WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

Geology, Water Resources, and Seawater Intrusion Assessment of Marrowstone Island, Jefferson County, Washington

Water Supply Bulletin No. 59

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ERRATA SHEET: Water-Supply Bulletin No. 59

Table of Contents, page iv:

In the titles for Figures 3F, 3G, and 3H, "Marrowstone Shale" should read "Marrowstone Formation".

Figures 3F, 3G, and 3H (pages 19 & 21):

"Marrowstone Shale" should read "Marrowstone Formation".

Plate 2 -- Geologic Map and Cross Sections:

In the unit description for unit designated as "Tm", "Marrowstone Shale" should read "Marrowstone Formation".

Selected References, page 79 & 80:

Citation, "Collins, W.D., 1923" should end with "p. 394." on the second line. The rest of the citation, beginning with, "Crandell" should be deleted.

Citation, " Economic and Engineering …., 1993" should end with "Port Townsend, WA." on the third line. The rest of the citation, beginning with, "Fairchild" should be deleted.

Appendix C, page C-9:

Heading on 4th column should read, "Sulfate (SO_4-2)".
Heading on 5th column should read, "Total Phosphate (PO_4-3)".
Heading on 6th column should read, "Nitrate + Nitrite (NO_3-+NO_2-)".
Heading on 7th column should read, "Total Alkalinity".

Geology, Water Resources, and Seawater Intrusion Assessment of Marrowstone Island Jefferson County, Washington

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Water Supply Bulletin No. 59

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Conversion Factors and Abbreviations

Those readers preferring to use metric (international system) units rather than inch-pound units may do so by using the following conversion factors:

Multiply inch-pound unit	by	To obtain metric unit
Length		
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4047	square meter (m2)
acre	0.4047	hectare (ha)
square foot (ft2)	929.4	square centimeter (cm2)
square foot (ft2)	0.09294	square meter (m2)
square mile (mi2)	259.0	hectare (ha)
square mile (mi2)	2.590	square kilometer (km2)
Volume		
cubic foot (ft3)	0.02832	cubic meter (m3)
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m3)
Discharge		
cubic foot per second (ft3/s)	0.02832	cubic meters/second (m3/s)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
Aquifer Properties		
Hydraulic Conductivity		
feet per second (ft/s)	0.3048	meters per second (m/s)
(U.S. gal/day/ft2)	0.000000472	meters per second (m/s)
Transmissivity		
(ft2/s)	0.0929	(m2/s)
(U.S. gal/day/ft)	0.0000001438	(m2/s)

Acknowledgements

This study would not have been possible without the support and cooperation of Marrowstone Island's residents. We wish to acknowledge the kindness extended us by the many residents who shared their knowledge of the island's history and allowed us to access their wells for water level and water quality monitoring. In particular, we thank John Illman, Rita Kepner, Lynn Klein, and Robert VanEtten for their help in locating and arranging access to wells. We thank Herb Harrington (Port Townsend weather service volunteer), John Illman, Mel Degerness, William Steenrod, Wendell Stout, and Robert VanEtten for their assistance in collecting and tabulating local precipitation records. We wish to thank Norm Dion (USGS), and John Covert, Chuck Lehotsky, and Tom Culhane of Ecology, for their thoughtful review of this report and Keith Ikerd of the Dept. of Natural Resources for drafting Plates 3 and 4. We also wish to thank Sonya Kirkendall of Ecology's Word Processing Unit for the many hours she spent designing the report layout. Lastly, we thank Linton Wildrick, technical editor for this report.

Abstract

In 1990, the Washington State Department of Ecology (Ecology), Water Resources Program, initiated a hydrogeologic investigation of Marrowstone Island in northeast Jefferson County. The study was undertaken in response to public concern about the effects of sea-water intrusion on the island's fresh water aquifers.

Sea-water intrusion is a common problem in Washington State. By studying Marrowstone Island, a small and relatively easy system to describe, we intended to evaluate methods of assessing water-quality information which might be of use in sea-water-intrusion determinations. These methods could then be applied elsewhere in the state to address sea-water-intrusion concerns.

Ground water on Marrowstone Island is contained within two principal hydrogeologic units: Eocene bedrock consisting of fractured sandstone and shale and Pleistocene glacial drift composed of sand, gravel, silt, and minor clay.

Recharge to the island's aquifers is derived from local precipitation which averages approximately 20.4 inches per year. The island's ground water generally flows from areas of recharge in the island interior toward the island perimeter. Ground water that is not withdrawn for human use discharges along the coast via seeps and springs and as subsurface discharge to the Puget Sound.

The most productive aquifers on the island are contained in glacial drift deposits, where well specific capacities average about 7.2 gpm/ft of drawdown and range from <0.01 to 30 gpm/ft of drawdown. The bedrock aquifers are generally less productive, with well specific capacities ranging from <0.01 to 1.5 gpm/ft of drawdown and averaging 0.19 gpm/ft of drawdown.

The island's ground water is generally acceptable for domestic drinking water purposes, with the exception of Total Dissolved Solids (TDS), pH, and chloride. TDS concentrations in water from 23 wells exceeded the recommended Maximum Contaminant Level (MCL) of 500 mg/L, for drinking water. Four wells produced water with pH values falling outside the recommended MCL range of 6.5 to 8.5. Eleven wells produced water that exceeded the 250 mg/L MCL for chloride. Twenty-one wells produced water that exceeded the 100 mg/L chloride concentration threshold for sea-water-intrusion.

A comparison of chloride concentrations in wells sampled during this and a previous investigation (Dion and Sumioka, 1984) indicates that sea-water intrusion has worsened over time in some areas of the island.

We used five analytical methods, with varying degrees of success, to identify sea-water intrusion: (1) chloride concentrations compared to the 100 mg/L threshold; (2) ion ratios and grouping by water types; (3) graphic analyses including a) cumulative percentages of TDS, b) mixing diagrams, and c) trilinear diagrams. Sea-water intrusion was indicated by all five methods.

To minimize sea-water-intrusion effects, it will be necessary for the residents of Marrowstone Island to use the limited ground water as wisely as possible. Water conservation is the most economical line of defense against sea-water intrusion.

Introduction

Marrowstone Island, in northeastern Jefferson County, supports a small but growing community that depends on ground water and rainfall-catchment systems to meet its potable water needs. In recent years, concern about sea-water intrusion into the fresh-water aquifers of the island prompted several residents to contact the Department of Ecology (Ecology) to discuss what they perceived to be a worsening problem. This report presents the results of an investigation undertaken by Ecology in February 1990, in response to these discussions.

Purpose and Scope of the Investigation

The purpose of this investigation was to assess the extent and severity of sea-water intrusion on Marrowstone Island and to determine how the island's geology, hydrology, and water-use patterns contribute to its sea-water-intrusion problem. A secondary objective of the study was to provide Ecology staff with examples of common analytical and graphical techniques for evaluating water-chemistry data for evidence of sea-water intrusion.

Between February 1990 and December 1992, we conducted field investigations to locate and tag wells, determine well-head elevations, measure ground-water levels, and collect ground-water samples for laboratory analysis of chlorides and other dissolved inorganic constituents. During this period we also mapped the coastal geology of the island to clear up interpretive discrepancies between prior investigators and to aid in our interpretation of well reports from the island interior.

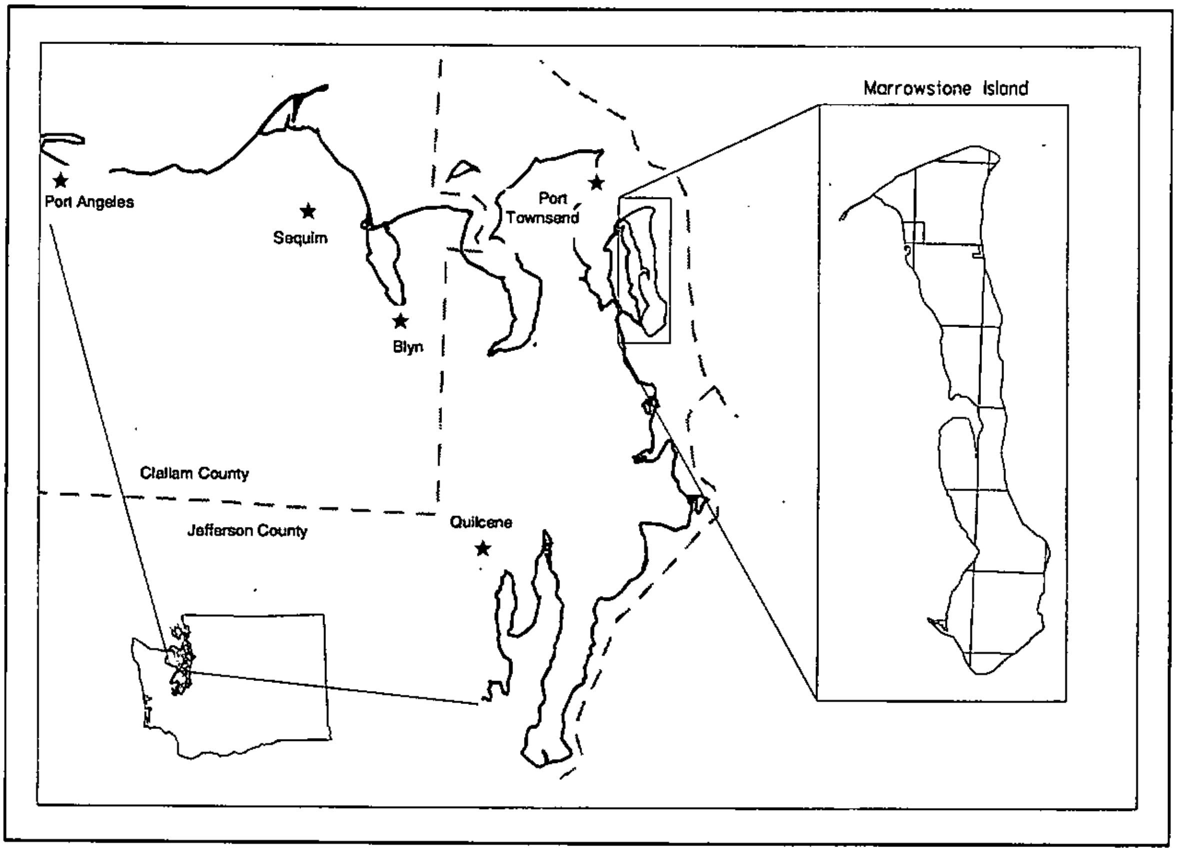
Physiographic Setting

Marrowstone Island is located in northeastern Jefferson County, Washington State, within Townships 29 and 30 North, and Range 1 East of the Willamette Meridian (Figure 1). It is bordered by Admiralty Inlet to the east and Kilisut Harbor to the west.

The elongate, north-south trending island encompasses an area of approximately 6 square miles (4018 acres) and reaches a maximum elevation of approximately 180 feet above mean sea level (MSL). The island interior has fairly gentle relief, with most of the land surface lying above an elevation of 60 feet. A majority of the island perimeter is marked by vertical to slightly overhanging bluffs and cliffs, extending from sea level to heights of 60 to more than 120 feet. Surface-water drainage from the island interior is limited to small intermittent streams that form during severe storm events or that emanate seasonally from the island's many wetlands.

Figure 1.

Location of Marrowstone Island



Climate

The climate of Marrowstone Island with its mild, damp winters and cool, dry summers is typical of western Washington. Port Townsend, with the nearest National Weather Service station (Figure 1), receives an average of 19.4 inches of precipitation per year (Table 1), while the towns of Port Angeles and Quilcene average 25.4 and 50 inches, respectively. The variability in precipitation between Port Townsend, Port Angeles, and Quilcene is due largely to the rain shadow effect of the Olympic Mountains.

Six rain gages have been monitored on Marrowstone Island by five residents during the period 1978 to present (Table 2 and Plate 1). Based on the data from these stations, Marrowstone Island receives an average of 20.4 inches of precipitation annually. Evaluation of the total monthly precipitation for these stations indicates that precipitation on the island decreases to the north and that Port Townsend receives less precipitation, on average, than southern Marrowstone Island but more than the north end of the island.

TABLE 1.
Total Precipitation, in Inches, by Month and Year for Port Townsend, WA, (EarthInfo, 1993)
Location: 30N/01W-11, Latitude 48°06'00", Longitude 122°46'00".

