

HIGH CHLORIDE CONCENTRATIONS
IN GROUND WATER WITHDRAWN FROM
ABOVE SEA LEVEL AQUIFERS,
WHIDBEY ISLAND, WASHINGTON

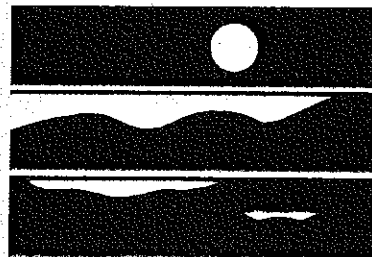
by
Tom Culhane

December 3, 1993

OFTR 93-07

Water Resources Program

OPEN-FILE TECHNICAL REPORT



WASHINGTON STATE
DEPARTMENT OF
E C O L O G Y

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This open file technical report represents the results of a hydrologic investigation by the Water Resources Program, Department of Ecology. It is intended as a working document and has received internal review. This report may be circulated to other Agencies and the Public, but it is not a formal Department of Ecology Publication.

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ABSTRACT

Recent information indicates the presence of several Whidbey Island wells producing water with high chloride levels from aquifer zones above sea level. Seventeen suspect wells, six control wells, and two ocean locations were sampled during the investigation. Field measurements indicate that only 20 of the 23 sampled wells are actually completed above sealevel. Several methods were utilized to analyze for the presence of seawater. These included constructing Stiff diagrams, hardness and chloride versus specific conductivity plots, and Piper diagrams. Study results suggest that 16 of the 23 wells produce water with chemical compositions resembling very hard ground water rather than dilute seawater. Of the various methods used during the study, Stiff diagrams and chloride/hardness versus conductivity plots appear to be the simplest and most reliable for distinguishing very hard ground water from ground water influenced by seawater.

It is possible to produce chemistry resembling that of dilute seawater by contaminating very hard water with man induced nutrients. Consequently, water samples were analysed for nitrates and other nutrients. Of the 23 sampled wells, seven produced water with nitrite plus nitrate nitrogen concentrations exceeding 2 mg/l. A comparison indicated that three of these seven wells were also included as one of the seven wells which produced water with chemical compositions resembling dilute seawater. Of the remaining four wells, two are completed significantly below sea level, and one appeared to be seawater influenced according to only one of the four graphical techniques. Taking into consideration all known well information, it appears likely no more than one or two of the 20 above sea level wells may actually be influenced by seawater. The source(s) of the seawater component(s) for these wells is unknown, but possibilities include irrigation with saline water, sea spray, and dilution with relict water.

ACKNOWLEDGEMENTS

The author would like to thank the many property owners and water system managers of central Whidbey Island who helped make this study possible. I am also grateful to the Island County Health Department for their interest and cooperation. Thanks also to Dave Garland and Erin Guthrie who reviewed the draft and provided very helpful advice.

TABLE OF CONTENTS

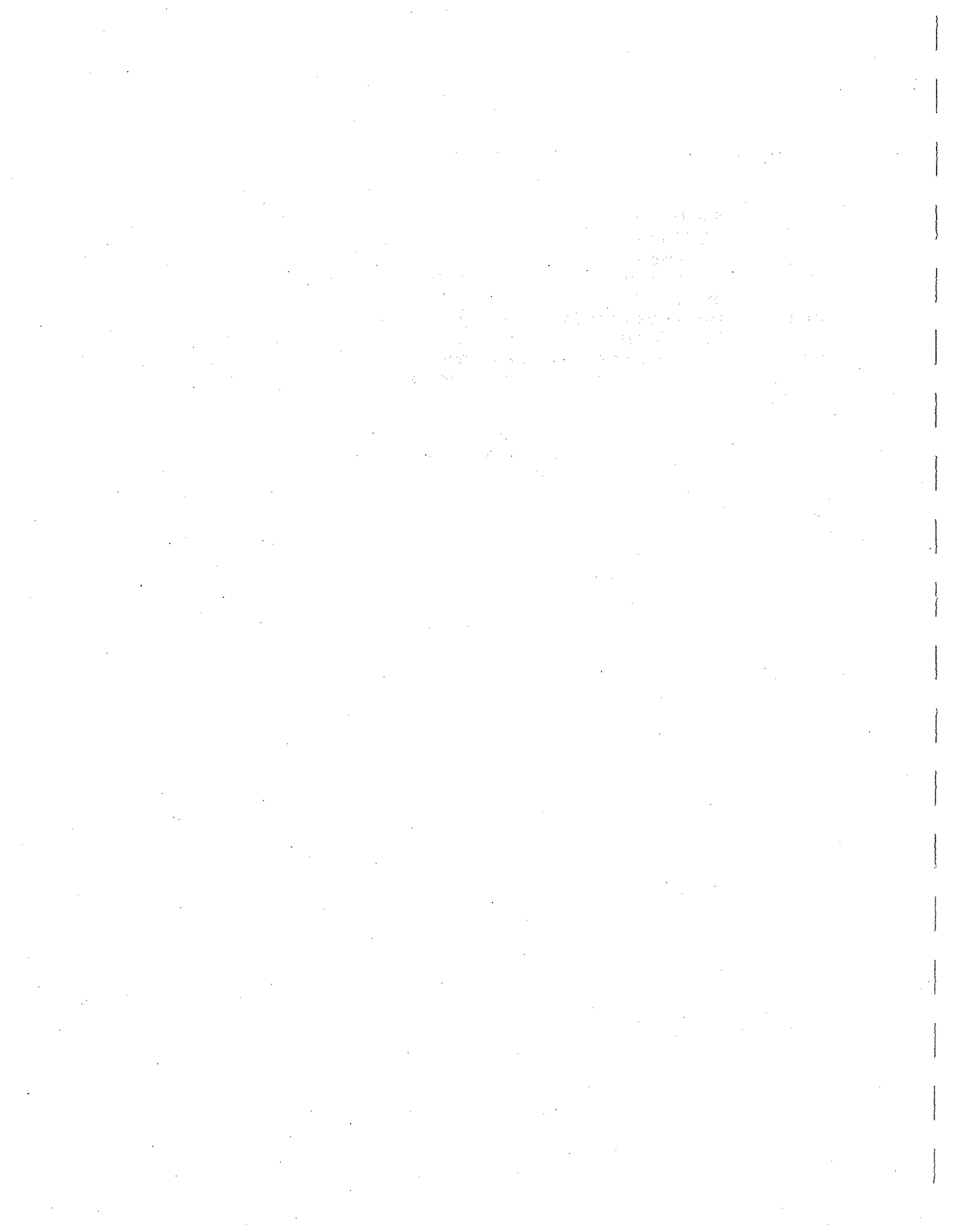
ABSTRACT	i
ACKNOWLEDGEMENTS	ii
INTRODUCTION	1
Background and Purpose	1
Location and Extent of the Study Area	1
Previous Investigations	1
Geologic/Hydrogeologic Setting	3
METHODS	5
Review and Analysis of Existing Data	5
Sampling, Surveying and Laboratory Analysis	5
RESULTS	9
Water Quality	9
Graphical Methods of Representing Water Quality Data	9
Bromide Analyses	15
Analyses for Nitrates and other Nutrients	15
POTENTIAL SOURCES OF CHLORIDE	18
The Occurrence of Saline Ground Water within Island County	18
Upconing	18
Very Hard Ground Water	19
The Presence of Relict (Connate) Pleistocene Epoch Seawater	19
Man-Induced Contamination of the Aquifer(s)	20
Irrigation with Saline Water	21
Sea Spray Depositing Saline Water on the Land Surface	21
Whidbey Island Mainland Source Theory	21
DISCUSSION OF RESULTS	23
CONCLUSIONS AND RECOMMENDATIONS	26
REFERENCES	29
APPENDIX A	31
Stiff Diagrams	32

LIST OF FIGURES

Figure 1	Site location map	2
Figure 2	Well location map	6
Figure 3	Stiff diagrams	12
Figure 4	Ground water chloride content versus specific conductance plot	14
Figure 5	Ground water hardness versus specific conductance plot	14
Figure 6	Piper diagram	16
Figure 7	Wells with greater than 2 mg/ℓ nitrate	17
Figure 8	Above MSL wells which may be seawater influenced	27

LIST OF TABLES

Table 1	Well data	7
Table 2	Ground water quality testing parameters	8
Table 3	Ground water quality data	10
Table 4	Comparison of analysis results	24



INTRODUCTION

Background and Purpose

In December of 1991 Ecology adopted a Seawater Intrusion Policy as part of its ground water protection efforts within the State. Ecology's policy establishes seawater intrusion risk categories based on chloride levels in pumping wells. Chloride is the major ion least affected by the chemical processes seawater undergoes as it passes through soil and sediments (Revelle, 1941).

Recent investigations revealed the presence of several wells located on Whidbey Island which were producing water with relatively high chlorides, even though they were completed above mean sea level (MSL). Seawater intrusion is not typically considered a phenomena occurring in aquifer zones above sea level, so it appeared likely the high chlorides were due to some other cause(s). As chloride concentrations play a key role in water right allocation decisions for areas of suspected seawater intrusion, it was necessary to conduct this study to determine the source of the high chlorides.

The purpose of this study was to (1) determine the extent and occurrence of high chloride levels in wells with intakes above MSL, (2) develop likely explanations for the chloride source(s), and (3) produce a strategy for discerning between wells intruded by seawater and wells with high chlorides due to other causes. For the purposes of this study, MSL corresponds with the National Geodetic Vertical Datum of 1929 and high chloride water is that containing at least 100 milligrams per liter (mg/l) of chloride.

Location and Extent of the Study Area

Whidbey Island, the largest island in the lower 48 United States (GTE Northwest, 1993), is located in Island County in the north-central Puget Lowland of western Washington. The study area is a very irregularly shaped, roughly seven by eleven mile portion of Whidbey Island. This area extends from Smith Prairie in the center of the Island, to the area west of Oak Harbor in the northern portion of the Island (see Figure 1). The study boundaries were chosen based on information regarding high chloride Island County wells known or reported to have intakes at elevations above MSL.

