0.02	6/4/97
ABS288	W	0.03	6/4/97
ABS289S	C	0.02	6/4/97
ABS290	W	< 0.01	6/5/97
ACN797	W	0.02	6/3/97

Table B2. Chloride concentrations, temperature, specific conductance, and pH in Vashon aquifer monitoring wells and springs.

* = parameter not measured

Unique Well ID	Date Sampled	Chloride (mg/L), field analysis	Chloride (mg/L), lab analysis	Temperature (degrees C)	Specific Conductance (umhos/cm2)	pH	Comment
AAF220	6/3/97	10	*	10.9	165	7	
	9/24/97	*	4	12.5	120	7	
	12/17/97	*	4	10.6	170	*	
	3/12/98	*	4	*	140	*	
AAF221	6/3/97	10	*	12.1	141	6.9	
	9/23/97	*	5	12.9	120	7.5	
	9/23/97	*	5	12.9	120	*	lab duplicate
	12/23/97	*	5	10.8	140	*	
	3/12/98	*	5	*	100	*	
AAF224	6/4/97	5	*	11.7	160	6.7	
	9/23/97	*	3	12.7	170	*	
	12/17/97	*	2	10.4	70	*	
	3/12/98	*	2	*	80	*	
AAF226	6/4/97	20	17	11.6	236	6.5	
	9/23/97	*	5	12.1	190	6.8	
	12/23/97	*	16	*	*	*	
	12/25/97	*	*	8.1	250	*	
	3/12/98	*	5	*	*	*	
AAF228	6/5/97	5	4	14.1	92	5.7	collector trench
	9/23/97	*	6	14.9	90	*	“
	12/17/97	*	4	10.8	90	*	“
	3/12/98	*	4	*	80	*	“
AAF229S	6/5/97	15	1	12.2	216	6.2	spring
AAF230S	6/4/97	10	*	13.5	127	5.9	spring
AAF353	2/24/95	*	42	*	294	*	TPCHD analysis
	6/3/97	10	*	11.7	140	7.4	
	9/23/97	*	5	12.2	130	7.9	
	12/17/97	*	4	10	150	*	
	12/17/97	*	4	*	*	*	lab duplicate
	3/13/98	*	4	*	60	*	
AAF357	6/3/97	10	*	16.6	210	6.9	
	9/23/97	*	3	14.6	190	7.2	
	3/12/98	*	3	*	200	*	

Table B2. Chloride concentrations, temperature, specific conductance, and pH in Vashon aquifer monitoring wells and springs--Continued.

* = parameter not measured

Unique Well ID	Date Sampled	Chloride (mg/L), field analysis	Chloride (mg/L), lab analysis	Temperature (degrees C)	Specific Conductance (umhos/cm2)	pH	Comment
AAF360	6/4/97	10	*	12.1	120	6.8	
	9/23/97	*	4	14	120	7.6	
	12/17/97	*	3	8.5	140	*	
	12/23/97	*	*	11	130	*	
	3/12/98	*	3	*	140	*	
	3/12/98	*	3	*	140	*	lab duplicate
ABE909	6/4/97	10	*	11.2	100	7	
	9/23/97	*	4	12	120	7.7	
	3/26/98	*	3	10	120	*	
ABS283S	6/3/97	10	*	13	70	6.4	spring, house supply
ABS289S	6/4/97	10	7	12.2	130	6.5	collector trench

Table B3. Chloride concentrations, temperature, specific conductance, and pH in Sea Level aquifer monitoring wells.