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1948	----	----	----	----	----	2.48	1.66	1.89	1.93	2.07	2.56	2.35	----
1949	0.59	2.91	0.94	1.56	0.50	0.69	0.88	0.67	0.82	1.23	2.67	3.41	16.87
1950	3.23	2.65	2.58	0.80	0.45	0.48	1.98	0.75	0.93	2.22	2.65	1.24	19.96
1951	3.34	0.93	1.13	0.52	1.78	0.10	0.13	1.37	0.58	----	2.62	2.80	----
1952	1.93	0.98	1.76	0.94	0.48	1.01	0.65	0.09	0.43	1.01	1.03	2.66	12.97
1953	2.54	0.88	1.61	0.60	2.08	2.60	0.32	1.27	0.76	1.05	2.36	1.72	17.79
1954	2.90	1.51	1.82	1.19	1.00	1.84	1.15	1.31	1.88	0.51	2.08	1.91	19.10
1955	1.08	2.29	2.01	2.25	1.70	2.31	1.14	0.06	0.44	1.27	3.16	3.93	21.64
1956	3.78	1.69	2.39	0.03	0.60	2.43	0.06	1.19	1.52	3.83	0.70	2.43	20.65
1957	2.24	2.68	2.86	1.53	0.69	0.55	1.15	0.55	0.37	1.43	1.61	1.76	17.42
1958	1.68	2.39	0.89	1.18	1.80	1.03	0.01	0.18	1.15	2.56	3.60	1.95	18.42
1959	3.58	1.89	2.06	0.85*	1.77	0.69	0.24	0.45	1.81	1.60	4.27	2.24	21.45
1960	2.19	1.55	1.07	0.81	1.78	0.79	0.06	2.35	0.63	1.41	3.69	1.16	17.49
1961	0.64	3.54	2.27	1.77	2.34	0.61	0.74	0.36	0.68	1.43	1.59	2.58	18.55
1962	0.88	0.98	1.95	1.15	1.63	0.95	0.47	1.68	1.39	2.57	4.13	1.54	19.32
1963	0.88	1.15	0.67	2.16	1.28	2.40	1.21	0.66	0.54	1.92	2.85	2.78	18.50
1964	2.06	1.55	2.72	1.78	1.43	2.47	1.46	0.63	1.85	0.39	2.28	3.12	21.74
1965	4.71	2.01	0.63	1.82	0.76	0.50	0.37	1.64	1.04	0.74	1.72	2.99	18.93
1966	2.06	1.04	3.46	0.99	1.87	0.95	2.14	0.47	1.39	1.50	2.44	3.18	21.49
1967	3.40	1.47	3.47	2.86	1.03	1.08	0.22	0.00	1.48	2.69	0.84	4.90	23.44
1968	2.75	1.27	2.20	1.47	1.41	0.88	0.50	1.51	1.14	1.27	2.25	3.64	20.29
1969	----	3.24	0.26	1.91	----	----	----	----	----	----	----	----	----
1970	----	0.64	0.89	----	----	----	----	----	----	----	----	----	----
1971	----	----	----	----	----	----	----	0.74	1.33	1.02	2.71	5.28	----
1972	2.45	1.17	1.84	3.41	0.33	2.24	0.60	2.00	1.48	0.99	1.56	3.30	21.37
1973	0.87	0.44	1.83	0.73	0.68	0.88	0.14	0.68	0.66	1.51	4.12	3.03	15.57
1974	3.73	2.25	1.89	0.87	1.22	0.70	2.93	0.12	0.41	1.00	1.47	3.24	19.83
1975	2.98	2.06	1.54	1.83	1.67	1.78	0.85	2.80	0.14	1.56	2.63	2.65	22.49
1976	1.62	1.75	1.60	1.45	2.02	1.00	1.04	2.47	1.04	0.75	0.62	1.18	16.54
1977	0.93	0.30	2.31	1.22	2.83	0.91	1.51	2.38	1.75	0.96	----	2.27	----
1978	2.05	2.51	1.32	1.43	1.93	0.14	1.92	0.59	2.27	0.62	3.45	2.19	20.42
1979	1.00	2.13	0.74	2.36	1.35	0.47	1.22	0.38	0.73	1.64	0.87	3.58	16.47
1980	1.96	1.37	1.94	1.77	1.31	3.15	0.28	0.65	0.85	----	----	0.40	----
1981	1.05	1.65	1.39	1.19	1.63	2.04	0.77	0.32	1.26	1.87	2.08	4.66	19.91
1982	3.62	1.84	2.61	1.35	0.52	0.75	1.34	0.73	1.46	1.90	1.87	4.19	22.18
1983	3.68	1.63	1.74	1.37	2.58	2.08	0.97	0.57	3.18	0.51	3.86	2.15	24.32
1984	2.68	2.79	1.67	1.05	2.27	2.76	0.04	0.41	2.82	1.14	3.94	2.11	23.68
1985	0.25	1.58	0.97	0.84	1.36	1.46	0.19	1.01	1.15	4.23	2.21	0.41	15.66
1986	1.72	1.67	1.18	1.68	1.80	1.11	0.86	0.10	1.46	0.75	3.47	0.95	16.75
1987	2.65	0.94	1.29	1.39	1.04	0.14	0.65	0.64	0.35	0.01	----	----	----
1988	----	0.37	1.98	2.67	2.16	1.06	0.61	0.34	0.52	1.14	2.08	1.69	----
1989	1.98	1.73	2.33	0.58	1.92	0.26	0.49	1.01	0.07	1.49	2.79	1.95	16.60
1990	2.27	1.44	1.05	1.75	2.61	1.72	0.44	----	----	----	----	2.71	----
1991	1.13	2.25	2.30	1.08	0.74	1.00	1.07	1.49	0.08	1.46	3.69	1.26	17.55
1992	2.33	1.58	1.52	2.71	0.38	1.78	1.60	1.35	0.68	0.94	4.06	3.07	22.00
Min	0.25	0.30	0.26	0.03	0.33	0.10	0.01	0.00	0.07	0.01	0.62	0.40	12.97
Max	4.71	3.54	3.47	3.41	2.83	3.15	2.93	2.80	3.18	4.23	4.27	5.28	24.32
Mean	2.18	1.69	1.74	1.45	1.43	1.29	0.86	0.95	1.10	1.45	2.53	2.54	19.35

TABLE 2
Total Precipitation, in Inches, by Month and Year, for Marrowstone Island

Location: 30N/01E-18R, Latitude 48°05'00", Longitude 122°42'00"
(Degerness, 1993)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1984	2.72	2.97	1.54	1.46	2.56	2.32	0.01	0.28	2.84	1.37	4.35	2.24	24.66
1985	0.28	1.67	1.40	1.07	1.38	1.42	0.02	1.25	1.81	4.05	1.71	0.66	16.72
1986	1.42	1.56	1.64	1.69	1.87	1.14	1.21	0.06	1.24	1.01	3.16	1.36	17.36
1987	3.14	0.61	1.41	1.45	0.92	0.50	0.73	0.73	0.48	0.08	2.33	3.60	15.98
1988	0.80	0.56	2.00	2.25	1.92	1.20	0.48	0.44	0.05	1.83	2.63	1.19	15.35
Mean	1.67	1.47	1.60	1.58	1.73	1.32	0.49	0.55	1.28	1.67	2.84	1.81	18.01

Location: 30N/01E-33C, Latitude 48°03'00", Longitude 122°41'00"
(Illman, 1993)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1978	—	—	—	—	—	—	—	—	0.73	1.52	1.57	2.20	—
1979	3.30	2.59	1.78	2.03	3.04	0.46	1.63	1.37	1.64	0.69	1.70	2.18	22.41
1980	3.40	2.04	2.20	3.16	1.61	3.12	0.30	1.64	0.92	0.55	3.31	2.45	24.70
1981	1.65	2.41	1.75	2.74	2.21	2.20	0.74	0.20	1.95	2.79	4.02	6.68	29.34
1982	3.64	1.84	2.51	2.74	0.33	0.67	2.65	1.03	1.41	2.88	2.41	6.37	28.48
1983	3.85	2.12	2.86	0.94	1.95	1.89	1.59	0.67	1.00	0.41	5.59	2.62	25.49
1984	2.47	2.87	2.05	1.73	2.95	2.76	0.02	0.50	3.37	1.64	1.30	2.28	23.94
1985	0.26	1.86	1.79	0.90	1.78	1.30	1.18	0.85	2.10	4.75	1.34	1.09	19.20
1986	2.24	1.93	1.60	2.32	2.55	0.98	1.38	0.08	1.38	1.56	4.45	1.79	22.26
1987	4.45	1.03	1.94	2.79	1.19	0.83	0.80	0.61	0.70	0.05	1.59	5.51	21.49
1988	1.24	0.44	2.59	2.51	2.56	1.22	0.74	0.43	0.79	1.06	3.44	2.40	19.42
1989	2.05	2.16	3.17	0.83	2.71	0.30	0.72	1.13	0.13	2.19	3.46	0.55	19.40
1990	—	—	—	—	—	—	—	—	—	—	—	—	—
1991	1.18	3.46	3.85	1.69	1.24	1.34	1.05	1.94	0.22	0.73	4.40	1.27	22.37
1992	3.48	2.42	1.38	3.64	0.71	2.39	1.23	0.99	0.54	0.78	4.56	3.53	25.65
Mean	2.55	2.09	2.27	2.16	1.91	1.50	1.08	0.88	1.21	1.54	3.08	2.71	23.40

Location: 30N/01E-33P, Latitude 48°02'00", Longitude 122°40'00"
(Stout, 1990)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1978	—	—	—	—	—	—	—	—	2.41	0.32	2.70	1.69	—
1979	0.54	2.80	0.31	2.61	0.77	1.09	0.33	0.65	0.52	1.81	0.65	3.67	15.75
1980	2.09	1.83	2.00	1.89	1.01	2.79	0.05	1.68	0.90	0.23	2.80	2.28	19.55
1981	1.44	2.57	2.25	1.88	1.63	2.87	0.47	0.65	1.50	2.59	3.58	7.21	28.64
1982	3.23	2.93	1.91	2.04	—	1.25	1.77	0.75	1.20	3.14	2.69	6.29	—
1983	4.00	2.66	2.99	0.70	2.30	1.68	1.28	1.65	—	—	5.03	2.49	—
1984	2.25	2.67	2.23	1.53	2.23	2.60	0.00	0.35	3.67	1.60	4.72	2.07	25.92
1985	0.30	1.41	1.16	0.73	1.35	2.03	0.15	0.50	1.62	4.70	1.21	0.48	15.64
1986	2.04	2.07	1.50	2.47	2.14	0.95	1.50	0.00	1.49	1.25	3.57	1.79	20.77
1987	4.19	0.48	1.48	1.38	1.40	0.20	0.54	0.50	0.60	0.05	2.32	4.45	17.59
1988	1.26	0.28	2.48	2.46	2.18	0.99	0.33	0.40	0.74	0.88	2.98	3.78	18.76
1989	4.00	1.86	2.61	0.60	2.63	0.05	0.53	1.69	0.05	1.91	2.95	1.06	19.94
Mean	2.30	1.96	1.90	1.66	1.76	1.50	0.63	0.80	1.34	1.68	2.93	3.10	20.28

TABLE 2 (continued)
Total Precipitation, in Inches, by Month and Year, for Marrowstone Island

Location: 29N/01E-05H, Latitude 48°02'00", Longitude 122°41'00"
(VanEtten, 1993)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1983	4.06	2.65	2.60	0.80	0.25	3.10	1.35	0.40	2.85	0.25	5.45	2.00	25.76
1984	2.80	1.60	1.75	1.15	2.60	1.65	0.00	0.35	4.25	1.15	3.50	2.75	23.55
1985	0.40	1.80	2.40	1.00	1.60	1.25	0.15	0.90	2.00	4.15	1.60	0.55	17.40
1986	1.85	2.05	1.20	2.50	1.65	0.80	1.15	0.00	1.40	0.70	4.15	1.50	18.95
1987	3.20	1.30	1.60	0.75	0.65	0.80	0.40	0.65	0.40	0.00	1.20	6.05	17.00
1988	1.30	0.20	2.25	2.00	2.50	0.80	0.45	0.25	0.60	0.90	3.06	1.90	16.21
1989	2.50	2.40	2.10	0.75	2.25	0.20	0.60	1.60	0.00	2.10	3.00	0.95	18.45
1990	2.75	2.35	1.75	2.00	2.70	2.65	0.35	0.95	0.15	3.00	3.95	2.00	24.60
1991	0.80	4.15	3.35	1.60	1.30	1.05	1.00	1.60	0.00	0.55	3.85	0.90	20.15
1992	3.65	2.85	1.15	3.60	0.00	2.05	1.00	1.20	0.25	0.45	3.55	3.50	23.25
Mean	2.33	2.13	2.01	1.61	1.55	1.43	0.64	0.79	1.19	1.32	3.33	2.21	20.53

Location: 29N/01E-09A, Latitude 48°01'00", Longitude 122°40'00"
(Steenrod, 1990)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1985	—	—	—	—	—	—	—	—	0.29	4.38	1.42	0.60	—
1986	2.86	1.68	1.73	2.13	2.21	1.17	1.25	0.06	0.12	0.20	4.69	1.97	20.07
1987	—	—	—	—	0.92	0.80	0.70	0.62	0.40	0.02	1.52	5.30	—
1988	1.26	0.35	—	2.85	—	1.43	0.46	0.80	—	1.52	3.64	2.43	—
1989	1.88	2.49	3.41	1.04	2.16	0.84	1.22	0.38	0.18	1.98	3.40	1.09	20.07
Mean	2.00	1.51	2.57	2.01	1.76	1.06	0.91	0.46	0.25	1.62	2.93	2.28	20.07

Location: 29N/01E-09R, Latitude 48°00'00", Longitude 122°40'00"
(Degerness, 1993)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1989	2.09	2.25	2.89	1.26	1.79	1.03	0.60	1.02	0.13	2.46	2.62	0.89	19.03
1990	3.39	1.69	1.67	1.81	2.90	2.18	0.46	0.87	0.22	2.30	3.22	2.01	22.72
1991	0.50	3.52	2.64	2.09	0.14	2.58	0.57	1.43	0.07	1.12	3.26	0.87	18.79
1992	3.50	2.01	1.48	3.25	0.52	1.97	1.31	1.16	0.60	0.50	2.69	—	—
1993	—	—	0.73	2.14	3.53	1.70	2.07	0.27	0.21	0.35	1.93	—	—
Mean	2.37	2.37	1.88	2.11	1.78	1.89	1.00	0.95	0.25	1.35	2.74	1.26	20.18

Land Use and Development

The early development of Marrowstone Island closely followed that of nearby Port Townsend. The initial Island settlers were bachelors and Norwegian fisherman, attracted to the area by free land made available under the Homestead Act of 1862 (Russell and Bean, 1978). The early settlers lived in relative isolation and sustained themselves by exploiting the abundant fishery and timber resources of the island and surrounding environs. In 1892, the town of Nordland (Plate 1) was platted by Peter Nordby and became the first established community on the island.