Previous Investigations

Island County's geology was described by Easterbrook in Washington Water Supply Bulletin No. 25 (1968). The County's ground water resources were characterized by VanDenburgh and Anderson within that same bulletin. The Island County aquifers were identified and studied for seawater intrusion by Jones (1985). Garland and Safioles (1988) characterized the seasonal variation of chloride in ground water on southern Camano Island. Sapik et al. (1988), constructed a model of the ground water flow and addressed water quality, seawater intrusion, and overdraft potential issues within the County. In

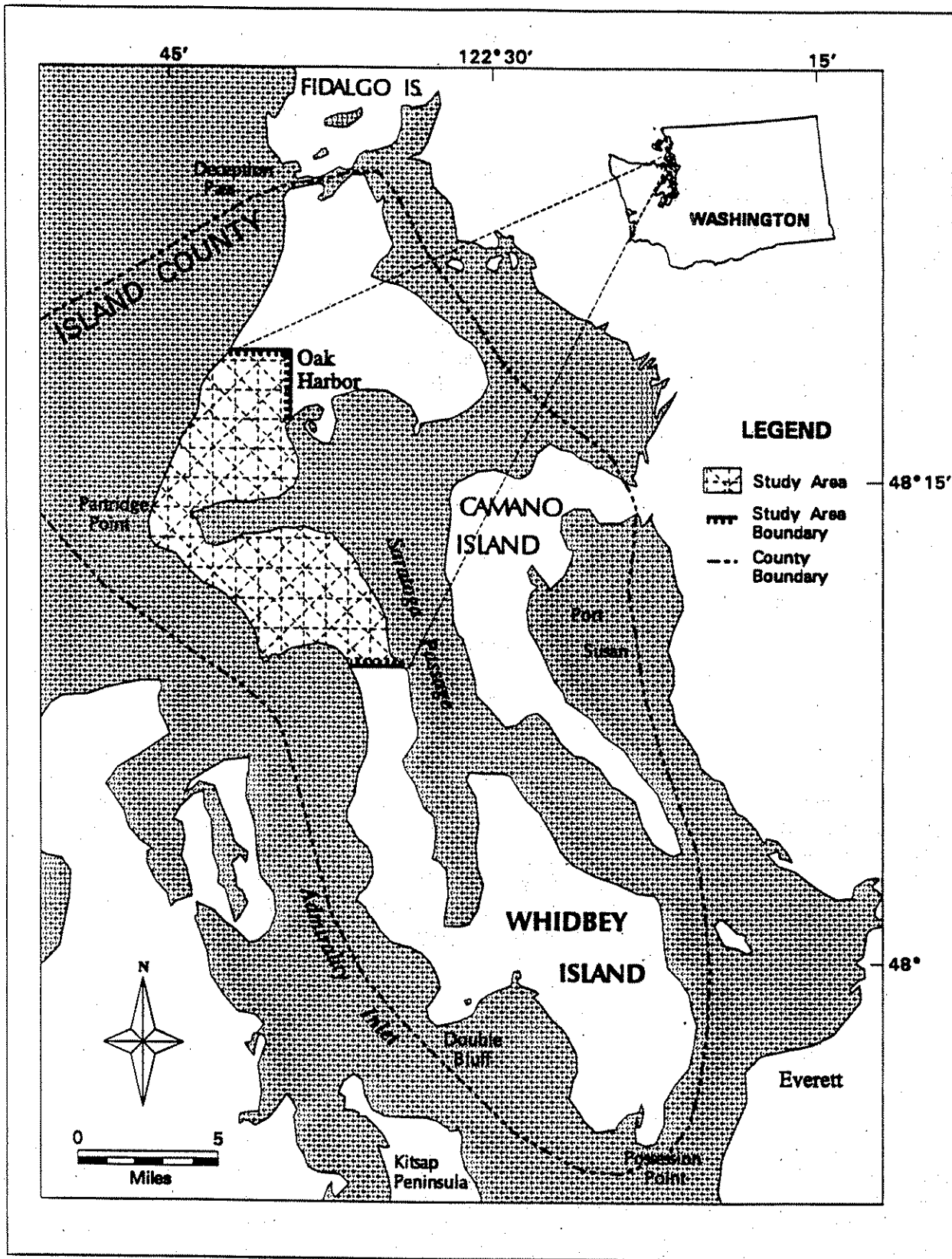


Figure 1 - Site Location Map.

1989 Economic and Engineering Services, Inc. produced the Island County Groundwater Management Plan Technical Memorandum, which primarily consolidated and elaborated on data collected during previous studies.

Geologic/Hydrogeologic Setting

The entire geologic character of Whidbey Island has been shaped by the extensive Pleistocene glaciation that formed the Puget Lowland. All but the very northern portion of the Island consists of deposits representing three glaciations and three interglaciations. According to Easterbrook (1992) the Pleistocene geologic-climate succession now recognized in the central Puget Lowland is as follows:

Fraser Glaciation
Sumas Stade
Everson Interstade
Vashon Stade
Evans Creek Stade
Olympia Nonglacial Interval
Possession Glaciation
Whidbey Interglaciation
Double Bluff Glaciation

The surficial geology of the study area was mapped by Pessl et al. (1989) and consists predominantly of deposits of the Vashon Stade of the Fraser Glaciation. These deposits include mainly till, recessional continental deposits, and recessional marine deposits (from oldest to youngest). The Pessl et al. mapping suggests all three deposits may have been successively deposited over one another, but the younger deposits have been subsequently removed in places. Significant exposures of all three deposits are present on the surface throughout the study area.

In general the hydrogeology of Whidbey Island can be described as a layered series of glacial deposits which serve as aquifer and aquitard units of varying thickness and permeability. The aquifers contain highly permeable sands and gravels. These range from relatively continuous units to units consisting of multiple, smaller, poorly-interconnected aquifers. The aquitard units contain mostly low permeability silts and clays, although they also include occasional pockets of higher permeability material. The aquifers, aquitard units, and layers within the units themselves vary greatly in thickness and frequently inter-finger with each other unpredictably. The land surface's ability to absorb water varies, however most portions contain some areas of gravelly and sandy soils which provide a relatively rapid route for rainfall penetration. This water percolates downward through the maze of aquifer and aquitard units to recharge the majority of the Island's aquifers.

Jones (1985) and Sapik et al. (1988) separated Island County's stratigraphy into 5 aquifers and 5 confining units, with the confining units defined as layers of generally fine-grained materials with hydraulic conductivities at least one order of magnitude lower than that of the aquifer materials. Subsequently the confining units are actually typically semi-confining units. The aquifer units were labeled A through E with the uppermost

(youngest) unit labeled E. Economic and Engineering Services (EES) presented numerous cross sections in the Island County Groundwater Management Plan Technical Memorandum, in which they used this same stratigraphic nomenclature. Although the distinctions between the aquifers and confining units are not as simple or well defined as suggested by EES, these cross sections do provide approximate locations and thicknesses for the aquifers.

The EES cross sections suggest that the two most productive aquifers within the study area are aquifers C and D. The elevations, thicknesses and/or gradients of these aquifers change abruptly in places. Generally aquifer C is found at or below MSL, with overlying aquifer D dipping below MSL in places. Both aquifers C and D are locally absent in portions of the study area, although thicknesses may exceed as much as 100 to 125 feet respectively. In general both aquifers are relatively flat, although there is a draping effect such that both have an overall downward gradient heading outward from the center of the Island. This draping effect resulted from the preferential scouring action of glaciers and the resultant preservation of preglacial highlands. Based on the cross sections and specific well information, it can be surmised that the majority of the study area's above MSL high chloride wells are completed within aquifer D.

Sapik, et al. made probable correlations between aquifers/confining units and the Pleistocene stratigraphy of Whidbey Island. According to their report aquifer C generally correlates with the Whidbey Formation. These deposits consists mostly of sand, silt, and clay with interbedded peat and lenses of gravel. The interglacial sediments of the Whidbey Formation were deposited by meandering streams flanked by floodplain lakes and swamps. The complex nature of the Whidbey Formation's depositional environment explains the unpredictable nature of the contact between that aquifer and its associated confining units.

Aquifer D generally correlates to either the Quadra Formation of the Olympia Interglaciation or the Esperance Sand member of the Vashon Drift. Easterbrook (1968) indicated the County's only recognized Quadra Formation deposit consists of a peat bed located near Strawberry Point about six miles east of Oak Harbor. As Easterbrook also identified the Esperance Sand south of Swantown in the Fort Casey upland sea cliffs, it is likely Aquifer D is associated with the latter deposit within the study area. The Swantown deposit includes 200 feet of moderately well sorted fluvial sand and pebbly sand with occasional lenses of gravel. Vashon till likely rests unconformably over much of the Esperance Sand throughout the study area. This till is either exposed directly at the surface or is covered by Vashon Stade recessional continental or marine deposits.

METHODS

Review and Analysis of Existing Data

The field investigation began with a review of existing well data within the vicinity of the reported anomalous high chloride wells. The review relied mainly on chloride data contained in data bases belonging to the Washington State Departments of Ecology and Health, and an archived U.S. Geological Survey data base developed by Sapik et al. (1988). The Island County Health Department also provided some water quality data collected during a recent Coupeville landfill study. During the initial review it was necessary to rely on topographic maps and well logs to determine completion elevations.

The initial review identified 23 wells suspected of being completed above MSL and producing water with greater than 99 mg/l of chloride. Figure 2 includes those initially identified wells which were sampled during the study (17 wells, indicated using 100 series numbers). The wells are located anywhere between 900 feet to 1.75 miles inland. These wells are distributed throughout the entire study area, however appear to occur in four clusters. Of the wells initially identified, 13 are single domestic sources, five are used as irrigation sources, four supply group domestic systems, and one supplies a campground.

In addition to those wells described above, the data review identified 60 study area wells completed below MSL with chlorides in excess of 99 mg/l. Of these wells, 2 are completed greater than 400 feet below MSL, with the remainder having completion elevations ranging from a few feet to 173 feet below MSL.

Sampling, Surveying and Laboratory Analysis

Due to access problems, only 17 of the 23 initially identified wells were sampled. In addition to these 17, six control wells were sampled. These wells were selected based on their proximity and similar completion elevation to initially identified wells. Control wells are indicated with 300 series numbers on Figure 2.