* = parameter not measured

Unique Well ID	Date Sampled	Chloride (mg/L), field analysis	Chloride (mg/L), lab analysis	Temperature (degrees C)	Specific Conductance (umhos/cm2)	pH	Comment
AAE123	12/16/96	*	3	*	131	*	
AAF216	6/3/97	5	*	11.2	140	7.7	
	9/23/97	*	4	11.1	120	*	
	12/17/97	*	4	9.5	160	*	
	12/17/97	*	4	9.5	160	*	lab duplicate
	3/12/98	*	3	*	160	*	
AAF217	6/3/97	260	347	11.2	1302	6.6	
	6/3/97	*	338	11.2	1302	6.6	lab duplicate
	9/23/97	*	216	11.5	830	*	
	12/17/97	*	198	10.9	1230	*	
	12/17/97	*	235	10.9	1230	*	lab duplicate
	3/12/98	*	160	*	910	*	
	3/12/98	*	164	*	910	*	lab duplicate
AAF218	6/3/97	30	*	11	616	6.8	
	9/23/97	*	23	12	560	*	
	9/23/97	*	23	12	560	*	lab duplicate
	12/17/97	*	22	10.8	640	*	
	3/12/98	*	22	*	600	*	
AAF219	6/3/97	25		11.4	373	6.8	
	9/23/97	*	15	13.2	310	*	
	12/17/97	*	14	10.6	180	*	
	3/12/98	*	13	*	350	*	
AAF222	6/4/97	80	68	12	458	6.8	
	9/24/97	*	54	13.8	350	6.7	lab duplicate
	9/24/97	*	57	13.8	350	6.7	
	12/17/97	*	123	10.6	510	*	
	3/12/98	*	35	*	340	*	
AAF223	6/4/97	10	*	14.6	210	7.1	from cistern by well
	9/24/97	*	6	17.3	160	7.5	
AAF265	9/23/97	*	79	10.9	560	*	
	3/13/98	*	85	*	640	*	
	3/13/98	*	87	*	640	*	field duplicate
	3/26/98	*	100	10	640	*	lab duplicate
AAF354	6/3/97	260	209	13.1	840	7.2	
	9/23/97	*	207	12	790	7.7	
	12/17/97	*	207	10	900	*	

Table B3. Chloride concentrations, temperature, specific conductance, and pH in Sea Level aquifer monitoring wells--Continued.

* = parameter not measured

Unique Well ID	Date Sampled	Chloride (mg/L), field analysis	Chloride (mg/L), lab analysis	Temperature (degrees C)	Specific Conductance (umhos/cm2)	pH	Comment
AAF354	3/12/98	*	198	*	910	*	
AAF355	6/3/97	15	*	12.5	140	6.7	
AAF356	6/3/97	15	*	12.7	190	7	
	9/23/97	*	5	12	180	7	
	12/17/97	*	4	10	160	*	
	3/12/98	*	4	*	200	*	
AAF358	6/4/97	10	*	14.2	90	6.9	
	9/23/97	*	3	15.6	80	6.9	
AAF358	12/17/97	*	3	11	100	*	
	3/12/98	*	2	*	90	*	
AAF359	6/4/97	240	160	14.1	730	6.9	
	9/23/97	*	167	13	680	6.9	
	9/23/97	*	174	11	770	*	field duplicate
	12/17/97	*	177	*	780	*	
AAF361	4/2/96	*	5	*	129	*	TPCHD analysis
AAF362	11/1/94	*	4	*	140	*	TPCHD analysis
	6/5/97	10	*	*	150	*	
	9/24/97	*	4	13.2	140	7.1	
	9/24/97	*	4	*	*	*	lab duplicate
	12/17/97	*	4	10.4	150	*	
	3/15/98	*	4	*	150	*	
	3/15/98	*	4	*	*	*	lab duplicate
AAF363	6/5/97	50	13	11.4	170	6.3	
	6/5/97	50	13	11.4	170	6.3	lab duplicate
AAF364	6/5/97	15	*	11.4	170	6.3	
	9/23/97	*	5	15.3	190	7.7	
	9/23/97	*	5	15.3	190	7.7	field duplicate
	12/17/97	*	4	7.5	150	*	
	12/17/97	*	4	*	150	*	field duplicate
	3/12/98	*	4	*	210	*	
ABF485	6/5/97	10	5	12.4	180	7	field duplicate as AAF486
	6/5/97	*	4			*	
	12/17/97	*	5	8.6	200	*	
	3/12/98	*	5	*	200	*	

Table B3. Chloride concentrations, temperature, specific conductance, and pH in Sea Level aquifer monitoring wells--Continued.