Near the turn of the century, construction of fortifications at Fort Flagler (Plate 1) resulted in a period of great prosperity for the island community. Land initially cleared through logging was purchased and renovated for crop, fruit, and poultry production, with some of the production going to support the fort's inhabitants. At the conclusion of World War I, the need for Fort Flagler waned, and by 1926, only a skeletal crew remained. The local agricultural community was relatively stable up through World War II and produced poultry, berry, and other products for the Puget Sound market. In 1952, the Portage Canal bridge was completed, thereby connecting Indian and Marrowstone Island to the mainland. With easy access to the mainland assured, the Island's agricultural community has largely been replaced, in the ensuing years, by residential development.

In 1990 there were approximately 686 full-time residents living on Marrowstone Island (Jefferson County Planning Dept., 1993). Based on building permit information, the Jefferson County Planning Department (1993) predicts that the population of the island will increase over the next 20 years as shown in Table 3.

TABLE 3
Population Projections for Marrowstone Island

Year	Population Increase	Total Population
1993	109	795
1994	35	830
1999	127	1,057
2004	78	1,035
2009	46	1,081
2014	34	1,115

Previous Investigations

Marrowstone Island and vicinity have been the subject of numerous studies. However, no previous authors have specifically addressed the hydrology of the island. Arnold (1906) conducted the earliest geologic mapping of the eastern Olympic Peninsula. Weaver (1916) was the first author to mention the Tertiary rock units of the Scow Bay area. He later (1937) mapped and described the Tertiary stratigraphy of the area. In all three studies, Marrowstone Island was a small part of a larger study area.

In his reports of Oligocene fossil assemblages, Durham (1942, 1944) was the first to describe Marrowstone Island's bedrock units and, in so doing, coined the unit names "Marrowstone Shale" and "Quimper Sandstone". Allison (1959) and Thoms (1959) mapped and described the Eocene geology, stratigraphy, and paleontology of the Quimper Peninsula and Marrowstone Island. Allison named the Scow Bay Formation, and measured and described a type section for the unit on the west side of Marrowstone Island. Armentrout and Berta (1977) refined the age dating of Marrowstone Island's sandstone units based on new paleontologic evidence. Armentrout, in partnership with other authors (Armentrout and Cole, 1979; Armentrout, 1984; and Fairchild and Armentrout, 1984) studied, in detail, the sedimentary petrology of the Eocene sandstones and attempted to determine the source area for the sediments.

Gayer (1976) and Gower (1980) mapped the geology of the area but neither made changes to previous interpretations of Marrowstone Island's geology. Melim (1984) studied the sedimentary petrology, sedimentology, and depositional environment of the Scow Bay Formation. Rauch (1985) studied the sedimentary petrology and depositional environments of the Marrowstone Shale and Quimper Sandstone.

Numerous studies of the Puget Sound Lowlands have been conducted to map and define the stratigraphy and geologic history of the complicated glacial deposits that dominate the area's geology. Some of the authors that contributed significantly to this effort and who's work was consulted for this report are: Crandell and others (1958); Easterbrook (1968, 1969, 1986); Hasse (1987); Pessl and others (1989); and Stoffel (1981). Of these authors, Easterbrook's work is the most germane to Marrowstone Island. Much of his work concentrated on Whidbey Island, but he also included the glacial stratigraphy of Marrowstone Island in some of his discussions. Grimstad and Carson (1981) wrote the most comprehensive hydrogeologic report about eastern Jefferson County.

Marrowstone Island was included in at least three large-scale reconnaissance studies of sea-water intrusion in Washington. Walters (1971) sampled fifteen Marrowstone Island wells during his 1966-68 evaluation of sea-water intrusion along coastal Washington. Dion and Sumioka (1984) revisited nine of these wells during their 1978 follow-up study. Forbes and CH2M HILL (1993) sampled five Marrowstone Island wells during their sea-water-intrusion study of eastern Clallam and Jefferson Counties. Economic and Engineering Services, Inc. and Pacific Groundwater Group (1993) summarized previous studies about the ground water of eastern Jefferson County.

The citizens of Marrowstone Island have collected considerable climatic and ground-water chemistry data. VanEtten and others (1986) collected and analyzed samples for chloride and nitrate. VanEtten (1993), Degerness (1993), Steenrod (1990), Illman, (1993), and Stout (1990) have all collected precipitation data on a regular basis and provided that data to us for this study (Table 2).

Study Methods

This section contains brief descriptions of the methods and procedures we used for well numbering, monitoring-well selection, measurement of ground-water levels, ground-water sampling, and laboratory analyses. The data reporting and water-quality sampling for this study conform with standard methods and procedures as described in Department of Ecology publications by Blair and Darr (1988) and Huntamer and Hyre (1991).

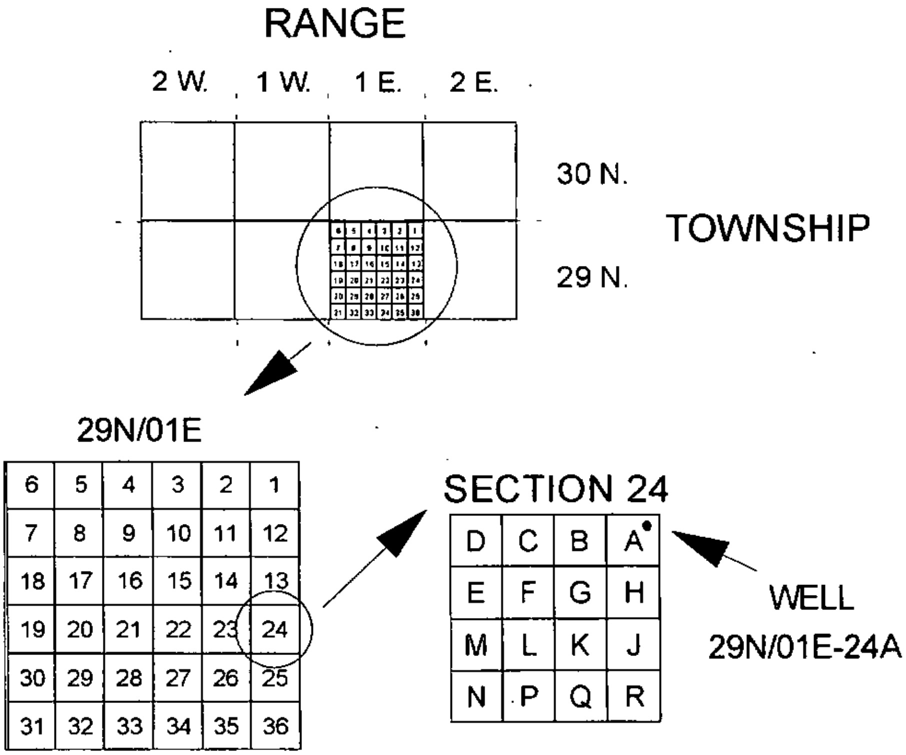
Well Numbering and Location System

All wells monitored during this study were assigned unique identification numbers consisting of three letters followed by three numbers (i.e. AAB069). The identification number is stamped on a metal tag that is secured to the well casing or another nearby permanent fixture of the water system. Wells used solely for geologic control purposes were not tagged but are referenced herein using a geologic-control number (i.e. GC-007).

Well locations are defined in terms of township, range, section, and quarter-quarter of the section. Township designations include an "N" and range designations include an "E" to indicate the well lies north and east of the Willamette baseline and meridian, respectively. The quarter-quarter section is represented by a single capital letter. For example, a well in the northeast quarter of the northeast quarter of Section 24, Township 29 North, Range 01 East, is recorded as 29N/01E-24A (Figure 2). If more than one well is referenced per quarter-quarter section, a sequential number is included after the quarter-quarter designation to assure uniqueness of identification

Figure 2.

Well Numbering and Location System



Selection of Monitoring Wells

We considered several criteria when selecting monitoring wells including a) ease of access for water-level measurement and sample collection, b) owner's permission to monitor the well, c) the need to obtain a uniform areal coverage of the island and d) the desire to collect representative ground-water samples from the island's various geologic formations. Where possible, we sampled only those wells that appear to withdraw water from a single aquifer, as verified by the drillers report.

During this study, we field located a total of 79 wells (Plate 1). Of this total, we used 73 wells to help refine our understanding of the island's geology, 68 to measure ground-water levels, and 46 to monitor water-quality. We sampled 34 wells on 5 separate occasions for chloride, temperature, conductivity, and pH. We sampled 10 wells in May 1990 for laboratory analysis of major cations and anions.

Thirty-five of the water-quality-monitoring wells withdraw water from Vashon advance outwash while nine withdraw water from Tertiary bedrock (see Hydrogeology section). Two wells probably withdraw water from both the outwash and bedrock aquifers. The location of these wells and their production zone(s) are shown on Plate 1.

Determination of Well-Head Elevations and Ground-Water Levels

We determined well-head elevations via a combination of two methods: 1) interpolation from 7.5 minute topographic maps and 2) field measurements using a surveying altimeter. The elevations referenced in this report should be considered accurate to ±5 feet.

To evaluate seasonal and tidal effects on ground-water levels, we conducted water-level measurements in 56 wells on seven occasions during the period May 1990 to December 1992 (Appendix A). We measured water levels to an accuracy of 0.01 feet and rounded to the nearest 0.10 foot for reporting purposes.

Ground-Water-Sampling Procedures

The ground-water samples we collected during this study were obtained from domestic wells using the installed pumps and piping. Where possible, we collected samples from faucets ahead of any pressure tank or storage system. We sampled only those wells where we could obtain an untreated water sample. Prior to collecting the sample, we purged the well until water temperature and specific conductance stabilized. We measured pH at the time of sample collection. We stored the samples on ice prior to their arrival at the laboratory.

Analytical Procedures

We collected ground-water samples for analysis of field parameters, nutrients, major cations, major anions, and other dissolved constituents (Table 4). We determined field parameters using methods described by Wood (1976). For those wells with complete cation/anion analyses we determined TDS by summing the mg/L concentrations of all dissolved constituents. For those wells with incomplete analyses we determined TDS by multiplying the specific conductance by 0.65 (Hem, 1985).

Laboratory analyses were conducted at the Ecology/EPA laboratory in Manchester Washington, or at a certified contract laboratory.

TABLE 4
Summary of Target Analytes, Analytical Methods, and Method Detection Limits

Target Analyte	Analytical Method	Reference	Method Detection Limit
Field Parameters			
Water Level	Electric Well Probe/Steel Tape	NA	0.1 feet
Specific Conductance	YSI Model 3000 TLC Meter	NA	~ 3 percent
pH	Piccolo/Beckman pH Meter	NA	~ 0.1 std. units
Temperature (^oC)	YSI Model 3000 TLC Meter	NA	~ 0.1 C^o
Nutrients			
Nitrate/Nitrite-N	EPA-353.2	USEPA (1983)	0.01 mg/L
Total Phosphorous	EPA-365.3	USEPA (1983)	0.01 mg/L
Major Cations			
Calcium	EPA-200.7	USEPA (1983)	0.01 mg/L
Magnesium	EPA-200.7	USEPA (1983)	0.03 mg/L
Sodium	EPA-200.7	USEPA (1983)	0.03 mg/L
Potassium	EPA-200.7	USEPA (1983)	1 mg/L
Major Anions			
Chloride	EPA-330.0	USEPA (1983)	0.1 mg/L
Bicarbonate Alkalinity	EPA-310.1	USEPA (1983)	1 mg/L
Carbonate Alkalinity	EPA-310.1	USEPA (1983)	1 mg/L
Sulfate	EPA-330.0	USEPA (1983)	0.5 mg/L
Other Constituents			
Iron	EPA-200.7	USEPA (1983)	0.02 mg/L
Silica	EPA-200.7	USEPA (1983)	2 mg/L
Total Dissolved Solids	Calculated	HEM (1985)	NA

Soils

Marrowstone Island is mantled largely by soils of the Whidbey-Dick Association which includes soils of the Whidbey series and the Dick series (McCreary, 1975).