The field methods included verifying the mapped locations of the wells, measuring static water levels, purging well water, and sampling wells. All water levels were measured within ± 0.01 foot using an electric wire probe. In many instances it was not possible to measure static water levels as wells had recently pumped or well access was limited. Access problems and limited field time further prevented purging a full three well casing volumes from certain wells prior to sampling.

Well head elevations were surveyed for eleven of the 23 sampled wells. A digital altimeter was used to verify the well head elevations of the remaining 12 wells. Based on field measurements and well log data, it appears wells 119, 122 and 306 are completed below MSL, however these wells were sampled for comparison purposes. The completion elevations of the remaining sampled wells appear to range from about five to 72 feet above MSL (see Table 1).

TABLE 1. - WELL DATA

STUDY ID	LOCAL ID	WELL DEPTH (FEET)	LAND SURFACE ELEVATION (FEET)	COMPLETION ELEVATION (FEET)
1*	31N/01E-23E			
2*	33N/01E-29H			
101	31N/01E-02D	171	201**	30
105	31N/01E-02E	173	190**	17
106	31N/01E-10G	64	95.6**	31.6
107	31N/01E-10G	65	94.5**	29.5
109	31N/01E-10J	35	78**	43
110	31N/01E-03R	170	177	7
111	32N/01E-30M	49.8	55**	5.2
112	33N/01E-32H	48	77**	29
113	31N/01E-03J	156	184	28
115	32N/01E-20C	111	150	39
116	32N/01E-18A	155.7	161.1**	5.4
117	33N/01E-28R	116	139	23
118	33N/01E-28A	117	130**	13
119	33N/01E-27C	175	172	-3
121	31N/01E-32Q	58	67	9
122	33N/01E-28H	155	135	-20
123	31N/01E-02N	172	190.4**	18.4
301	31N/01E-10J	35	71**	36
302	31N/01E-03A	146	200	54
303	33N/01E-28R	122	139	17
305	32N/01E-18J	128	200	72
306	32N/01W-35N	87	67	-20
307	32N/01E-17D	136	169	33

*Ocean sample

**Surveyed elevation

NOTE: All elevations are measured relative to the National Geodetic Vertical Datum of 1929. In some instances the surveyed land surface elevations may actually represent the elevations of the top of casing. In instances where there was doubt about the land surface elevation of a well, the deepest well completion elevation was used.

All samples were refrigerated and transported to the Ecology Environmental Laboratory in Manchester where they were analysed within holding times specific to the methods of analysis. The purpose of the laboratory analysis was to provide chemistry data for distinguishing between ground water influenced by seawater and that with high chlorides from other sources. All ground water samples were analyzed for specific conductance, major cations and anions, bromide, ammonia, nitrite plus nitrate nitrogen, and phosphate. Table 2 lists the parameters tested, EPA methods of analysis, and practical quantitation limits ("PQL").

PARAMETER	METHOD	PQL
Specific Conductance	EPA Method 120.1	1.0 umho/cm
Calcium	EPA Method 200.7	0.01 mg/l
Magnesium	EPA Method 200.7	0.01 mg/l
Sodium	EPA Method 200.7	0.07 mg/l
Potassium	EPA Method 200.7	1.0 mg/l
Alkalinity	EPA Method 310.1	1.0 mg/l
Bromide	EPA Method 300.0	0.05 mg/l
Chloride	EPA Method 330.0	1.0 mg/l
Sulfate	EPA Method 330.0	0.5 mg/l
Ammonia-N	EPA Method 350.1	0.01 mg/l
Nitrate + Nitrite-N	EPA Method 353.2	0.01 mg/l
Total Phosphate	EPA Method 365.1	0.01 mg/l

Table 2. Ground water quality testing parameters, methods (EPA, 1983), and practical quantitation limits.

In addition to sampling 23 wells, seawater was sampled from two locations to provide an indication of local ocean water chemistry. The sampled locations included Admiralty Bay and the Strait of Juan de Fuca, identified as 1 and 2 on the well location map respectively (see Figure 2). Sampling protocol included wading out into the surf and sampling approximately one foot below the surface of the water. The Admiralty Bay sample underwent an analysis identical to that of the wells. The Strait of Juan de Fuca sample underwent an analysis identical to that of the wells except for nutrients.

All ground water samples and the Admiralty Bay sample were analysed for concentrations of nitrite plus nitrate nitrogen. Nitrite concentrations, however, are generally negligible in comparison to nitrate. Consequently nitrite plus nitrate nitrogen concentrations were assumed to be equivalent to nitrate and they are referred to simply as nitrate in the narrative of this report.

RESULTS

Water Quality

Ground water quality results for the 23 sampled domestic and irrigation wells and two ocean water samples are tabulated in Table 3. The calcium and magnesium results for well 305 are anomalous, thus this well has been omitted during all subsequent analyses and discussions involving these specific cations. The analyses indicate that most of the ground water sampled was relatively hard, as indicated by the high levels of calcium and magnesium. Calcium in the ground water samples ranged from 23 to 202 mg/l with a median concentration of 62.6 mg/l. Magnesium in the ground water samples ranged from 25.7 to 154 mg/l with a median concentration of 62 mg/l.

Ground water quality in the area was generally good, with the exception of elevated levels of chloride and nitrate in several of the wells. Chloride in the ground water samples ranged from 55.2 to 461.0 mg/l with a median concentration of 86.6 mg/l. The Water Quality Standards for the Ground Waters of Washington State, WAC 173-200 (1990), establish chloride as a secondary chemical contaminant at levels of 250 mg/l or more. Nitrate in the ground water samples ranged from 0.01 (undetected) to 34.4 mg/l with a median concentration of 0.89 mg/l. WAC 173-200 establishes nitrate as a primary chemical contaminant at levels of 10 mg/l or more.

Graphical Methods of Representing Water Quality Data

During the study, Stiff diagrams were used to graphically represent some of the well sampling data. Constructing Stiff diagrams involves converting subject chemical concentrations to meq/l and placing the major cations (K, Na, Mg, and Ca) on one side, and anions (HCO₃, SO₄, and Cl) on opposite sides of an axis. During his investigation, VanDenburgh (1968) produced a much simpler plot with the concentrations of major cations and anions included on the same side of an axis. Stiff diagrams were used during the current study only because their use is more standard, however both methods produce distinctive graphical shapes which facilitate rapid comparison of multiple analyses. Figure 3 contains Stiff diagrams representing VanDenburgh's examples of normal dilute, very hard, and seawater influenced ground water. Appendix A contains Stiff diagrams for all well and ocean water sampled during the current study.

There are several striking differences between VanDenburgh's examples of seawater influenced and very hard ground water. These include a greater concentration of chloride with respect to bicarbonate, as well as sodium with respect to calcium and magnesium, for the seawater influenced samples. It is also interesting to note that many of the study data patterns are different from all three of those suggested by VanDenburgh. For example, it is common for some study data patterns to resemble VanDenburgh's very hard water example, except that calcium is less than sodium and potassium.

TABLE 3. - GROUND WATER QUALITY DATA
(Concentrations in mg/l)

STUDY ID	SAMPLE DATE	DEPTH		CHLORIDE	COND.	CARB.	BICARB.	TOTAL ALK.	SULFATE
		TO SWL							
1	10/23/92			17600.0	4690	U	108	108	2290.0
2	10/23/92			17300.0	4690	U	108	108	2310.0
101	10/29/92	152		57.7	879	U	364	364	35.4
105	10/21/92			86.6	1081	U	448	448	36.2
106	10/21/92			152.0	1490	U	576	576	46.3
107	10/21/92			160.0	1540	U	581	581	47.4
109	10/21/92			461.0	2150	U	333	333	47.1
110	10/21/92			59.7	727	U	280	280	25.5
111	10/22/92			87.0	660	U	131	131	43.7
112	10/28/92			163.0	1330	U	255	255	59.2
113	10/28/92	107		104.0	925	U	319	319	32.6
115	10/22/92	89		80.8	952	U	379	379	25.3
116	10/22/92			77.7	833	U	333	333	.5
117	10/23/92			76.3	897	U	341	341	27.5
118	10/28/92			123.0	972	U	287	287	51.5
119	10/23/92			55.2	835	U	344	344	26.4
121	10/28/92	42		127.0	983	U	277	277	60.4
122	10/23/92	118		150.0	1258	U	418	418	48.4
123	10/21/92	114		71.2	764	U	284	284	22.3
301	10/21/92	13		425.0	2620	U	650	650	147.0
302	10/28/92			58.4	909	U	349	349	39.0
303	10/23/92	88		82.2	984	U	393	393	28.9
305	10/22/92	111		75.8	890	U	327	327	29.4
306	10/29/92			175.0	1390	U	459	459	52.8
307	10/22/92	109		65.8	539	U	155	155	20.0

U = Undetected

TABLE 3. - GROUND WATER QUALITY DATA - CONT.
 (Concentrations in mg/L)

BROMIDE	AMMONIA	NITRATE- NITRITE	PHOSP.	CALCIUM	MAGNESIUM	POTASSIUM	SODIUM
57.90	.014	.332	.066	355.000	1110.000	341.000	9000.0
57.70				357.000	1120.000	341.000	9000.0
.19	.010	.891	.055	86.400	50.600	6.660	33.7
.27	.039	.010	.065	63.700	87.600	8.610	51.7
.49	.088	1.300	.084	114.000	95.000	8.000	87.9
.50	.032	2.050	.089	118.000	102.000	8.090	85.3
.36	.013	9.000	.010	110.000	88.700	4.770	206.0
.21	.091	.010	.091	53.300	40.800	12.300	42.2
.18	.036	5.170	.040	37.900	25.700	3.600	62.5
.47	.046	34.400	.010	77.500	81.400	7.340	63.2
.35	.039	.010	.045	56.800	58.900	6.160	54.8
.32	.035	.065	.030	49.800	61.600	6.880	74.0
.26	2.890	.010	.474	63.900	47.800	6.050	43.0
.25	.141	2.470	.149	41.300	62.300	11.800	55.4
.29	.014	1.410	.140	62.900	56.400	6.430	56.9
.22	.010	1.450	.093	55.200	48.800	6.920	54.5
.32	.014	.634	.048	41.600	67.400	3.500	67.0
.37	.160	.010	.062	62.300	76.800	10.300	95.2
.25	.101	.010	.114	54.300	41.800	12.600	48.1
.81	.010	9.720	.010	202.000	154.000	6.830	153.0
.16	.013	6.640	.018	80.500	51.900	7.070	42.0
.30	.070	.614	.165	48.000	68.300	13.700	60.3
.29	.010	.210	.032	.166	.080	1.300	212.0
.51	.231	1.310	.015	85.600	64.700	8.080	121.0
.22	.056	.010	.018	23.000	28.800	5.270	44.0