* = parameter not measured

Unique Well ID	Date Sampled	Chloride (mg/L), field analysis	Chloride (mg/L), lab analysis	Temperature (degrees C)	Specific Conductance (umhos/cm2)	pH	Comment
ABM984	3/29/94	*	4	*	193	*	
	1/15/97	*	5	*	206	*	
ABM985	9/28/67	*	9	*	*	7	
	1/8/97	*	8	*	165	*	
	1/16/92	*	2	*	182	*	
	10/26/95	*	14	*	207	*	
	1/8/97	*	8	*	165	*	
	9/25/97	*	11	11	160	*	
	3/12/98	*	11	*	210	*	
ABM986	10/26/95	*	8	*	182	*	
	1/17/97	*	4	*	182	*	
	9/25/97	*	5	11	160	*	
	9/25/97	*	5	*	*	*	field duplicate
	3/12/98	*	5	*	210	*	
ABM987	12/18/96	*	3	*	155	*	
ABM988	12/11/96	*	2	*	137	*	
ABM990	1/16/92	*	10	*	191	*	
	10/26/95	*	9	*	171	*	
ABM990	1/10/97	*	12	*	181	*	
	9/25/97	*	13	11	140	*	
	3/12/98	*	12	*	210	*	
	3/12/98	*	12	*	*	*	lab duplicate
ABM991	12/13/96	*	2	*	306	*	
ABS280	6/3/97	10	*	12.2	150	6.7	
	9/24/97	*	5	12.7	150	*	
	12/18/97	*	4	8.5	170	*	
	3/13/98	*	4	*	160	*	
ABS281	6/3/97	15	2	14.4	170	7.3	lab recorded as AAF281
	9/23/97	*	16	13.8	180	*	
	12/17/97	*	10	10.4	200	*	
	3/12/98	*	9	*	190	*	
ABS282	6/3/97	10	*	11.7	150	6.9	
	9/23/97	*	4	14.5	160	*	
	12/23/97	*	3	11	190	*	

Table B3. Chloride concentrations, temperature, specific conductance, and pH in Sea Level aquifer monitoring wells--Continued.

* = parameter not measured

Unique Well ID	Date Sampled	Chloride (mg/L), field analysis	Chloride (mg/L), lab analysis	Temperature (degrees C)	Specific Conductance (umhos/cm2)	pH	Comment
ABS282	3/12/1998	*	3	*	170	*	
cont.	3/12/1998	*	3	*	170	*	lab duplicate
ABS283	6/5/1997	195	186	12.2	760	7.8	
	9/25/1997	*	185	11.9	730	*	
	12/18/1997	*	196	9	790	*	
ABS284	6/4/1997	10	< 1	11.1	120	7.9	lab recorded as AAF284
	6/4/1997	*	< 1	*	*	*	field duplicate as ABT288
	9/24/1997	*	4	11.1	110	*	
	12/17/1997	*	4	9	130	*	
	12/17/1997	*	4	*	130	*	lab duplicate
	3/12/1998	*	4	*	140	*	
ABS285	6/4/1997	*	10	11.7	100	7.5	
	9/24/1997	*	4	11.6	110	*	
ABS286	6/4/1997	*	10	11.1	110	7.1	no well log
ABS287	6/4/1997	10	*	12.2	170	6.9	
	9/24/1997	*	4	14.5	160	7.4	
	12/17/1997	*	3	11.5	190	*	
	3/12/1998	*	3	*	180	*	
ABS288	6/4/1997	10	*	11.7	200	7.4	
	9/24/1997	*	8	11.9	190	*	
	12/23/1997	*	7	10.7	230		
	3/12/1998	*	7	*	220	*	
ABS290	6/5/1997	10	*	10.5	150	7	
	9/23/1997	*	5	10.9	140	*	
ACN797	5/1/1992	*	4	*	*	*	TPCHD analysis
	6/4/1997	10	*	16.2	150	7.7	
	9/24/1997	*	3	16.4	140	7.4	
	12/17/1997	*	3	14	170	*	
	3/13/1998	*	3	*	160	*	

Appendix C. Water-Right and Claim Information

Table C1. Water rights and pending application.