Approximately 70 percent of the island's soils belong to the Whidbey series, having formed from glacial till under vegetative cover of western red-cedar, Douglas-fir, and salal. These soils are distributed fairly evenly throughout the island. In a typical profile, Whidbey soils consist of approximately 3 inches of dark-gray, gravelly, sandy loam overlying approximately 18 inches of dark-brown, gravelly, sandy loam. This in turn overlies approximately 5 inches of grayish-brown, gravelly, sandy loam. Below a depth of approximately 26 inches, the soil is underlain by cemented till (McCreary, 1975).

Whidbey soils are moderately permeable above the cemented till. Under saturated conditions, they pass water at a rate of 2 to 6 inches per hour. Whidbey soils produce moderate amounts of runoff and are capable of retaining 2 to 4 inches of water within a typical soil profile.

Soils of the Dick series cover about 5 percent of the island land mass, including much of the area immediately south of Fort Flagler. They also occur along the east coast of the island near Mystery Bay. Dick soils were formed from glacial outwash under native vegetation consisting of western hemlock, rhododendron, salal, Douglas-fir, and huckleberry. These soils consist of approximately 4 inches of grayish-brown, loamy sand overlying approximately 6 inches of brownish-gray, loamy sand. Between 10 and 60 inches below ground surface, the soil is composed of olive-brown to light olive-brown, loamy sand. Below a depth of approximately 40 inches, the soil contains discontinuous, firm, dark yellowish-brown iron banding (McCreary, 1975).

Dick soils are generally quite permeable, passing water at rates of 6 to 20 inches per hour, under saturated conditions (McCreary, 1975). Dick soils produce little runoff and are capable of retaining 4 to 6 inches of water within a typical soil profile.

The island's remaining soils consist of relatively small, broadly-distributed patches of gravelly, sandy, or clay loam, with peat or muck soils occurring locally in wetland areas. In total, these soils belong to 15 separate series and will not be described in detail here.

Hydrogeology

Geologic Setting

Marrowstone Island lies on the northwest edge of the extensive glacial deposits of the Puget Lowland and on the eastern edge of the volcanic and sedimentary rocks of the Olympic Peninsula. All three lithologic types are present on Marrowstone Island. The southern end of the island and Griffith Point are underlain by Tertiary bedrock composed of the Marrowstone Formation, Quimper Sandstone, the Scow Bay Formation, and basalt dikes possibly related to the Cresent Formation (Plate 2). The bedrock formations are overlain by glacial drift of varying thicknesses (Plates 2 and 5). The northern end of the island is underlain by Pleistocene glacial deposits that reach thicknesses of over 1400 feet and extend to depths of more than 1200 feet below sea level.

Geologic History

Tertiary Period

The bedrock of Marrowstone Island was deposited as sediments on the floor of the ancient Pacific Ocean, during the middle to late Eocene Epoch (55 to 38 million years ago)(Table 5). Over many millennia these sediments were converted to rock (lithified) through heat, pressure, compaction, and cementation. As the Olympic Mountains formed during the late Miocene to early Pliocene Epochs, about 7 to 12 million years ago (Brandon and Calderwood, 1990), the lithified sediments, which now make up the bedrock of Marrowstone Island, were uplifted, faulted, and folded. This massive mountain-building activity was a direct result of the tectonic processes associated with the subduction of the Juan de Fuca Plate into the Cascadia Subduction Zone off the coast of Washington.

Quaternary Period

Pleistocene Epoch

The geologic character of Marrowstone Island and the surrounding area has been shaped by the extensive glaciations that formed the Puget Lowland. Glaciers advanced and withdrew at least five times during the Pleistocene Epoch (Table 5). Each advance and retreat left behind a complex assortment of glacial drift composed of till, advance and recessional outwash, glaciolacustrine sediments, and glaciomarine sediments. In addition, each glacial episode tended to alter and redistribute the deposits of former glaciations. This complex glacial history created a complicated geologic framework upon which the citizens of Marrowstone Island are totally dependent for ground-water supplies.

The contact between the bedrock formations and the overlying glacial drift is an erosional contact shaped by the advance and retreat of the glaciers. The Bedrock Elevation Contour map (Plate 5), based on our interpretation of lithology described by drillers on their well logs (Appendix D), shows the shape of the bedrock/glacial-drift contact.

The last major glaciation affecting the Puget Sound region was the Fraser Glaciation, the first advance of which began about 20,000 years before present with the Evans Creek Stade (Tables 5 and 6). It ended, in the vicinity of Marrowstone Island, with the retreat of the Vashon ice sheet about 13,000 years ago (Grimstad and Carson, 1981). Since the Fraser Glaciation was the last, its deposits and effects on the land surface are the most prominent.

The pre-Fraser (Table 6) deposits of Double Bluff Drift, the Whidbey Formation, the Possession Drift, and the Olympia Non-Glacial Interval are exposed on nearby Whidbey Island (Easterbrook, 1968), but there are no known exposures on Marrowstone Island. Pre-Fraser deposits probably lie at depth at the northern end of Marrowstone Island where wells deeper than about 200 feet probably encounter deposits of the Olympia Non-Glacial Interval, the Possession Drift, or the Whidbey Formation (Table 6).

TABLE 5
The Geologic Time Scale

Period	Epoch	Glacial Ages	Years Before Present
Quaternary	Holocene		10,000 to present
	Pleistocene		2 million to 10,000
		Fraser	20,000 to 10,000
		Possession	90,000 to 28,000
		Double Bluff	250,000 to 100,000
		Salmon Springs	1.2 million to 800,000
		Stuck	> 1.2 and > 2 million
		Orting	about 2 million
Tertiary	Pliocene		12 to 2 million
	Miocene		26 to 12 million
	Oligocene		37 to 26 million
	Eocene		53 to 37 million
	Paleocene		65 to 53 million

Sources: Blunt and others (1987), Easterbrook (1986), and Noble (1990)

Holocene Epoch

Since the retreat of the Vashon ice sheet, erosion and depositional processes have shaped Marrowstone Island and vicinity. Sea bluffs have been eroded by wind and wave action and redeposited, in part, as beaches, spits, tombolos, and barriers. Streams have eroded land surfaces and transported sediments to flood plains and the Puget Sound. Organic sediment has collected in ponds, lakes, and wetlands forming peat deposits. These processes continue today.

Stratigraphic Units and Their Hydraulic Characteristics

Tertiary Period

The following section discusses the stratigraphy and hydraulic characteristics of the four Tertiary bedrock units on Marrowstone Island.

Scow Bay Formation

The oldest rock unit exposed on Marrowstone Island is the Scow Bay Formation which was described and named by Allison (1959). Although subsequent authors have not used the name "Scow Bay Formation", we use it here because Allison (1959) measured and described the type section along the west coast of Marrowstone Island.

Most of the Scow Bay Formation can be examined where it crops out on wave-cut beaches (Plates 2, 3, and 4). The base of the formation is not exposed anywhere in the east Jefferson County area, however. The Scow Bay Formation probably overlies the Crescent Formation basalt or an as yet unnamed stratigraphically equivalent basalt (Melim, 1984).

The Scow Bay Formation consists of interbedded, tuffaceous shale and arkosic sandstone (Durham, 1944). Both Allison (1959) and Melim (1984) measured the exposed section of the Scow Bay Formation to be about 1800 feet thick. They described the unit as repetitive thinning and fining-upward sequences of course-to-medium grained sandstone interbedded with siltstone and shale (Figures 3A and 3B). The siltstone and shale layers range in thickness from less than one inch to about 1 foot and tend to be much thinner than the massive sandstone layers. Allison (1959) indicates that the siltstone/shale beds can be as much as 100 feet thick. The gray shale at the base of the wave-cut cliffs on Liplip Point and Kinney Point is probably one of the thick shales mentioned by Allison (Figure 3C).

Sandstones of the Scow Bay Formation are generally light greenish-brown, very-fine to medium grained and poorly sorted with sub-rounded to sub-angular grains. The non-calcareous sandstone is moderately hard and resistant to weathering. Outcrops tend to weather to light grayish-brown, smoothly rounded surfaces. The sandstones are highly fractured, but most of the fractures have been filled with calcite.

A striking characteristic of the Scow Bay Formation is the presence of abundant, round concretions in the sandstones. The calcareous cement in the concretions makes them considerably harder and more resistant to weathering than the surrounding sandstone. This characteristic makes them obvious in outcrops, such as at Nodule Point, where they stick out of the sandstone as large, prominent knobs or, having fallen from the sandstone, lie on the beach like barnacle-covered bowling balls (Figure 3D). The concretions consist of the same mineral constituents as the surrounding sandstone except that the sand grains are less altered by diagenesis. It is not clearly understood why the concretions formed. Melim (1984) indicates that they formed in the very early stages of sediment deposition before compaction of the deposits. Raiswell (1971) suggested that concretionary growth such as this may occur to relieve supersaturation of dissolved calcareous minerals in the pore waters of the early sediments. The formation of the concretions, in the early stages of deposition, protected the enclosed sediments from subsequent diagenetic changes, including compaction. As such, the concretions provide an excellent means by which to view the original composition of the Scow Bay Formation sandstones (Melim, 1984).

Since fractures within the Scow Bay Formation tend to be filled with calcite, most wells completed in this unit produce only small amounts of water.

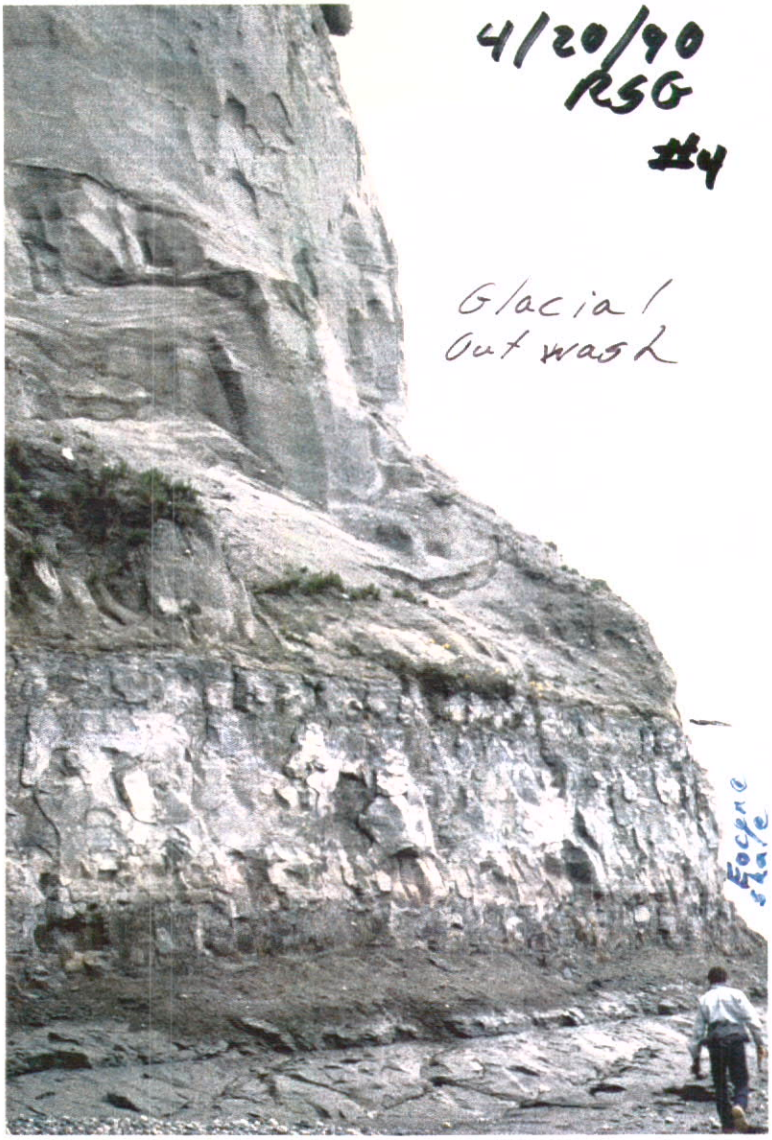
Figure 3A

Scow Bay Formation sandstone, SE coast Marrowstone Island

Figure 3B

Scow Bay Formation sandstone overlain by Vashon till, W. coast Marrowstone Island

4/20/90
RSG
#4



Glacial
Outwash

Eocene
shale

Figure 3C

Scow Bay Formation shale/claystone, at base of cliff, overlain by Vashon advance outwash deposits, Lip Lip Point, Marrowstone Island

Figure 3D

Concretionary nodules weathered from The Scow Bay Formation on Nodule Point, Marrowstone Island

Volcanics

Sometime after deposition of the Scow Bay Formation and probably before deposition of the Quimper Sandstone, tectonism tilted the older sediments and injected basalt dikes into the fractured sediments of the Scow Bay Formation. One such dike is a prominent feature on the southern side of Nodule Point on Marrowstone Island's east coast (Plate 2 and Figure 3E). This dike is oriented at N 56 E, is essentially vertical, and appears as a 22-foot wide, trench-like feature between walls of hard sandstone. The dike appears as a "trench" because thermal metamorphism, caused by the molten lava, made the sandstone on either side more resistant to weathering than the dike itself.