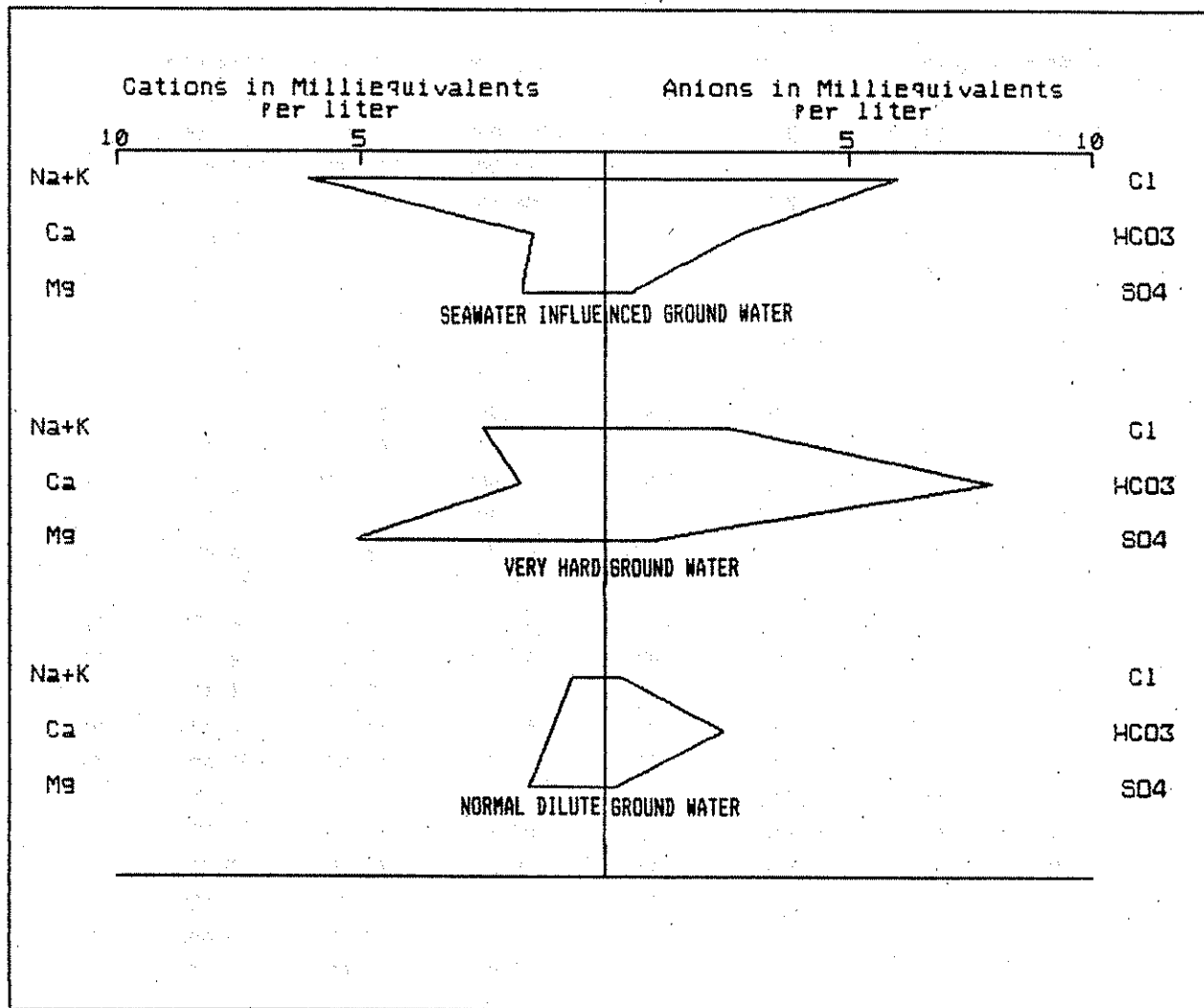


Figure 3 - Stiff diagrams of VanDenburgh's three basic ground water types.

Based on somewhat arbitrary distinctions, wells 105, 106, 107, 110, 113, 115, 116, 117, 118, 119, 122, 123, 302, and 303 appear to have patterns similar to very hard water (inclusive of wells with the noted calcium deviation). Only wells 109 and 111 appear to have patterns similar to the seawater influenced water. The remaining seven wells appear to be some mixture of both. Not surprisingly, Stiff diagrams for the ocean samples most resemble the seawater influenced example.

One method VanDenburgh presented for distinguishing between seawater influenced and very hard ground water involves examining the relationships between chloride content, water hardness and specific conductance. This method relies on the fact that specific conductance provides an indication of dissolved solids content. By constructing bivariate plots of conductance versus chloride content, one can determine the relative proportion of dissolved solids due to chloride. As chlorides comprise a very high proportion of the dissolved solids in seawater, this difference can be used to distinguish between very hard water and ocean influenced water. The relative proportion of dissolved solids due to calcium and magnesium can be determined by graphing conductance versus water hardness. As calcium and magnesium comprise a high proportion of the dissolved solids in very hard water, this difference may also be used to distinguish between very hard water and ocean influenced water.

Figure 4 includes VanDenburgh's chloride versus specific conductance plot for very hard ground water and seawater encroachment. Figure 5 includes VanDenburgh's water hardness versus specific conductance plot for very hard ground water and seawater encroachment. Both these figures also include VanDenburgh's plots for three stream samples collected from the Duwamish Estuary. The latter was plotted in an attempt to show the differences between mixing of dilute river water and seawater from the Puget Sound. In both Figures 4 and 5, data points for the subject wells were superimposed on VanDenburgh's plots. The following formula, taken from Freeze and Cherry (1979), was used to calculate water hardness for the data presented in Figure 5.

$$\text{Total hardness} = 2.5(\text{Ca}^{2+}) + 4.1(\text{Mg}^{2+})$$

Although there is some scatter, data points for most of the study wells plot near the very hard ground water plots. The most noticeable exceptions in Figure 4 were wells 109, 111, 301, and 307. The most noticeable Figure 5 exceptions were wells 109, 111, and 307. Well 305 was excluded from the latter group for reasons discussed previously.

Figures 4 and 5 also include data points representing a very deep well located just south of Coupeville, within Section 4, T. 31 N., R. 1 E. The well is one of only two very deep production wells located within the study area and is completed 433 feet below MSL. This well has produced chloride concentrations between 170 and 190 mg/l. Strong tidal influence on the well's static water levels suggests the elevated chloride level may be seawater derived. Data from the well plots slightly toward the seawater encroachment delineation on Figure 4 and clearly near that delineation on Figure 5.

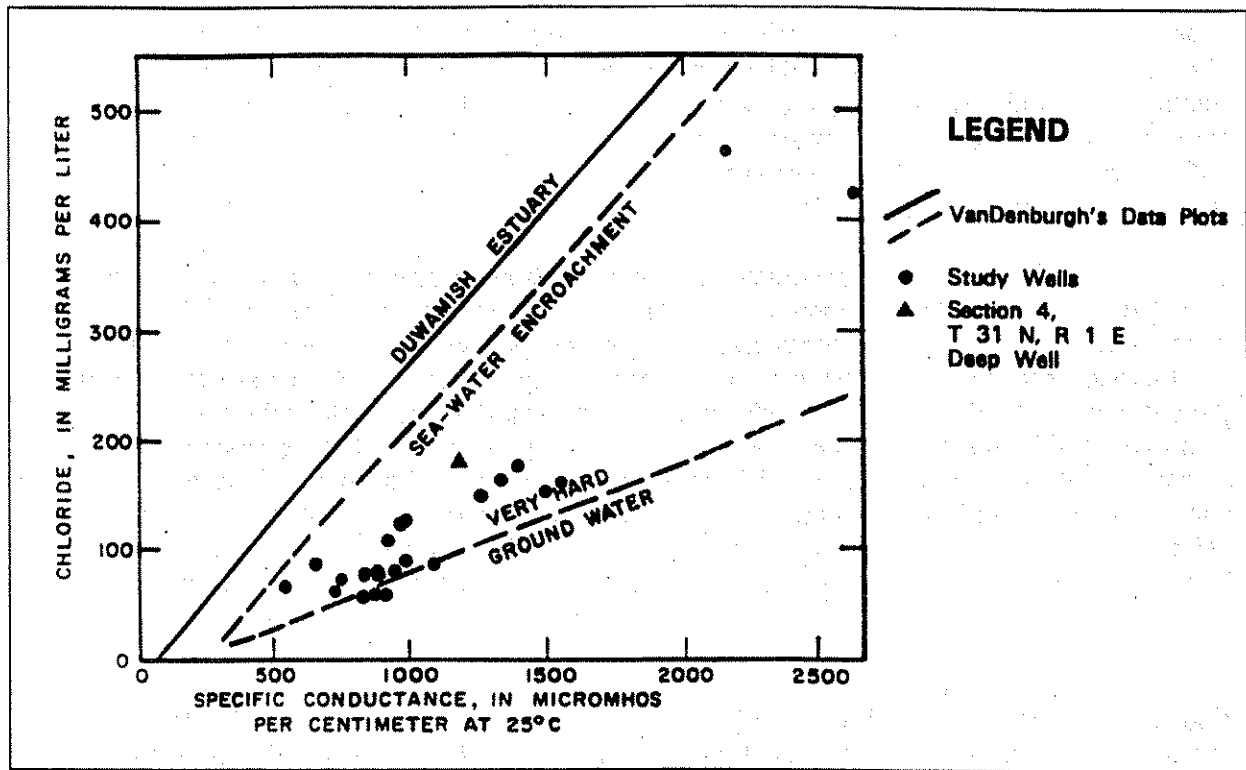


Figure 4 - Ground water chloride content versus specific conductance plot.