DS = domestic, single; DM = domestic, multiple; FS = fish propagation; IR = irrigation; ST = stock water, QI = instantaneous quantity; QA = annual quantity; W = Well; CT = collector trench; UST = unnamed stream; USP = unnamed spring; JL = Josephine Lake; FL = Florence Lake

Control Number	Source	Purpose of Use	Owner/Applicant Name	Priority Date	QI (cfs)	QI (gpm)	QA (af/y)	Acres Irri- gated	Township Range Section
Ground-Water Rights									
G2-00123CWRIS	W	DS	Treloar, F.W.	2/19/1971		20	0.5		20N/1E-33
G2-00475CWRIS	W	DM	Riveria Country Club	5/26/1970		300	240.0		20N/1E-33
G2-00477ALCWRIS	W	DM	Riviera Country Club	11/24/1970		900	352.0		19N/1E-04
G2-00478CWRIS	W	DM	Riviera Country Club	12/4/1969		400	282.0		20N/1E-32
G2-00553CWRIS	W	DM	Amsterdam Bay WC	1/15/1971		5	2.0		19N/1E-06
G2-00616CWRIS	W	DS	Frazier, W.M.	1/19/1972		10	1.0		19N/1E-17
G2-01108ALCWRIS	W	DM	Riviera Country Club	11/2/1967		800	70.0		19N/1E-04
G2-24334CWRIS	W	DM	Kooley, H.O.	11/2/1976		90	22.5		19N/1E-09
G2-24948CWRIS	W	DS	Tauscher, J. et ux.	7/5/1978		10	1.0		19N/1E-16
G2-26081CWRIS	W	DM	S Anderson Water	2/8/1982		37	9.0		19N/1E-07
G2-26981CWRIS	W	DM	Kooley, H.O.	10/17/1986		90	6.0		19N/1E-09
G2-27002CWRIS	CT	DS	Larsen, J&D	10/15/1986		2	0.5		19N/1E-17
Surface-Water Rights									
S2-01636CWRIS	UST	IR DS	Peterson, H. J.	3/5/1926	0.01	4		0.1	19N/1E-04
S2-09053CWRIS	UST	ST	Anderson, A.	9/6/1949	0.01	4			19N/1E-08
S2-09112CWRIS	UST	ST IR DS	Petersen, P. W.	9/26/1949	0.2	90		20.0	19N/1E-08
S2-12303CWRIS	UST	DS	Gulseth, C.	4/28/1953	0.005	2			20N/1E-33
S2-13047CWRIS	USP	DM	Gordon, D. L.	7/29/1954	0.01	4			19N/1E-06
S2-15799CWRIS	UST	DS	Johnson, J. A. et ux.	12/7/1959	0.005	2			20N/1E-32
S2-15891CWRIS	USP	DS	Johnson, O. L.	2/11/1960	0.01	4			20N/1E-32
S2-16145CWRIS	UST	DM	Green/Murra	6/28/1960	0.02	9			19N/1E-05
S2-16737CWRIS	USP	IR DM	Knowles, W. A. et ux.	6/22/1961	0.02	9	2.0	1.0	19N/1E-17
S2-17859CWRIS	UST	DS	Proctor, J. L.	4/22/1963	0.01	4			20N/1E-32
S2-00476CWRIS	JL	IR	Riviera Country Club	12/16/1970	0.28	126	15.3	18.0	19N/1E-04
S2-22193CWRIS	USP	ST DM	Long, J. et al.	4/10/1974	0.02	9	2.5		19N/1E-09
S2-24944GWRIS	FL	IR DM	Barsanti, R. et ux.	6/23/1978	0.02	9	4.0	1.5	19N/1E-04
S2-25292CWRIS	JL	IR	Riviera Country Club	7/2/1979	0.451	202	15.3	18.0	19N/1E-04
S2-27304CWRIS	FL	FS	Kingman, K.D.	3/16/1988	0.1	45			19N/1E-04
S2-27350	FL	IR	AI Parks & Rec.	7/11/1988	0.02	9	4.0	2.0	19N/1E-04
Pending Application									
G2-28909	W	DM	Kleppen, J.	8/26/1993		90			19N/1E-09

Table C2. Water Claims.