Volcanic units on Marrowstone Island contain little, if any, water and would act as an aquiclude where present.

Quimper Sandstone

The upper-Eocene Quimper Sandstone overlies the Scow Bay Formation in an angular unconformity. Although there is some variation within the unit, it generally consists of light greenish brown to light gray, fairly homogeneous, massive, very fine to medium grained, feldspathic sandstone. Outcrops of the Quimper Sandstone can be found on the west coast of Griffith's Point (Plates 2, 3, and 4). They weather to smoothly rounded, golden-tan to olive-green surfaces. According to Rauch (1985), the top of the section contains occasional leaf imprints, tree limbs and trunks, and abundant finely disseminated carbonaceous matter. The unit resembles the Scow Bay Formation but tends to be more massive, finer grained, less fractured, and contains fewer shale interbeds. Calcareous, concretionary beds up to about 1 foot thick occur occasionally while smaller irregular concretions are fairly common.

Like the Scow Bay Formation, fractures within the Quimper sandstone tend to be filled with calcite. Most wells completed in this unit produce only small amounts of water.

#24
6/14/90
RSG

Figure 3E

Basalt dike intruded into Scow Bay Fm., S. of Nodule Point on E. coast Marrowstone Island

#5/5/17/90

Figure 3F

Gradational contact between Quimper Sandstone and overlying Marrowstone Shale, W. coast Griffith's Point, Marrowstone Island

Marrowstone Formation

The Marrowstone Formation conformably overlies the Quimper Sandstone. It can be seen in outcrop along the north and western shores of Griffith's Point (Plates 2, 3, and 4). Figure 3F shows the gradational contact between the Quimper Sandstone (bottom one third) and the Marrowstone Formation (upper two thirds). The center one third of the photo shows the somewhat gradational contact zone and the upper one third shows more "typical" Marrowstone Formation. We mapped the Quimper SS/ Marrowstone Fm contact at the contact between the clean, massive, well cemented Quimper Sandstone at the base of the photo and the more silty, muddier, less massive unit in the center of the photo.

Durham (1944) named this unit the "Marrowstone Shale" and described it as moderately well-bedded fossiliferous, sandy shales. Allison (1959) also used the name Marrowstone Shale but described it as light-gray to buff, fine sandstone and fissile siltstone. During our field investigations, we observed the unit to be greenish-brown to orange-brown, interbedded, mudstone, siltstone and very-fine to fine grained sandstone. The mudstone and siltstone are somewhat fissile in places, but no shale was found. The unit is highly fractured, thinly layered to blocky, and contains abundant calcareous, limonitic concretions. Figures 3F, 3G and 3H illustrate the diversity of Marrowstone Formation deposits.

Given the predominance of siltstone and sandstone in this unit, it is difficult to justify the name "Marrowstone Shale" assigned by Durham (1944). We are therefore, using the name Marrowstone Formation, in this report, to avoid having the formation name convey an erroneous lithology.

At least three clastic sandstone dikes cut across bedding planes, at various angles, in the exposures of the Marrowstone Formation on the northwest coast of Griffith Point (Fig. 3H). Other authors make little mention of these dikes or their origins. The composition of the clastic dikes resembles that of the underlying Quimper Sandstone. This suggests that the Quimper Sandstone deposits may be the source for the clastic dikes. Compaction, diagenetic processes, and seismic activity associated with the nearby subduction zone may have provided the pressure necessary to squeeze Quimper Sandstone deposits into fractures in the overlying deposits.

The Marrowstone Formation is the most fractured and least cemented of Marrowstone Island's bedrock units. As such, wells completed in this unit will likely produce more water than those completed in either the Quimper Sandstone or Scow Bay Formation.

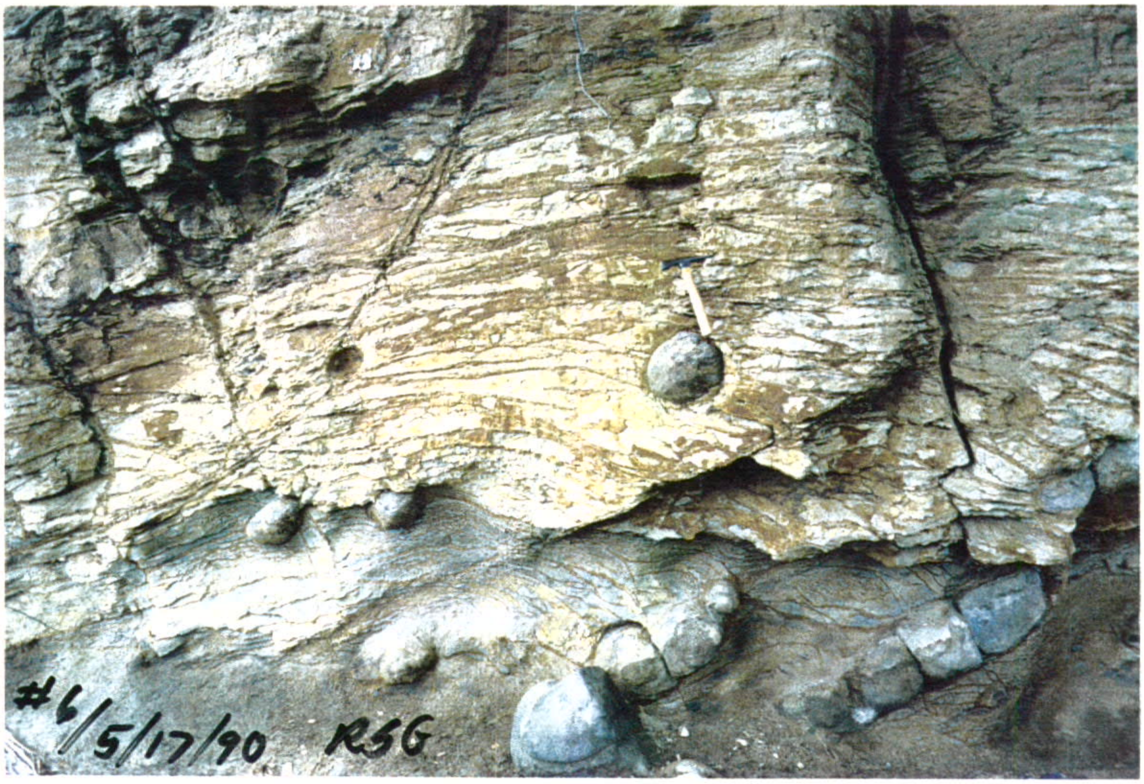


Figure 3G

Marrowstone Shale,
Griffith's Point,
Marrowstone Island - note
thin, contorted bedding,
concretions, and fractures

Figure 3H

Vertical clastic dike in
Marrowstone Shale,
Griffith's Point,
Marrowstone Island

Quaternary Period

Pleistocene Epoch

The Pleistocene Epoch was dominated by the glacial "ice age" which profoundly affected the geology and ground-water-bearing characteristics of Marrowstone Island. The glacial deposits exposed at the surface of Marrowstone Island are part of what is known as Vashon Drift (Table 6). Vashon Drift was deposited during the Vashon Stade of the Fraser Glaciation and includes all glacial sediments deposited between the advance and retreat of the last Pleistocene ice sheet which occupied the Puget Lowland in the vicinity of Marrowstone Island (Easterbrook, 1968; Blunt and Others, 1987).

On Marrowstone Island, Vashon Drift can be subdivided into three principle facies. They are from youngest to oldest, recessional drift, lodgement till, and advance outwash (Plate 2). Since the vegetative cover on the island made it impossible to map surficial geology by direct inspection, we used the Jefferson County Soil Survey (McCreary, 1975) as an indicator of the underlying geologic units from which the soils were formed. We lumped soils that are derived from till together and mapped the underlying deposits as till (Qvt). Similarly, we lumped soil units that are derived from glacial sands and gravels together and mapped the underlying deposits as advance outwash (Qva) or recessional outwash (Qvr).

The thickness of the glacial deposits on Marrowstone Island vary greatly (Plate 5). As shown on Plates 3 and 4, glacial deposits south and east of Nordland overlie relatively near-surface bedrock. Many wells in this area fully penetrate the glacial deposits which range in thickness from a few feet to about 200 feet. From Nordland, the glacial deposits thicken toward the north from only a few feet at Nordland and on Griffith Point, to greater than 1462 feet in a well at Fort Flagler State Park (Plates 3 and 4). We found no wells north of Mystery Bay that fully penetrate the glacial deposits. Grimstad and Carson (1981) suggest that the Vashon Drift is less than 200 feet thick at Fort Flagler which means there is a considerable thickness of pre-Vashon deposits in that area.

Vashon Recessional Drift. Relatively thin lenses, probably ranging from zero to a few feet thick, of recessional drift overly the till layer in isolated locations (Plate 2). Recessional drift consists of ice-contact stratified drift, some ablation till, and recessional outwash deposited during the retreat of the Vashon-age ice sheet. The unit is generally highly permeable and is composed of unconsolidated gravel and sand. Recessional drift can be a very productive aquifer where it occurs below the regional water table. Unfortunately, on Marrowstone Island, the unit consists only of isolated lenses and lies well above the water table. Accordingly, it is not an important aquifer.

TABLE 6
Glacial Stratigraphy of the Northern Puget Lowland

EPOCH	GLACIAL AGES	CLIMATE UNITS		Approx. Age (yrs)
Late Pleistocene	Fraser Drift	Sumas Drift		11,000 - 10,000
		Everson Glaciomarine Drift		13,000 - 11,000
		Vashon Drift	Vashon Till	20,000 - 13,000
			Esperance Sand	
			Lawton Clay	
	Olympia Non-Glacial Interval			28,000 - 20,000
	Possession Drift			90,000 - 28,000
	Whidbey Formation (Interglacial)			100,000 - 90,000
	Double Bluff Drift			250,000 - 100,000

Source: Blunt and Others, 1987

Vashon Till. Vashon Till, commonly known as "hardpan", covers most of the island and is the uppermost facies of the Vashon Drift in most areas (Plates 2, 3, and 4). The till was probably derived from debris carried in the basal part of the glacier and deposited at the interface of the land surface and the overriding ice sheet (Pessl and others, 1989).

Vashon till is generally composed of a very poorly sorted, compacted, moderate-to-well cemented mixture of clay, silt, and very-fine to course-grained sand, with varying amounts of intermixed gravel, cobbles, and boulders (Figures 3B, 3J, and 3K). Vashon till outcrops as the uppermost layer in many of the wave-cut cliffs on Marrowstone Island. The till is a relatively resistant layer, and acts as a cap rock on these cliffs, providing protection from weathering to the underlying, less resistant sands and gravels. This makes it possible for the distinctive cliffs, on the north and east side of the island to stand in the face of the elements until they are undercut by wind, precipitation, and wave action. The cliffs south of East Beach Park (Figs. 3J and 3K) are a classic example of this process. It is not uncommon for winter storms to undercut these cliffs and cause several feet of land surface to fall to the base of the cliff (Simmonds, 1990). Numerous large blocks of till lying on the beach in this area provide direct evidence of continuing weathering processes.

Vashon till is a poor aquifer because of its fine-grained, compact nature. Till covers much of the surface of the island and tends to increase runoff to the Puget Sound and impede recharge to the island aquifers.

Vashon Advance Outwash. Vashon advance outwash underlies the till and is well exposed in the cliffs along the north and east coasts of the island. This unit is predominantly glaciofluvial in origin, — it was deposited, by melt-water streams in front of the margins of the ice sheet as it advanced southward (Pessl and others, 1989). The outwash is composed mostly of moderately well-sorted, horizontally- and cross-stratified sand, gravel, and minor silt (Figs. 3J and 3K). Extensive cross-bedding is clearly evident in some cliff exposures (Fig 3J). These advance outwash deposits are probably part of the Esperance Sand (Table 6), which, at the northern end of the island, extends from the base of the till down to sea level or below (Plates 3 and 4). The Esperance Sand is probably underlain by the Vashon Lawton Clay and pre-Fraser deposits of the Olympia Non-Glacial Interval, Possession Drift, Whidbey Formation, and the Double Bluff Drift — none of which are exposed anywhere on the island (Table 6).

The advance outwash aquifer consists of hundreds of interconnected layers and lenses of unconsolidated, water-bearing sands and gravels and aquitards of silt and clay (Plates 3 and 4). Of the various aquifers on the island, the advance outwash is the best producer of ground water. The complexly interwoven mix of gravel, sand, silt, and clay will generally yield water to most wells completed in it. But it is difficult to predict the depths of wells and the quantity and quality of water that may be produced at specific locations. Well owners on Marrowstone Island have reported highly varied results from wells drilled in close proximity to one another.