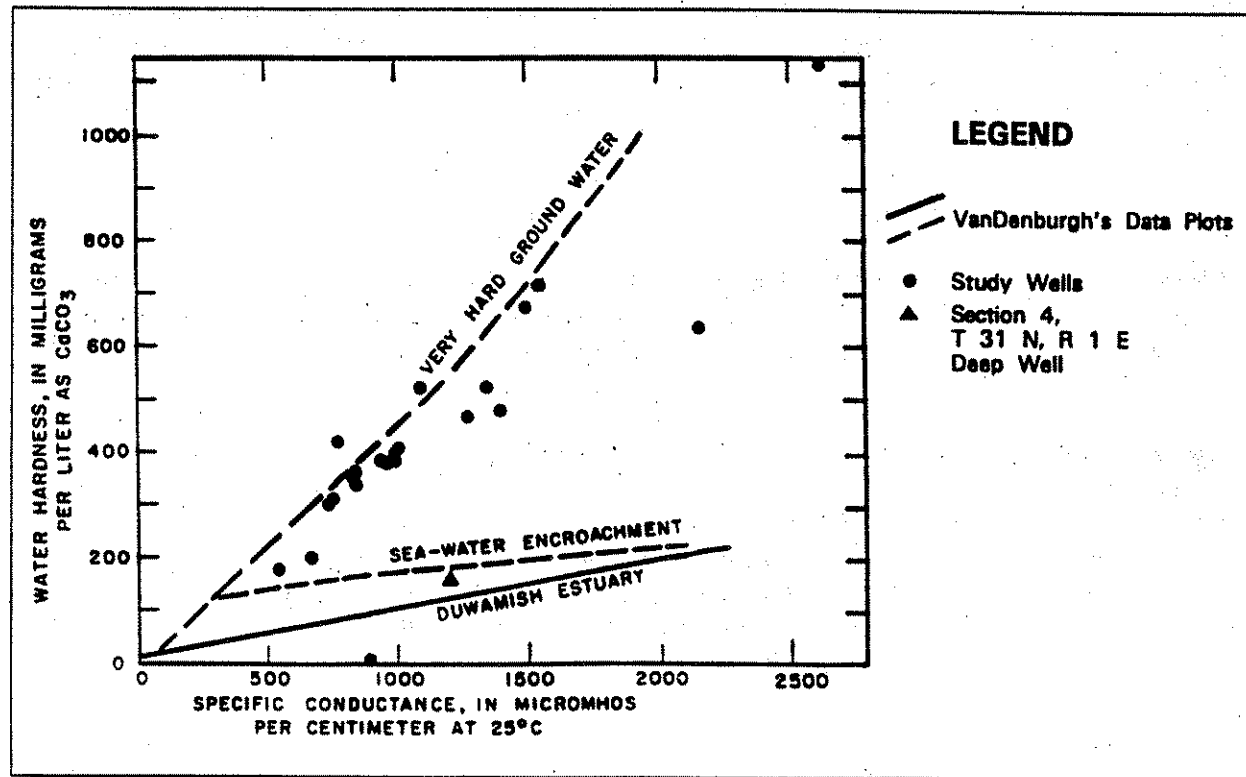


Figure 5 - Ground water hardness versus specific conductance plot.

Figure 6 is a trilinear diagram developed by Piper (1944), from a similar design by Hill (1940). Individual well numbers were omitted in order to facilitate the size reduction required to include the figure in this report. Trilinear diagrams permit the cation and anion compositions of many samples to be represented on a single graph in which major data groupings or trends can be viewed. For comparison purposes, Figure 6 also includes data points for the two ocean water samples and VanDenburgh's examples of normal dilute, very hard, and seawater intruded ground water.

The data point scatter on the trilinear diagram suggests varying degrees of similarity between the subject waters and seawater. Although not apparent on Figure 6 due to the absence of well numbers, some of the sampled water demonstrated properties similar to seawater on one plot but not on others. Only the chloride/sulfate/carbonate-bicarbonate portion of the diagram shows the clear linear trend suggestive of seawater intrusion for all the samples collectively. Based on somewhat arbitrary distinctions, it appears wells 109, 111, 121, 122, 306, and 307 plot toward seawater on all three plots.

Bromide Analyses

As seawater has a higher concentration of bromide than freshwater, concentrations of this anion can be a good indicator of seawater. The analyses indicated, however, that only trace levels of bromide were present in the study samples. These ranged from 0.16 to 0.81 mg/l, with a median concentration of 0.29 mg/l. For study purposes an arbitrary threshold of 0.40 mg/l was chosen for separating those samples suspected of containing elevated bromide levels. Based upon this cut off, it appears five wells had elevated bromide levels including wells 106, 107, 112, 301 and 306.

Analyses for Nitrates and other Nutrients

Nitrate appeared to be the most useful indicator of nutrient contamination. Historical nitrate concentrations in Island County ground water ranged from 0.01 to 2.3 mg/l with a median of 0.13 mg/l for 23 sites sampled by the U.S. Geological Survey (Turney, 1986). Nitrate in the 23 ground water samples taken during the current study ranged from 0.01 (undetected) to 34.4 mg/l with a median concentration of 0.89 mg/l.

Seven of the 23 sampled wells produced water with nitrate concentrations exceeding 2 mg/l, the arbitrary threshold chosen for separating samples suspected of nitrate contamination. These included wells 107, 109, 111, 112, 117, 301, and 302. Well 112, which is located at a former dairy site, produced water with 34.4 mg/l of nitrate. Such a high concentration and the site history strongly suggest this well has been contaminated by dairy waste. Wells 107, 109, and 301 were also interesting, in that they are all clustered within a relatively small area located near a source of dairy waste (see Figure 7).

Only well 116 had high levels of ammonia, but this well also had low sulfate and high phosphate concentrations. Possible sources for these anomalous results include fertilizer applications, detergent contamination and/or laboratory error.

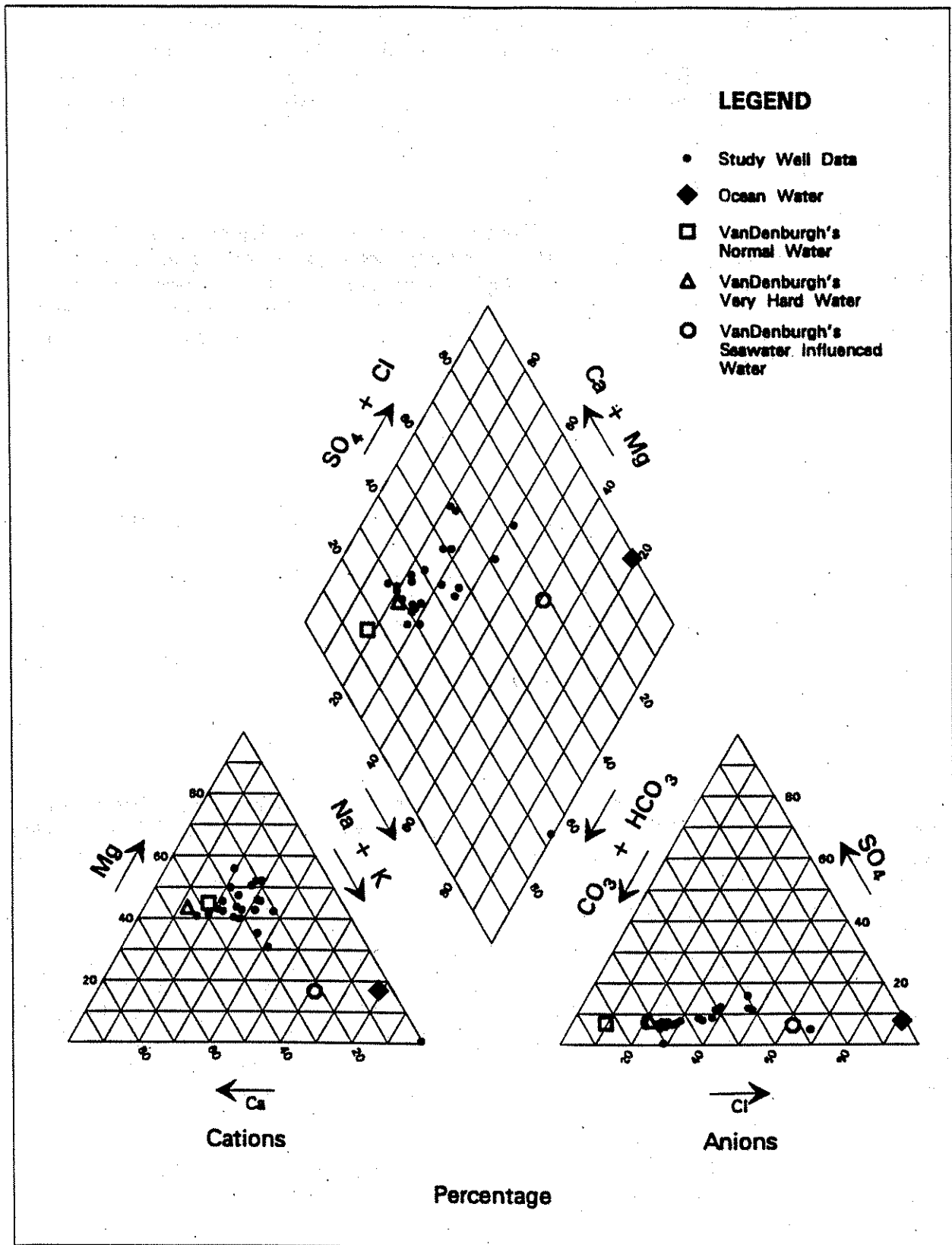


Figure 6 - Piper trilinear diagram with results represented as percentages of meq/l.