DG= domestic, general; IR = irrigation; ST = stock water

Control Number	Source	Purpose of Use	Claimant Name	Priority Date	Acres Irrigated	Township Range Section
Ground Water						
G2-002430CL		DG IR	Peck, C.J.	January 1, 1912	3	20N/1E-32
G2-006813CL		DG	Burg, C.A.	January 1, 1912		20N/1E-33
G2-006814CL		DG ST	Burg, C.A.	January 1, 1912		20N/1E-33
G2-006933CL		DG IR	Kase, S.	January 1, 1966	2	20N/1E-32
G2-007983CL		DG	Cammon, R.E.	January 1, 1963		20N/1E-29
G2-009158CL		DG	Doering, R.E.	January 1, 1961		20N/1E-33
G2-009302CL		DG	Heckman, E.D.	January 1, 1952		20N/1E-33
G2-009915CL		DG	Pipitone, J.	January 1, 1965		20N/1E-33
G2-010679CL		DG	Heckman, E.D.	January 1, 1963		20N/1E-32
G2-014044CL		DG	Buchanan, C.R.	January 1, 1943		20N/1E-30
G2-014349CL		DG	Creton, V.	January 1, 1967		19N/1E-17
G2-014350CL		DG	Creton, V.	January 1, 1960		19N/1E-17
G2-015359CL		DG	Vinther, N.H.	January 1, 1967		19N/1E-09
G2-016276CL		DG	Leach, J.A.	January 1, 1968		20N/1E-33
G2-025169CL		DG	Faulkner, P.H.	January 1, 1957		20N/1E-33
G2-025924CL		DG	Johnson, S.E.	January 1, 1951		19N/1E-17
G2-026462CL		DG	Engvall, L.R.	January 1, 1906		19N/1E-05
G2-027481CL		DG	Dahlgreen, A.H.			19N/1E-09
G2-028357CL		DG	Taylor, F.B.	January 1, 1941		19N/1E-06
G2-032830CL		DG	Hamilton, J.A.			20N/1E-32
G2-032887CL		DG	Krepky, M.			20N/1E-32
G2-032990CL	Well	DG	Engrall, L.R.	January 1, 1914		19N/1E-08
G2-032991CL	Well	DG	Engrall, L.R.			19N/1E-08
G2-032992CL	Well	DG	Engrall, R.F.	January 1, 1951		19N/1E-09
G2-033751CL		DG	Turner, H.K.			19N/1E-17
G2-037460CL		DG	Johnson, H.C.			19N/1E-17
G2-041197CL	Well	DG	Miller, D.J.	January 1, 1946		19N/1E-06
G2-041198CL	Well	DG	Miller, D.J.	January 1, 1968		19N/1E-06
G2-041199CL	Well	DG	Miller, D.J.	January 1, 1968		19N/1E-07
G2-044625CL	Well	DG	Anderson, E.A.			19N/1E-17
G2-045252CL	Well	DG	Garrett, J.A.	January 1, 1973		19N/1E-09
G2-046103CL	Well	DG	Anderson, C.	January 1, 1923		19N/1E-08
G2-047489CL	Well	DG	Anderson, C.			19N/1E-08
G2-047754CL		DG	Johnson, A.W., Jr.			20N/1E-33
G2-050207CL	Well	DG	A.I. Water Co.	January 1, 1954		19N/1E-06
G2-053830CL		DG	Johnson, O.B.			19N/1E-17
G2-055075CL	Well	DG	Mcdougall, G.N.	January 1, 1935		19N/1E-05
G2-056946CL	Well	DG	Patricio, L.R.	January 1, 1945		19N/1E-07
G2-057726CL		DG	Backstrom, E.A.			20N/1E-33
G2-058219CL		DG	Carstens, T.			20N/1E-33
G2-058789CL	Well	DG	Johnson, B.E.	January 1, 1916		20N/1E-33
G2-058796CL	Well	DG	Ziegler, J.B.	January 1, 1956		19N/1E-06

Table C2. Water Claims--Continued.