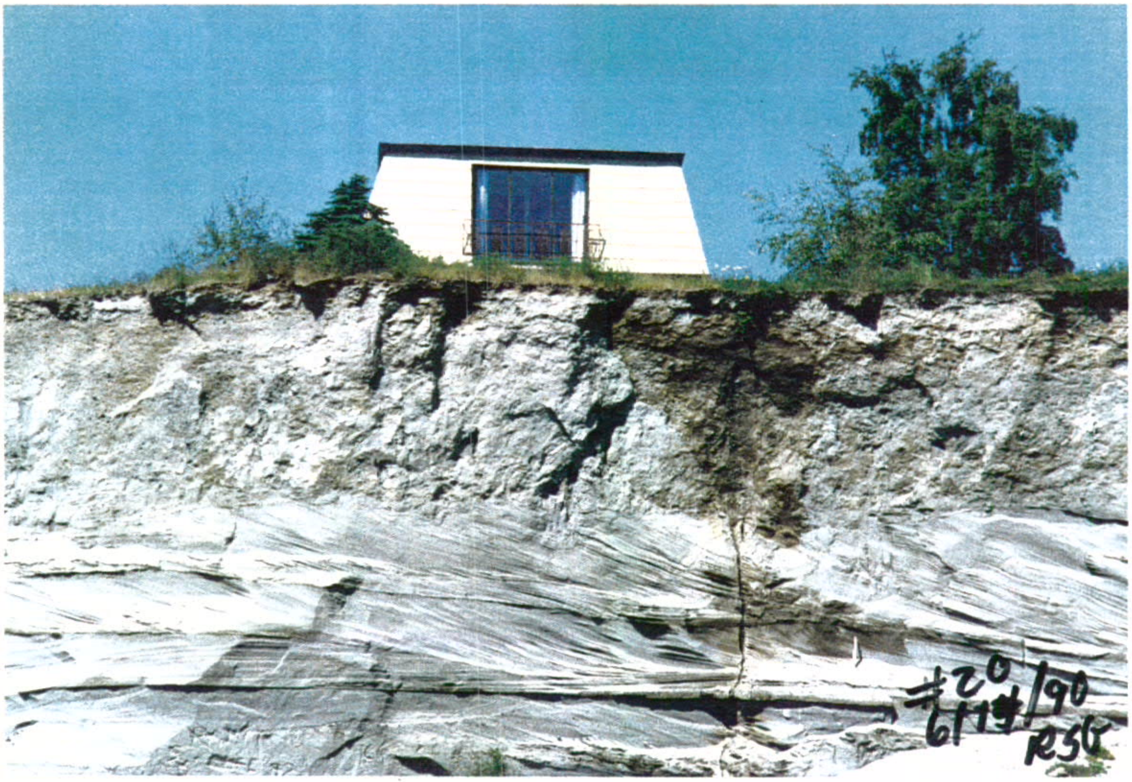


Figure 3J

Cross-bedded Vashon advance outwash overlain by massive Vashon till at the top of the cliff, S. of East Beach Park, Marrowstone Island. Note the wetting of the units - probably from the septic system drain field or roof runoff from the house above. Wetting of this sort may cause instability and premature collapse of the cliff face and should be avoided.

Figure 3K

Vashon advance outwash deposits overlain by Vashon till in cliff S. of East Beach Park, Marrowstone Island.

Ground Water

Well Production on Marrowstone Island

Ground water on Marrowstone Island is contained within two distinct aquifer types: 1) the glacially deposited Vashon Advance Outwash and 2) fractured bedrock. To aid our comparison of well yields, we calculated specific capacity for selected Marrowstone Island wells. Specific capacity gives a clearer picture about well yield than mere production rates in gallons per minute (Table 7). Specific capacity is derived by dividing the pumping rate, in gpm, by the drawdown, in feet, and is reported herein as gallons per minute per foot of drawdown (gpm/ft). In general, the larger the specific capacity the more likely the well will be able to handle pumping without excessive drawdown.

Specific capacities for 35 wells completed in Vashon advance outwash ranged from less than 0.01 gpm/ft to 30.00 gpm/ft with an average of 7.2 gpm/ft. Specific capacities for 12 bedrock wells ranged from less than 0.01 gpm/ft to 1.50 gpm/ft with an average of 0.19 gpm/ft.

Marrowstone Island can be split into four general water-production areas based on the areal distribution of aquifers (Plates 3 and 4) and well specific capacities (Plate 6).

North End: This area includes the narrow neck of land between Mystery Bay and Admiralty Inlet and all the area north of East Beach Road. Water production in this area is varied with specific capacities ranging from less than one to greater than 10 gpm/ft of drawdown (Plate 6 and Table 7). This wide variety is a reflection of the variability in glacial drift deposits (Cross Sections E-E′ and F-F′, Plates 2, 3, and 4). Most wells in this area will probably produce enough water for normal single domestic use without the need for storage tanks, cut-off switches, and other production-enhancement devices. However, most wells in the area produce from aquifers at or below sea level, and sea-water-intrusion tends to be a prevalent problem (Plate 7). Some home owners in the area have installed rain-water-collection systems to provide fresh water in sea-water-intruded areas.

Griffith's Point and Central: This area includes Griffith's Point and southeast toward Nodule Point to about Meade Road. Most water in this area is produced from the three bedrock formations, with very little water available from the glacial deposits (Cross Sections C-C′, D-D′, F-F′, and F′-F", Plates 2, 3, and 4). Wells generally have specific capacities of less than 1 gpm/ft of drawdown (Plate 6). Well production in this area generally will be marginal to inadequate for normal single-domestic supplies. Water production-enhancement devices such as storage tanks, cut-off switches, and rain water collection systems may be needed to provide reliable single-domestic supplies.

South Central: This area includes the topographic high that lies between Meade Road, on the north end, and Robbins Road at the south. Many wells in this area produce water from a sand and gravel aquifer that lies at about sea level (Cross Sections A-A′, B-B′, and F′-F", Plates 2, 3, and 4). This aquifer provides the best quality ground water on the island - probably because it appears to have poor hydraulic connection to the sea. Wells in this area generally have specific capacities ranging from greater than 5 gpm/ft to as high as 30 gpm/ft of drawdown (Plate 6 and Table 7) and should yield water adequate for normal single domestic use without water production-enhancement devices.

Southern and Southeastern Coasts: This area, includes most of the area south of Robbins Road and extends northeast along the coast to about Renier Road. It tends to have very low ground-water-production capabilities. Most wells in this area produce water from the contact between the Scow Bay Formation and the overlying glacial drift, consisting mostly of Vashon Till (Cross Sections A-A′ and F′-F", Plates 2, 3, and 4).

Specific capacities generally are less than 1 gpm/ft of drawdown (Plate 6 and Table 7) and water production-enhancement devices may be needed to provide reliable single domestic supplies.

Aquifers on Marrowstone Island are limited in size by the edges of the island. So, even a productive aquifer, such as the gravel aquifer in the south-central area of the island, that is producing adequate water supplies to a group of wells, cannot be considered an unlimited, long-term supply. Ground-water storage is limited by the volume of the aquifer and is replenished by recharge only at certain times of the year. Also, much of the ground water discharges to the sea.

Driller's logs indicate lenses of interbedded glacial silts and clays scattered intermittently throughout the outwash deposits. Locally, these lenses are aquitards which impede ground-water flow and may cause underlying production zones to behave as semi-confined aquifers.

Eocene shale, claystone, and siltstone of the Scow Bay Formation underlie the glacial deposits at the southern end of the island. Very little water penetrates these rocks, except minor amounts in occasional fractures. Water that penetrates to the top of these facies flows down slope, along the erosional unconformity between the Scow Bay Formation aquitard and the overlying advance outwash, and discharges to the Puget Sound at the coastal cliffs. Some wells at the southern end of the island produce a meager amount of water from this contact.

TABLE 7
Specific Capacities and Source Aquifers for Marrowstone Island Wells

WELL NUMBER	MAP ID	SPECIFIC CAPACITY (gpm/Ft)	SOURCE AQUIFER
AAB005	69	15.00	Glacial
AAB006	67	30.00	Glacial
AAB007	68	.40	Glacial
AAB009	58	.03	Bedrock
AAB010	64	15.00	Glacial
AAB011	65	1.20	Glacial
AAB012	61	9.30	Glacial
AAB019	60	10.00	Glacial
AAB020	54	.01	Bedrock/Glacial
AAB022	48	.03	Bedrock
AAB023	47	< .01	Bedrock
AAB024	40	10.00	Glacial
AAB025	37	5.00	Glacial
AAB026	29	1.60	Glacial
AAB028	27	5.00	Glacial
AAB030	21	8.00	Glacial
AAB031	18	7.50	Glacial
AAB034	13	5.00	Glacial
AAB036	16	.40	Glacial
AAB037	11	1.20	Glacial
AAB038	25	4.80	Glacial
AAB039	23	20.00	Glacial
AAB041	19	20.00	Glacial
AAB042	10	4.00	Glacial
AAB043	08	10.00	Glacial
AAB044	09	6.00	Glacial
AAB045	07	10.00	Glacial
AAB046	06	15.00	Glacial
AAB047	05	8.00	Glacial
AAB049	03	6.00	Glacial
AAB050	02	1.70	Glacial
AAB051	01	2.00	Glacial
AAB052	46	.02	Bedrock
AAB053	45	.50	Bedrock
AAB056	41	.03	Bedrock
AAB068	20	6.00	Glacial
AAB070	79	.90	Glacial
AAB073	73	2.00	Glacial
AAB078	59	5.00	Glacial
AAB079	66	< .01	Bedrock
AAB080	56	< .01	Bedrock
AAB084	26	< .01	Bedrock
AAB085	12	7.02	Glacial
GC-008	57	< .01	Glacial
GC-018	49	.01	Bedrock
GC-063	33	< .01	Bedrock
GC-064		< .01	Bedrock
GC-072	72	.10	Bedrock

Water-Level Changes

Water levels for 56 wells were measured quarterly from February, 1990 through June, 1991 (five measurements). Two subsequent water-level measurements were made on all of the wells in June and December of 1992 for a total of seven synchronous water level measurements. The water-level hydrographs in Figures 4A and 4B show water-level changes recorded in ten representative wells. These ten wells are the same wells sampled for major cations and anions (see water quality section and Appendix C, p. C-9). Seven of these wells are completed in glacial sediments and 3 are completed in bedrock.

Due to the lack of well-head elevation control, the water levels reported here cannot be used to determine exact water levels relative to sea level. Our well head elevations are accurate to within ±5 feet. This level of accuracy allows for general water-level comparisons to sea level.

Our water level measurements from the surface datum are accurate to within 0.1 ft. so they are a good indicator of relative changes. A number of factors can affect the water level in a well. Most of the wells used in this study are active domestic wells. It was impossible to know in all cases if wells had been recently pumped when we arrived to do water-level measurements. Therefore, some of the measurements recorded do not represent static water-levels but rather some level below static and in some phase of recovery from recent pumping. Many wells are also affected, to some degree, by daily tide cycles. Without detailed comparative data such as illustrated in Figure 5 (p. 36), it is not possible to know the tidal effects on water levels in specific wells.

We have made some general observations based on water-level hydrographs for the island:

1. Most water levels appear to be within 10 feet of sea level - either above or below.
2. Ground-water levels in the glacial wells we measured generally rose about one foot from the beginning to the end of the 32 month measurement period. This apparent rise probably resulted from a combination of natural controls such as: 1) seasonal fluctuations, 2) tidal influences, and 3) the wetness or dryness of the measurement period relative to long-term climatic conditions.

   Some owners of glacial wells, have reported that water levels occasionally drop below their pump intakes, or that they have noticed gradual long term water level declines in their wells. Our measurements confirm water level declines in some areas, but we can't be sure of the causes. More frequent (at least monthly), long-term water level measurements are needed to define trends or specific areas of water-level changes in the glacial drift aquifers.
3. Ground-water levels in the bedrock wells we monitored generally declined 2 to 10 feet from the beginning to the end of the measurement period. This suggests that, at least locally, annual ground-water withdrawals may be exceeding recharge to those bedrock aquifers. These measured declines are probably caused by a combination of factors including seasonal fluctuations in recharge, tidal influences, ground-water pumping, and normal climatic changes. More frequent (at least monthly), long-term water-level measurements are needed to define water-level trends or specific areas of water-level changes in the bedrock aquifers.
4. Two principal seasonal water-level highs are shown by the hydrographs.
   a. In some wells the seasonal high water level occurs in December. This seems to indicate that it takes about nine months, after the January to March recharge period, for recharge to reach the aquifers in which these wells are completed.

b. In other wells the seasonal high water level occurs in April or May. This may indicate that the aquifers are recharged within one to two months after the January to March recharge period.

We thought that the timing of recharge might be correlative with surficial geology - that wells with hydrographs exhibiting long recharge delays might be located in areas where till covers the surface. And, likewise, that wells with hydrographs exhibiting short recharge delays might be located where advance outwash is at the surface. However, our attempts to correlate the timing of recharge with the surficial geology were unsuccessful. This is probably because the timing of recharge is controlled not only by the surficial geology but also by the underlying geology through which recharge water must pass to reach the aquifers.