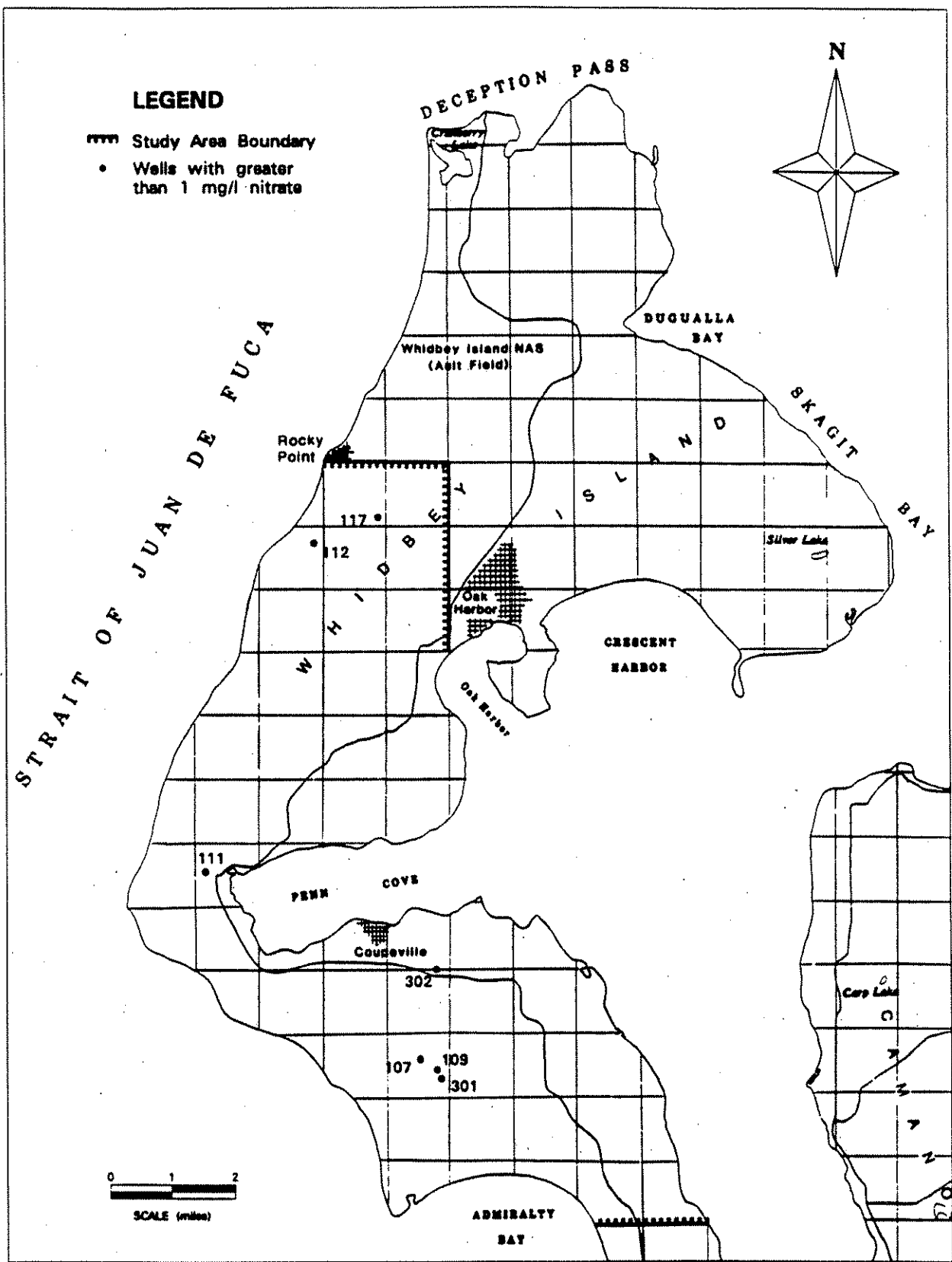


Figure 7 - Wells with greater than 2 mg/l nitrate.

POTENTIAL SOURCES OF CHLORIDE

The Occurrence of Saline Ground Water within Island County

Jones (1985) created frequency distributions of chloride concentrations and well intake elevations for Island County's five major aquifers. For aquifer E, the uppermost aquifer, she concluded 74 percent of the 39 sampled wells had chloride concentrations of 30 mg/l or less, with the maximum concentration being about 60 mg/l. For aquifer D, Jones indicated 106 of the 226 sampled wells were completed above MSL. Of these 106 wells, 76 percent had chloride concentrations of 30 mg/l or less, with the maximum being about 81 mg/l. For aquifer C, 41 of the 404 sampled wells were completed above MSL. Of these 41 wells, about 73 percent had chloride concentrations of 30 mg/l or less, with the maximum being about 80 mg/l. The Jones data suggests that roughly 75 percent of Island County above MSL wells have chloride concentrations of 30 mg/l or less, with an expected maximum concentration of about 81 mg/l.

The study wells had chloride concentrations ranging from 55.2 to 461.0 mg/l, with a median concentration of 86.6 mg/l. As these values are close to or greater than the expected maximum values, it is apparent these wells have unusually high chloride levels for Island County. The Ghyben-Herzberg relationship indicates that seawater occurs at a depth below MSL of about 40 times the height of fresh ground water above MSL under undisturbed, isotropic, homogeneous conditions. In other words, fresh ground water generally floats on top of denser saline ground water in natural environments. As the study wells have high chloride concentrations in spite of above MSL intake levels, it is likely the elevated concentrations are due to causes other than seawater intrusion.

Upconing

When an aquifer contains an underlying layer of saline water and a well penetrating the upper freshwater portion of that aquifer is pumped, a local rise of the fresh water/salt water interface occurs below the well. This phenomenon is known as upconing. If upconing exceeds a certain critical rise, then saline water accelerates upward to the well. Todd (1980) described an analytical solution for the maximum permissible pumping rate without saltwater entering a well through upconing. Todd's analytical method, however, assumed that an abrupt interface exists. As water at the upper edge of this interface is almost fresh water, upward movement of dilute saline ground water can occur readily with adjoining fresh water. Consequently Todd concluded that even with relatively low pumping rates, no limiting critical rise exists above which saline water will not rise. The situation with most of the subject wells, however, involves screen intervals above MSL, sizable vertical depths to the interface without pumping (based on static water levels measured during sampling and the Ghyben-Herzberg relationship), and possibly aquitards separating the wells from direct continuity with seawater. Consequently, it seems unlikely that upconing accounts for a significant saline component in the subject wells.

Very Hard Ground Water

VanDenburgh delineated areas within the County which had very hard water with specific conductance greater than 500 micromhos. With the exception of a small area at the northern tip of Camano Island, his hard water area corresponds closely to the study area depicted in Figure 1. In his report, VanDenburgh presents a strong argument supporting the idea that water hardness accounts for the high chloride content in many of the wells within that area. Furthermore he speculates on the chloride source for this hard water when he states, "Much of this chloride, and accompanying sodium, may have been associated originally with glaciomarine deposits. These generally fine-grained sedimentary materials accumulated in a marine or brackish-water environment during periods when the land surface was several hundred feet lower relative to sea level than it is today . . . Other principal components of the very hard ground water (calcium, magnesium, bicarbonate, and sulfate) have a different but unknown origin."

As indicated by VanDenburgh, it is problematic to come up with a source for the major dissolved constituents other than chloride and sodium. In order for the area's ground water to have high concentrations of calcium, magnesium, bicarbonate, and sulfate, it would appear these constituents must be present in high concentrations within some of the local glacial deposits. The deposits overlying Aquifer D are mainly Vashon Stade till, recessional continental deposits, and recessional marine deposits (Pessl et al., 1989). While many of these are relatively fine grained and could conceivably hold some principal hard ground water components, the occurrence of these deposits is widespread throughout the County. Consequently it is difficult to come up with an explanation for why the very hard water conditions are so localized.

The Presence of Relict (Connate) Pleistocene Epoch Seawater

During the Pleistocene Epoch sea level along the Washington coast was higher than present. Consequently relict or connate seawater was deposited along with the sediments now comprising aquifers C and D. The more than 13,000 years which have elapsed since deposition of the Vashon Drift (Blunt et al., 1987) suggest that most relict seawater has been flushed from the aquifers by now. Nonetheless, Dion and Sumioka (1984) surmised that many occurrences of saline ground water in coastal Washington are probably due to incomplete flushing of seawater.

If relict ground water was derived from Pleistocene oceanic sources, its chemical composition would have many similarities with modern seawater. If the subject wells were utilizing zones of this relict seawater directly, the salinity of the well water would be very high (in the thousands of mg/l). Although these high levels were not observed in the study wells, it is possible that the lower concentrations reflect the dilution of the relict sea water with surrounding fresh ground water. Richter and Kreitler (1991) discussed subtle differences of certain cations and anions in water influenced by relict and modern seawater, however most of these differences are detectable only at concentrations higher than those observed during the study.

Man-Induced Contamination of the Aquifer(s)

Chloride levels in ground water can be increased by certain land uses. These include cattle stockyards, dairy farming, agriculture, road salting, on-site septic systems, solid waste landfills, and land application of wastewater.

Manure has a very high salt content and there are several large dairy farming operations scattered throughout the study area. Dairy waste contamination resulting from either dairy lagoon leakage or direct land application of manure can provide a significant chloride source. Chloride is highly soluble and moves through the subsurface with little or no attenuation. Nitrate, on the other hand, does attenuate somewhat if it moves through the soil slowly. If elevated levels of both chlorides and nitrates are detected, this may indicate that manure is a significant contaminant source for an aquifer.

Dairy lagoons temporarily store animal wastes and wastewater during winter when nutrient uptake by vegetation is low and the potential for runoff from land application of waste is high. A recent study in Whatcom County by Erickson (1991) concluded that chloride, TDS, TOC, COD, total phosphate-P, and ammonia-N concentrations substantially increased down-gradient after dairy lagoons received wastewater. Concentrations of most of these contaminants, including chlorides, increased to a maxima usually three to four months after the main lagoon had received wastes, and then decreased. At the end of monitoring, 299 days after the main lagoon had received wastes, chloride concentrations in nearby wells had not returned to pre-disposal levels.