DG= domestic, general; IR = irrigation; ST = stock water

Control Number	Source	Purpose of Use	Claimant Name	Priority Date	Acres Irrigated	Township Range Section
G2-059907CL	Well	DG	Oebser, L.E.	January 1, 1971		20N/1E-29
G2-060195CL		DG	Deweyert, D.			19N/1E-07
G2-066202CL		DG	Parker, J.W.			19N/1E-17
G2-068587CL		DG IR	Baughman	January 1, 1910	5	19N/1E-06
G2-068812CL	Well	DG	Engvall, L.	January 1, 1974		19N/1E-05
G2-072376CL		DG	Williams, R.E.			19N/1E-17
G2-072577CL		DG	Ryan, J. E.			19N/1E-16
G2-075950CL		DG	St. Jean, L.J.			20N/1E-33
G2-076027CL		DG	Palumbo, D.			19N/1E-16
G2-076636CL		DG	Nohle, J.			19N/1E-16
G2-076664CL		DG	Wepfer, J.F.			19N/1E-09
G2-076671CL		DG	Nohle, J.			19N/1E-17
G2-079238CL	Well	DG	Gray, R.C.	January 1, 1958		20N/1E-32
G2-083543CL		DG	Falkenberg, E.			19N/1E-17
G2-084031CL		DG	Bearer, R.O.			19N/1E-05
G2-087773CL		DG	Adams, J.M.			19N/1E-05
G2-091123CL	Well	DG	Murphy, J.W.	January 1, 1970		19N/1E-17
G2-095135CL	Well	DG	Carlson, L.	January 1, 1915		19N/1E-17
G2-095136CL	Well	DG	Carlson, E.F.	January 1, 1944		19N/1E-17
G2-099486CL	Well	DG	Johnson, A.L.	January 1, 1966		19N/1E-17
G2-100851CL		DG	Hunt, N.			19N/1E-17
G2-101210CL		DG IR	Fransen, T.C.			19N/1E-16
G2-101858CL	Well	DG	Palmer, C.W.	January 1, 1974		19N/1E-17
G2-102763CL	Well	DG	Minckler, R.	January 1, 1971		19N/1E-06
G2-103040CL		DG IR	Johnson, L.V.			19N/1E-16
G2-103041CL		DG IR	Johnson, L.V.			19N/1E-17
G2-103042CL		DG IR	Johnson, L.V.			19N/1E-16
G2-106979CL	Well	DG	Swanberg, R. J.			20N/1E-33
G2-107432CL	Well	DG	Teal, L.M.	January 1, 1974		19N/1E-17
G2-109674CL	Well	DG	Kavanagh, J.J.	January 1, 1963		19N/1E-08
G2-111313CL	Well	DG IR	Mac Donald, S.E.	January 1, 1967	3	19N/1E-09
G2-111995CL	Well	IR	Camus, P.	January 1, 1955	3	19N/1E-06
G2-115140CL		DG IR	Ehricke, E.R.			20N/1E-33
G2-117226CL		DG	Kelley, C.B.			19N/1E-05
G2-120252CL		DG	Campbell, C.L.			19N/1E-16
G2-122938CL	Well	DG	Wilcox, E.H.	January 1, 1924		19N/1E-06
G2-123089CL	Well	DG	Camus, P.	January 1, 1954		19N/1E-06
G2-125462CL		DG IR	Mcdowell, T.E.			19N/1E-17
G2-132719CL			Anderson, A.R.			19N/1E-09
G2-133116CL	Well	DG	Kooley, D.C.	January 1, 1969		19N/1E-09
G2-138633CL	Well	DG	Fortiner, R.H.	January 1, 1936		19N/1E-17
G2-139101CL		DG IR	Geppert, R.C.			19N/1E-17
G2-140611CL	Well	DG	Eldien, P.T.			19N/1E-05
G2-140925CL	Well	DG	Weinrich, M.H.	January 1, 1930		19N/1E-17

Table C2. Water Claims--Continued.