5. Generally, the magnitude of water-level drawdown due to pumping is greater in the bedrock wells than in the glacial wells. This is due to the relatively small storage capacity of the bedrock fractures and their generally lower hydraulic conductivity as compared to the glacial drift aquifers.

Figure 4A.

Water Level Hydrographs for Selected Glacial Wells

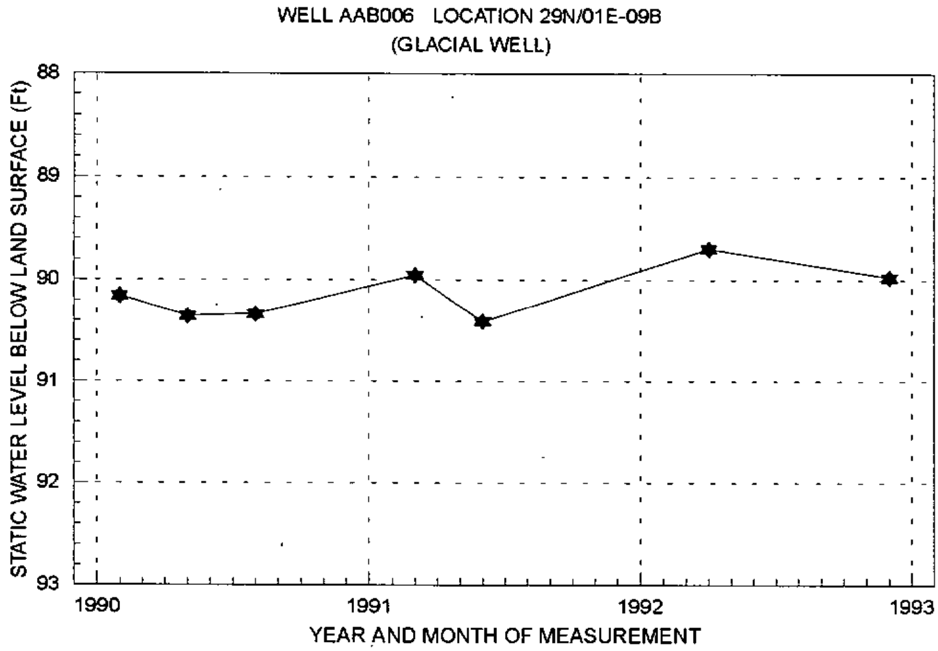
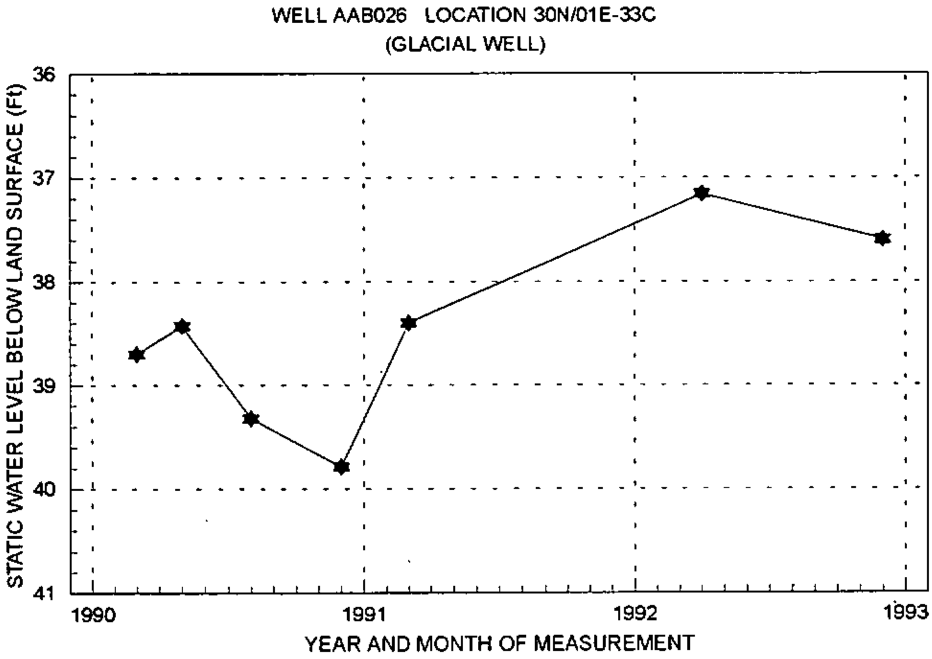


Figure 4A. (continued)

Water Level Hydrographs for Selected Glacial Wells



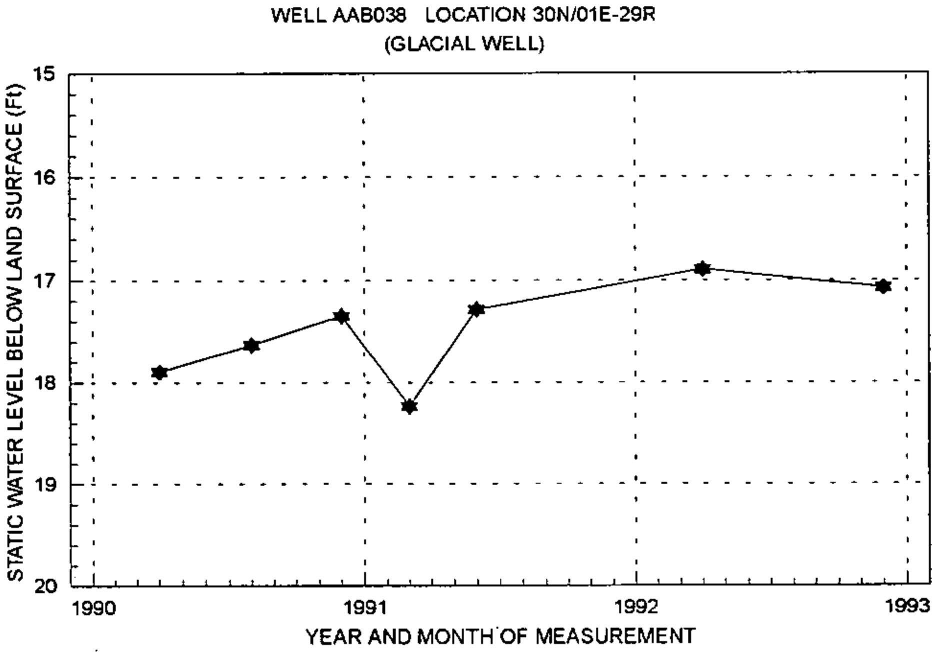
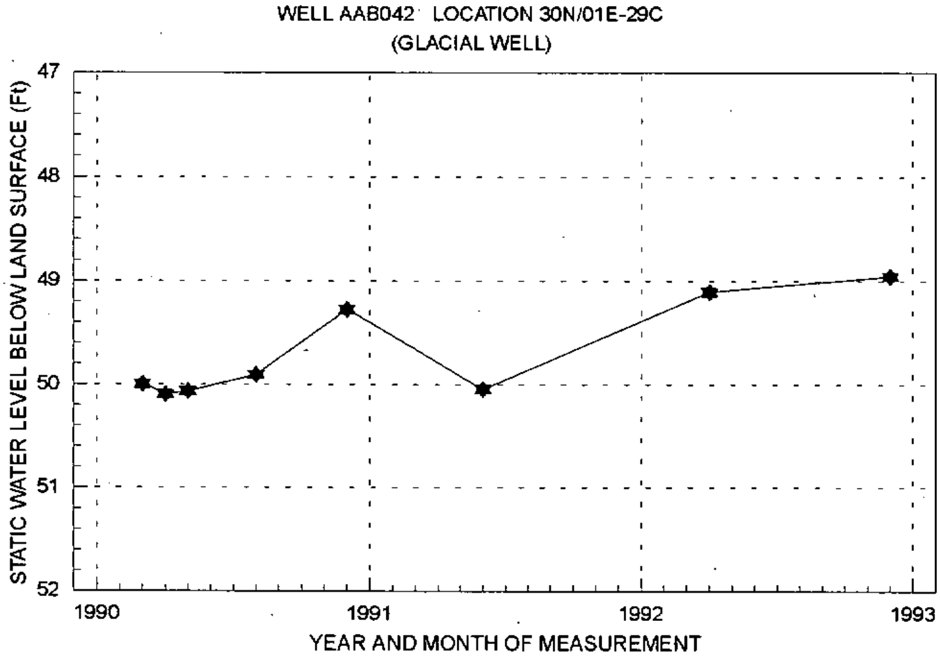


Figure 4A. (continued)

Water Level Hydrographs for Selected Glacial Wells



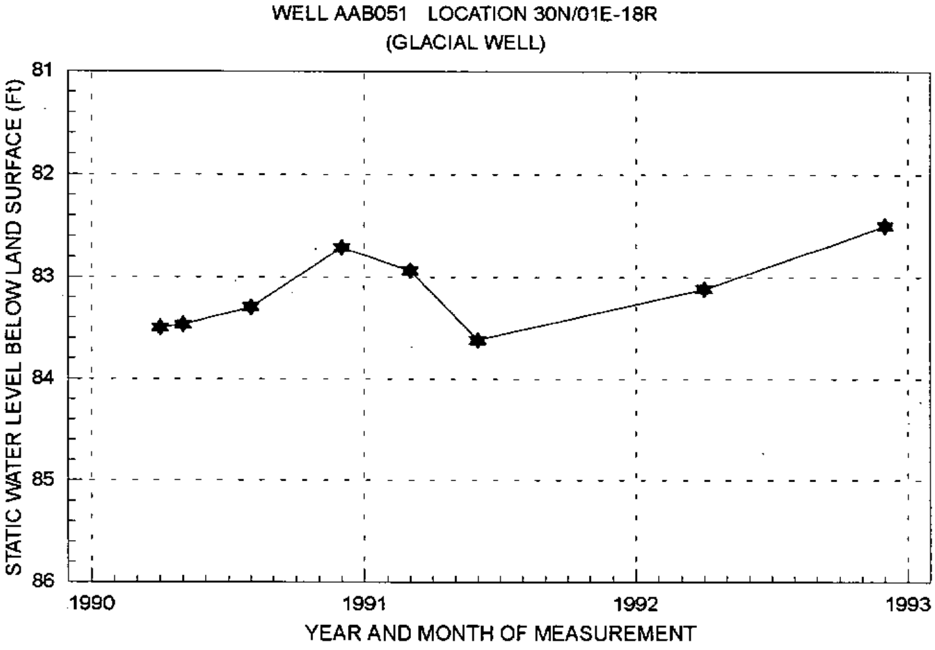
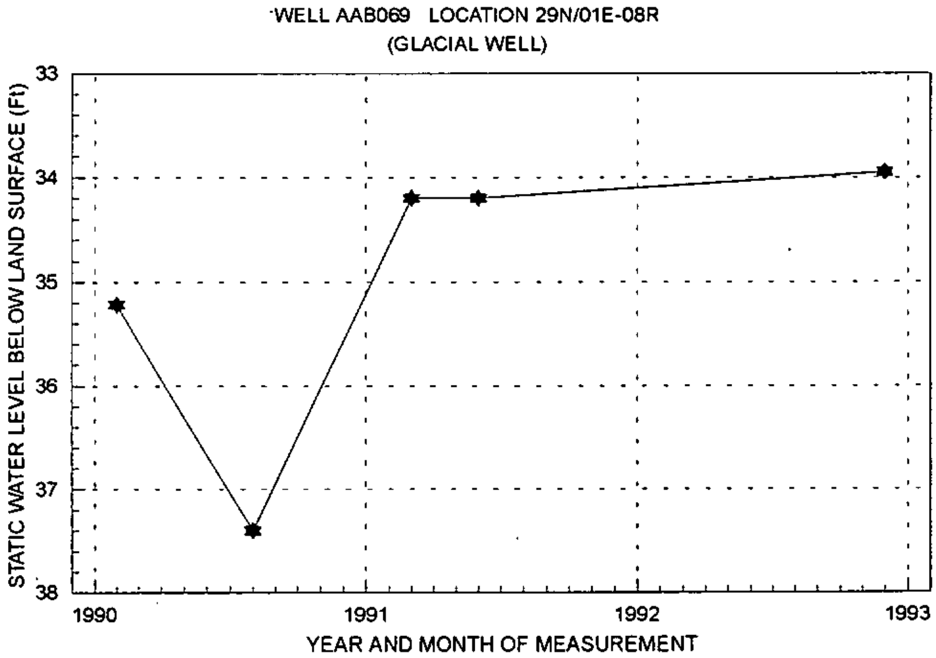


Figure 4A. (continued)