Agricultural use of soil amendments and fertilizers can degrade overall ground and surface water quality. Fertilizers specifically may pose a significant nitrogen contaminant source. Todd (1980) indicated that applications of soil amendments such as lime, gypsum, and sulfur can lead to increased chloride levels in ground water. According to one prominent local farmer, typical amendment applications may include lime once in every six years and gypsum once in every 20 years. As local soils frequently test low in sulfur, this is added regularly to the soil as part of fertilizer applications. Twenty years ago heavy fertilizer applications were common within the area, however recently these have been reduced by as much as 75 percent. Due in large part to increased land applications of dairy waste, it is now common to apply fertilizers only in the spring.

The high chloride wells with intakes above MSL appear to be concentrated in a relatively small portion of Island County, in an area roughly coincident with the study area boundaries. Road salting does not appear a probable source for the chloride levels detected in the subject wells since this activity would likely include a much larger area. Domestic sewage typically contains only 20 to 50 mg/l of chloride, thus on-site septic systems also are not a likely source for the high chloride levels. There is at least one large landfill located within the study area. The widespread occurrence of elevated chloride levels in the subject wells, however, suggests that some other source must be responsible for the contamination. There appear to be no land applications of wastewater within the study area.

Irrigation with Saline Water

Just southeast of Coupeville within Section 3, T. 31 N., R. 1 E., a farm has been irrigating a substantial portion of their more than 400 acres with saline water since 1988. This well, which is completed 417 feet below MSL, has produced chloride concentrations between 100 and 150 mg/l. While it seems inevitable that irrigating with such high chloride water for extended periods will adversely effect ground water quality in the shallower aquifers, the chloride problems within the study area predate this farm's irrigation. It is possible that other farms within the study area may have also irrigated with saline water during past years.

Sea Spray Depositing Saline Water on the Land Surface

Airborne salts originating from the air-water interface over the sea are a potential source of ground water salinity within coastal regions. Detailed studies conducted in Israel by Loengart (1961) suggest that salts are deposited on land by both precipitation and dry fall out in coastal areas. There is also evidence suggesting this process may be occurring near Cattle Point on San Juan Island, on a thin peninsula very susceptible to sea spray. In the case of the Whidbey Island study area, however, the wells are located as far as 2 miles inland. It is also very difficult to explain why sea spray would effect only the study area and not the remainder of the Island. Consequently, while it would appear that sea spray may have some effect upon the area's ground water, it is not likely a dominant factor here.

Whidbey Island Mainland Source Theory

It has long been speculated that ground water moves from the mainland through aquifers beneath Puget Sound to emerge beneath Whidbey Island. If this were true it could be theorized that this water mixes with saline water as it migrates upward toward the surface. The theory seems to be supported by the high chloride levels in the above MSL wells and some anomalous deep well information. Data from TH-4 and TH-9, two deep U.S. Geological Survey test wells located south of Coupeville, indicates that chloride levels increased with increasing depth only above 174 feet below MSL. Beneath that elevation chloride concentrations dropped off dramatically and continued to decrease. Yet despite this evidence suggesting the possibility of a deep, fresh water source, there are other significant reasons to distrust the validity of the mainland source theory.

Sapik, et al. (1988) specifically addressed the mainland source question when conducting their detailed investigation of Island County's ground water. Their report states, "Model computations of interface depths and hydraulic head indicate that aquifers in all areas except northeast Camano Island are not recharged by ground water moving from the mainland through aquifers beneath Puget Sound." When Sapik, et al. constructed their ground water model of Island County, they purposely utilized boundaries large enough to accommodate the existence of fresh water flow from the mainland. When the model was run, however, it consistently indicated that head produced by precipitation actually results in water flowing from Whidbey Island out into the Puget Sound.

Although comparisons of area well data and Puget Sound bathymetric data indicate that mainland ground water movement is theoretically possible, common sense dictates it is unlikely. The depths involved indicate that the freshwater conduit would likely be separated from the waters of the Sound by a layer less than 100 feet thick for a distance of roughly 10 miles. In order to separate 16,000 mg/l salt water from 20 to 200 mg/l fresh water, the separating layer would have to be either impermeable and/or there would have to be a tremendous head within the conduit.

One possible explanation for the anomalous U.S. Geological Survey well data is that ground water recharge for the deeper aquifers comes from portions of Whidbey Island outside the study area (likely the east). Provided a confining layer exists which separates the deeper aquifers from intruded overlying aquifers, it is possible that recharge does not come directly from above but rather travels horizontally from other areas of the Island. In a Long Island, New York study, Buxton and Modica (1992) found that recharge to the deepest aquifer occurred only through a narrow 0.5 mile wide band through the center of the Island. They found that once water penetrates through this band, it then spreads laterally.

DISCUSSION OF RESULTS

During this study several different graphical methods were used to represent water quality data. These methods included use of Stiff diagrams, a chloride versus conductivity plot, a hardness versus conductivity plot, and a Piper diagram. Table 4 contains a summary of most of the significant results of these analyses. The table indicates that 7 of the 23 sampled wells produced water with chemical compositions resembling dilute seawater according to at least one of the graphical methods. The 16 remaining wells produced water with chemical compositions similar to very hard ground water. The source for many of the dissolved constituents of the very hard water is not known.

There was some agreement between results based on the analyses using the four graphical methods. Wells 109, 111, and 307, for example, produced water which closely resembles dilute seawater according to at least three of the methods. Other wells such as 121, 122, 301, and 306 produced water which resembled dilute seawater according to only one of the four methods. There appear to be a total of seven wells, randomly distributed over the study area, which produce water resembling dilute seawater.

Nitrate appeared to be the most useful indicator of nutrient contamination. There are several large dairy operations located within the study area and at least a portion of the elevated nitrate concentrations appear to be due to improper manure disposal. Fertilizer and soil amendment applications by agriculture may also be responsible in part. Table 4 indicates which wells produced water with greater than 2 mg/l nitrate. Using this threshold, wells 107, 109, 111, 112, 117, 301, and 302 are all suspects for some type of dairy waste contamination. This conclusion is consistent with the work of Erickson (1991), who concluded nitrate and ammonia concentrations in ground water increased down gradient of dairy operations in Whatcom County. The observations are also consistent with the reported high mobility of nitrate (Freeze and Cherry, 1979) and chloride (Revelle, 1941).

As described above, the graphical analyses suggest that wells 109, 111, 121, 122, 301, 306 and 307 may have produced water with some component of seawater. It is possible, however, to produce water chemistry resembling that of dilute seawater simply by contaminating very hard water with nutrients. Wells 109 and 301 produced water with 9.0 and 9.72 mg/l of nitrate respectively, thus these wells are likely candidates for nutrient contaminated, very hard water. These wells are located near two potential dairy waste sources and another high nitrate well (well 107). Furthermore, they are pumped for single domestic use only, and are completed about 31.6 and 29.5 feet above MSL respectively. Well 111 produced a nitrate concentration of 5.2 mg/l and is pumped for single domestic use only, thus it too is a candidate for nutrient contaminated hard water.

The remainder of the suspected seawater influenced wells are 121, 122, 306, and 307. Only well 307, however, appeared to be seawater influenced according to more than one of the graphical methods. Wells 122 and 306 are completed 20 and 22 feet below MSL respectively, thus it is feasible that these wells may also be experiencing seawater influence. Well 121 is a very weak candidate for seawater influence.

TABLE 4. - COMPARISON OF ANALYSIS RESULTS

STUDY ID	WELLS WHICH APPEAR TO BE SEAWATER INFLUENCED ACCORDING TO THE FOLLOWING ANALYSES					WELLS WITH >2 mg/l NITRATE
	STIFF DIAGRAM	CHLORIDES VS. SPEC. COND.	HARDNESS VS. SPEC. COND.	PIPER DIAGRAM	>0.4 mg/l BROMIDE	
101						
105						
106					X	
107					X	X
109	X	X	X	X		X
110						
111	X	X	X	X		X
112					X	X
113						
115						
116						
117						X
118						
119						
121				X		
122				X		
123						
301		X			X	X
302						X
303						
305						
306				X	X	
307		X	X	X		

Potential sources for the suspected seawater influenced wells include irrigation with saline water, sea spray, and/or possible dilution with relict seawater. Unfortunately, chemical similarities make it difficult to distinguish between ground water influenced by these sources and ground water affected by modern seawater. There are unstable isotope age dating techniques which can be useful for distinguishing between components of relict and modern seawater, however costs associated with these are prohibitive. Other less expensive methods for distinguishing between these chemically similar sources likely would not work well at the relatively low concentrations observed in the study wells.

Table 4 identifies wells which produced water with greater than 0.4 mg/l bromide. This threshold is low for separating ground water with elevated bromide levels, however it was used due to the overall low bromide concentrations in the study samples. There does not appear to be strong agreement between the suspect wells indicated by the bromide analyses and those indicated by the graphical methods.

There are many reasons why bromide may not be useful as an indicator of seawater influence for the study wells. The relatively low concentrations of all dissolved solids in the study samples increases the likelihood that bromide is not very useful for distinguishing between ground water affected by modern seawater intrusion and other sources. Furthermore, the larger size of the bromide ion relative to the chloride ion makes it a less mobile component in ground water. Therefore, the bromide ion is more affected by the chemical and physical processes seawater undergoes as it passes through soil and sediments (Hem, 1989). The study data also indicates that many of the wells with elevated bromide concentrations also had elevated nitrate concentrations. This suggests that the bromide source(s) for these wells may be due to other sources such as fertilizer use or improper manure disposal.

CONCLUSIONS AND RECOMMENDATIONS

Wells with high chloride concentrations and intakes above MSL do exist on Whidbey Island. These wells are located over an area of north-central Whidbey Island approximately 45 square miles in extent, encompassing approximately one quarter of the Island. Analysis of the water chemistry of these wells suggests it is likely there are several different sources of chloride for the affected ground water.