DG= domestic, general; IR = irrigation; ST = stock water

Control Number	Source	Purpose of Use	Claimant Name	Priority Date	Acres Irrigated	Township Range Section
G2-143559CL	Well	DG	Munson, J.D.	January 1, 1937		19N/1E-08
G2-143560CL	Well	DG	Munson, J.D.	January 1, 1937		19N/1E-08
G2-143561CL	Well	DG	Munson, J.D.	January 1, 1937		19N/1E-08
G2-151596CL		DG IR	Hicok, V.H.			20N/1E-33
G2-153277CL	Well	DG	Hudson, F.E.	January 1, 1941		19N/1E-17
G2-154666CL	Well	DG	Gaspard, G.S.	January 1, 1950		19N/1E-17
G2-154667CL	Well	DG	Gaspard Beach Prop.	January 1, 1950		19N/1E-17
G2-154668CL	Well	DG	Gaspard, G.S.	January 1, 1930		19N/1E-17
G2-155970CL	Well	DG	Engelke, D.	January 1, 1969		20N/1E-33
G2-156021CL	Well	DG IR	Gordon, J.L.	January 1, 1966		19N/1E-06
G2-157748CL	Well	DG	Gordon, R.D.			20N/1E-33
G2-157750CL	Well	DG IR	A.I. Community	January 1, 1963		20N/1E-33
G2-157908CL		DG	Haney, A.J.			20N/1E-33
G2-158175CL	Well		Anderson, T.W.		30	19N/1E-09
G2-158819CL		DG	Johnson, H.L.	January 1, 1919		20N/1E-33
G2-158820CL	Well	DG	Johnson, H.L.	January 1, 1900		20N/1E-33
G2-160247CL		DG IR	Pasinetti, J., Sr.			20N/1E-32
G2-163832CL	Well	DG	Stacy, E.E.			20N/1E-32
Surface Water						
S2-015237CL		DG	Cunningham, C.R.	January 1, 1900		19N/1E-08
S2-026463CL		IR	Engvall, L.R.	January 1, 1906	1	19N/1E-05
S2-060540CL		DG	Sanbeck, C.E.	January 1, 1920		20N/1E-30
S2-068586CL		IR	Baughman, J.	January 1, 1910	40	19N/1E-06
S2-087772CL		IR	Adams, J.M.			19N/1E-05
S2-096107CL		IR	Camus, P.	January 1, 1900		19N/1E-06
S2-100137CL		DG ST IR	Long, J.L., Jr.	January 1, 1935	85	19N/1E-09
S2-111713CL		DG IR	Christensen, R.D.	January 1, 1909	2	20N/1E-32
S2-124204CL		DG IR	Ulsh, I.R.			19N/1E-05
S2-131097CL		DG ST IR	Buchanan, W. F.			20N/1E-33
S2-139479CL		DG	Sutherland, G.			19N/1E-08
S2-153088CL		DG ST IR	Anderson, R.G.			19N/1E-08
S2-155960CL		DG	Camus, N.H.	January 1, 1927		19N/1E-06
S2-156022CL		IR	Gordon, J.L.	January 1, 1917	2	19N/1E-06
S2-157749CL		DG	Gordon, D.L.	January 1, 1917		20N/1E-33
S2-157752CL		DG	La Rue, Mrs. R. V.	January 1, 1949		19N/1E-17
S2-158176CL			Anderson, T.W.			19N/1E-09
S2-163831CL		DG	Stacy, E.E.			20N/1E-32