Study results suggest that 16 of the 23 wells produce water with a chemical composition resembling very hard ground water rather than dilute seawater. Of the remaining seven wells, three produced water with nitrite concentrations exceeding 2 mg/l. As nutrient contamination of very hard water can produce chemistry resembling that of dilute seawater, it is likely these wells are nutrient rather than seawater affected. Of the other four wells, two are completed below MSL, and one appeared to be seawater influenced according to only one of the four graphical techniques. Taking into consideration all known well information, it appears likely no more than one or two of the 20 above MSL wells may actually be influenced by seawater (see Figure 8). The source(s) of the seawater component(s) for these wells is unknown, but possibilities include upconing, irrigation with saline water, sea spray, and dilution with relict water. Further study is needed to explore ways to distinguish between water influenced by these other sources.

One of the best methods for determining whether an aquifer has been influenced by recent seawater intrusion is to look for an increasing chloride trend in well water. This chloride trend can occur over a short time (as during a pump test) or over a period of years. If no historical data is available or data is inconclusive, then other means must be used to determine the chloride source(s). Listed below are several possible methods for discerning between wells influenced by seawater and wells with high chlorides due to other causes. Some of these may utilize existing data, while others require applicants to conduct additional sampling and laboratory analysis. No single method is sufficient to discern chloride source(s). Consequently, several methods should be applied when conducting investigations. Trilinear diagrams were excluded from this list as some of the other methods accomplish the same functions and are easier to use. The methods include:

Tidal Influence - A graph of a well's static water level over a 24 hour period can be analyzed to determine whether ground water levels mimic tidal fluctuations. If a tidal effect exists, the well may be significantly influenced by seawater.

VanDenburgh's Hard Water Map of Island County - A comparison of a well location with VanDenburgh's very hard water distribution map can indicate whether the well's high chlorides may be due to very hard water.

Chloride versus Specific Conductance Plots - Plotting chloride versus specific conductance on the graph contained in Figure 4 can indicate whether chlorides may be due to very hard water. (See "Review of Nitrate Data" discussion below)

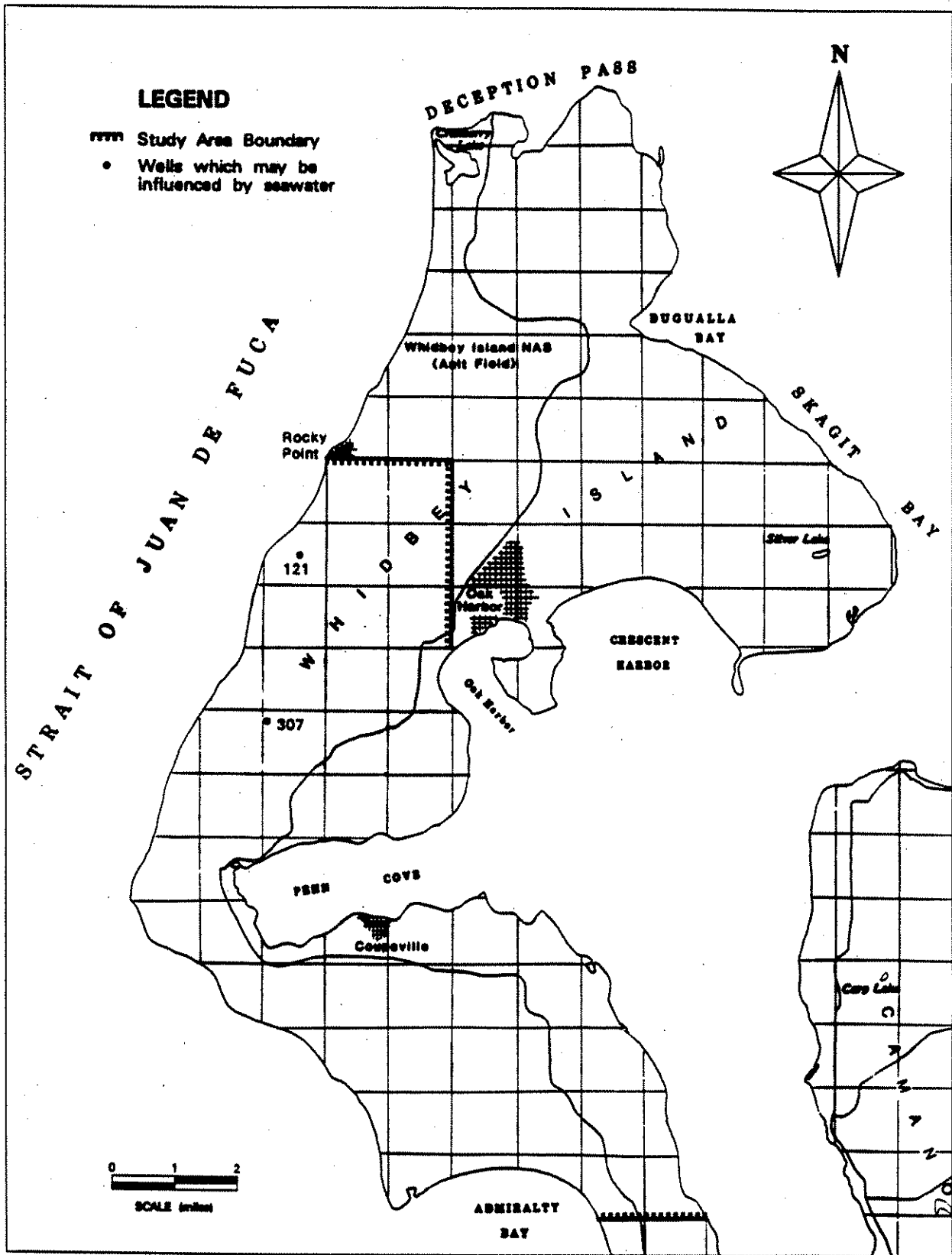


Figure 8 - Above MSL wells which may be seawater influenced.

Water Hardness versus Specific Conductance Plots - Plotting water hardness versus specific conductance on the graph contained in Figure 5 can indicate whether chlorides may be due to very hard water. (See "Review of Nitrate Data" discussion below)

Comparison of Major Dissolved Constituents - A comparison of major dissolved constituents is more involved than the previous two methods, but can indicate whether chlorides may be due to very hard water. The comparison can occur either by constructing a Stiff diagram, or a much simpler diagram such as those constructed by VanDenburgh. (See "Review of Nitrate Data" discussion below)

Review of Nitrate Data - Where a comparison between water hardness and other data suggest that wells may be producing dilute seawater, it is possible that the water chemistry is the result of nutrient contaminated hard water. In such cases, analysis of ground water samples for nitrate can be useful for determining potential source(s) of the elevated chloride levels.

REFERENCES

- Blunt, D.J., D.J. Easterbrook, and N.T. Rutter, 1987, Chronology of Pleistocene Sediments in the Puget Lowland, Washington. Washington Division of Geology and Earth Resources Bulletin 77.
- Buxton, H.T., and E. Modica, 1992, Patterns and rates of ground-water flow on Long Island, New York. Ground Water, Vol. 30, No. 6, pp. 857-866
- Dion, N.P., and S.S. Sumioka, 1984, Seawater intrusion into coastal aquifers in Washington, 1978. Washington Department of Water Resources Water Supply Bulletin No. 56.
- Easterbrook, D.J., 1968, Part I, Pleistocene stratigraphy of Island County. Washington Department of Water Resources Water Supply Bulletin No. 25.
- Easterbrook, D.J., 1992, Guidebook for Northwest Geological Society Field Trip to Whidbey Island.
- Economic and Engineering Services, Inc., 1989, Island County Groundwater Management Plan Technical Memorandum.
- Erickson, D.E., 1991, Edaleen Dairy lagoon ground water quality assessment. Washington State Department of Ecology report.
- EPA, 1983, Methods for Chemical Analysis of Water and Wastes, EPA-600/4-79-020, Revised March 1983.
- Freeze, R.A., and J.A. Cherry, 1979, Groundwater. Prentice-Hall Inc., Englewood Cliffs, N.J.
- Garland, D., and S. Safioles, 1988, Seasonal Variation of Chloride in Ground Water at Southern Camano Island, Island County, Washington. Washington State Department of Ecology Report 87-15.
- GTE Northwest, 1993, The Everything Pages, Eastside, Area Code 206, GTE Directory Corporation.
- Hem, J.D., 1989, Study and interpretation of the chemical characteristics of natural water. U.S. Geological Survey Water Resources Water-Supply Paper 2254.
- Hill, R.A., 1940, Geochemical patterns in Coachella Valley, Calif. Transcripts of the American Geophysical Union, 25.
- Jones, M.A., 1985, Occurrence of groundwater and potential for seawater intrusion, Island County, Washington. U.S. Geological Survey Water Resources Investigations Report 85-4046.

- Loengart, S., 1961, Air-borne salts - The major source of salinity of waters in Israel. Bull. Research Council Israel, v. 10G.
- Pessl, F., D.P. Dethier, D.B. Booth, and J.P. Minard, 1989, Surficial geologic map of the Port Townsend 30- by 60- minute quadrangle, Puget Sound Region, Washington. U.S. Geological Survey Miscellaneous Investigations Series, Map I-1198-F.
- Piper, A.M., 1944, A graphical procedure in the geochemical interpretation of water analysis. Transcripts of the American Geophysical Union, 25, pp. 914-923.
- Revelle, R., 1941, Criteria for recognition of seawater in ground-waters. Transactions American Geophysical Union, vol. 22, pp. 593-597.
- Richter, B.C., and C.W. Kreitler, 1991, Identification of sources of ground-water salinization using geochemical techniques. U.S. Environmental Protection Agency, Office of Research and Development, Robert S. Kerr Environmental Research Laboratory, Ecological Research Series EPA-600/2-91/064.
- Sapik, D.B., G.C. Bortleson, B.W. Drost, M.A. Jones, and E.A. Prych, 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.
- Todd, D.K., 1980, Groundwater Hydrology, John Wiley & Sons, New York.
- Turney, G.L., 1986, Quality of Ground Water in the Puget Sound Region, Washington, 1981. U.S. Geological Survey Water Resources Investigations Report 84-4258.
- VanDenburgh, A.S., 1968, Chemical quality of the ground water, in Anderson, H.W. Jr., Part II, Ground-water resources of Island County. Washington Department of Water Resources Water Supply Bulletin No. 25.

APPENDIX A

Stiff Diagrams