Water Level Hydrographs for Selected Glacial Wells



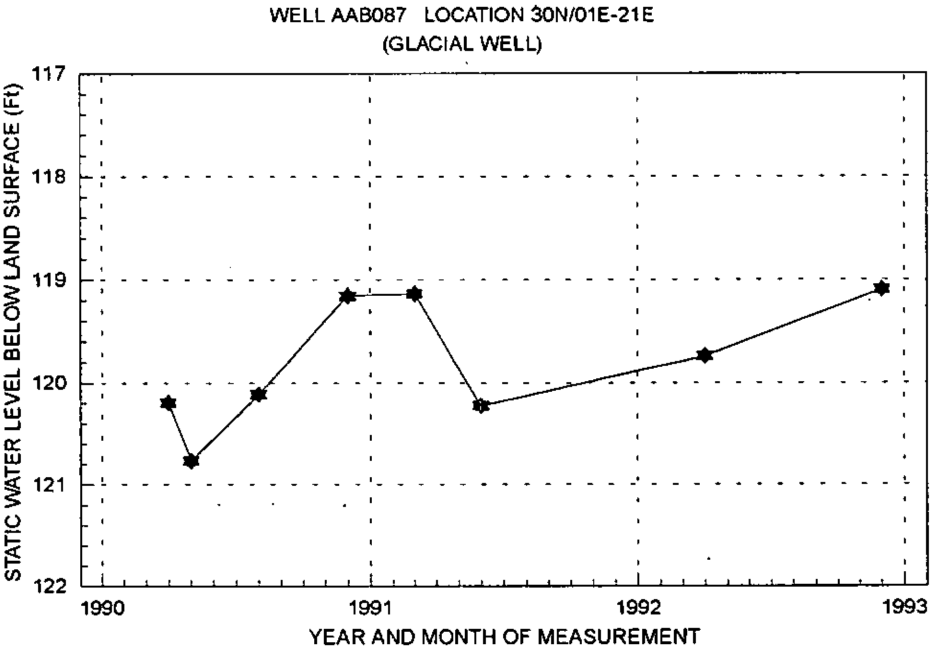
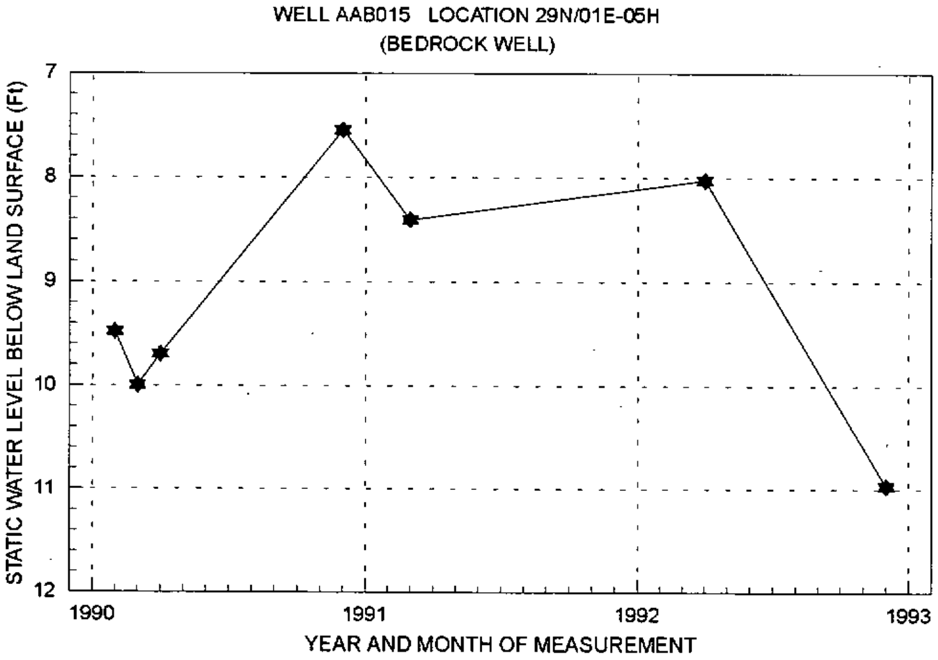
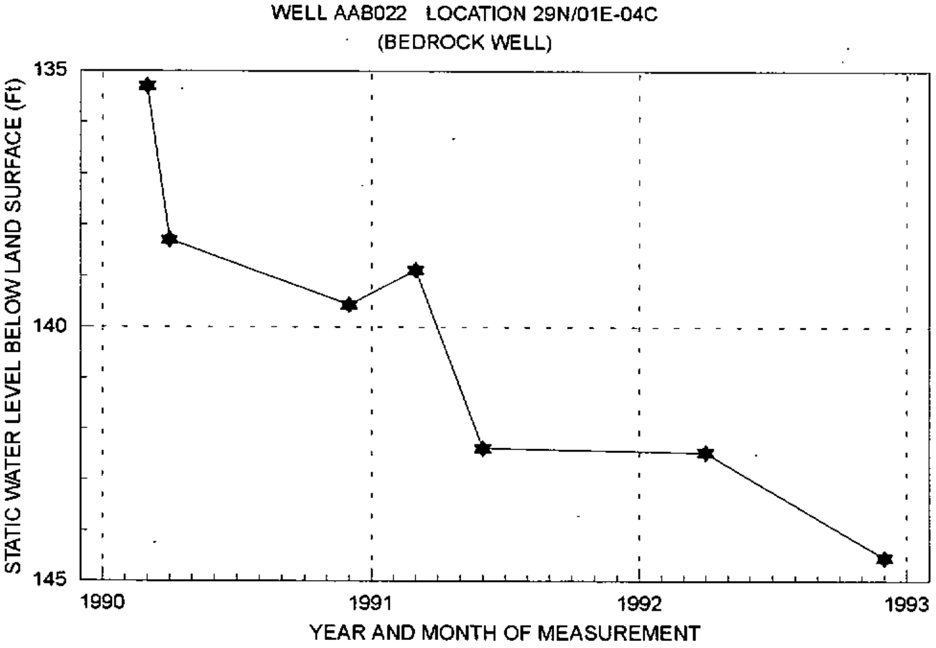


Figure 4B.

Water Level Hydrographs for Selected Bedrock Wells

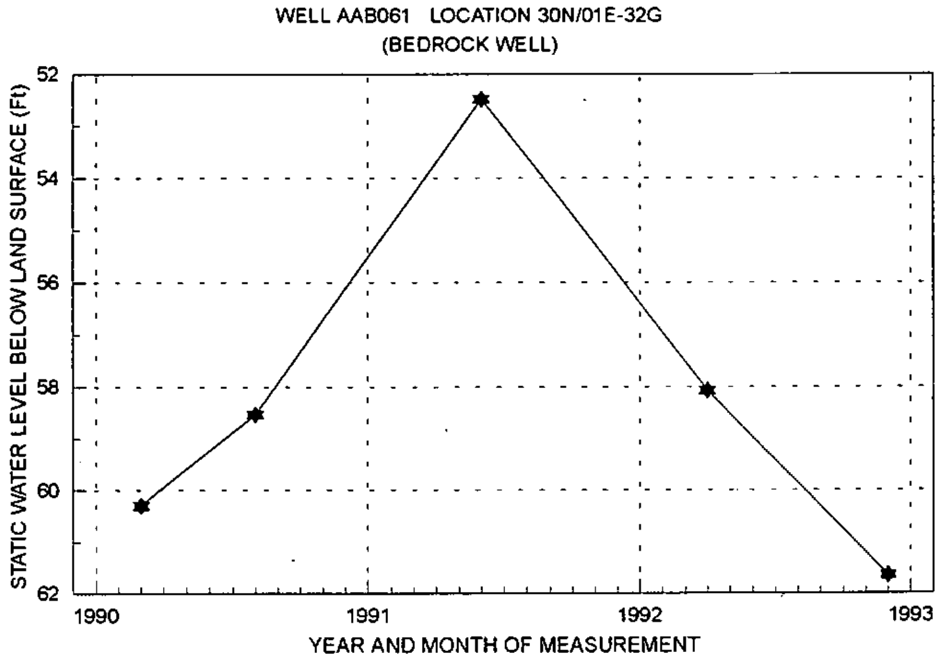




(Note: Vertical scale is twice that of all other hydrographs.)

Figure 4B. (continued)

Water Level Hydrographs for Selected Bedrock Wells



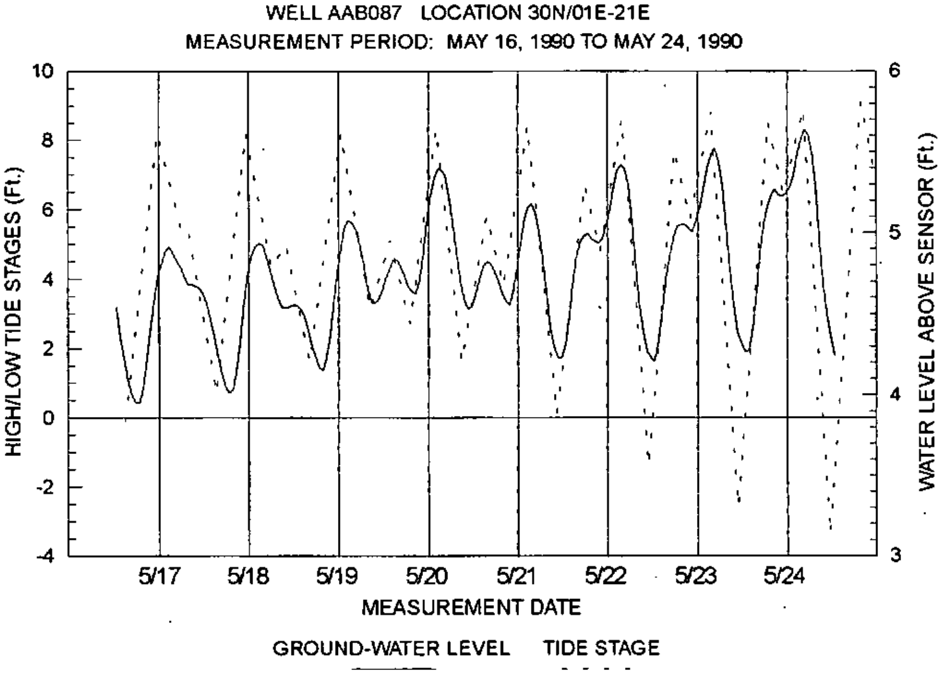
Tidal Influences on Water Levels in Marrowstone Island Wells

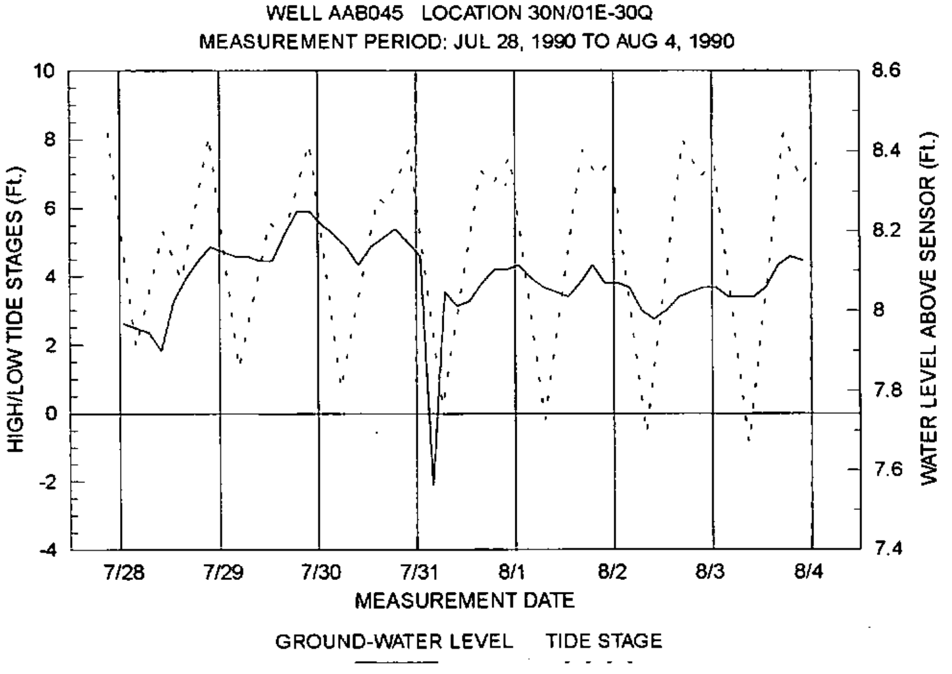
To evaluate tidal influence on ground-water levels, wells AAB038, AAB045, AAB083, and AAB087 were measured with a transducer and data logger at 15 to 30 minute intervals for a period of one to two weeks. These measurements were compared to Port Townsend tide stages for the same time period (Figure 5). Ground-water levels in well AAB087 (Figure 5), which is about 600 feet from the coast, showed obvious correlation to tidal cycles. Ground-water levels in well AAB045 (Figure 5), which is about 2,200 feet from the eastern shoreline, also showed definite, but less obvious, tidal correlations. Any possible tidal influence on well AAB038 was masked by frequent drawdown and recovery caused by pumping. Water levels in well AAB083, were not affected by changes in tide stages. It is not clear whether the lack of tidal response in well AAB083 is due to its poor production or a lack of connection with the sea. Movement of water to and from the well may be so slow that the relatively short tidal cycles cannot cause measurable changes in well water levels.

Our observations indicate that daily fluctuations in tide stages cause significant water-level fluctuations in some Marrowstone Island wells. Generally, we can probably assume that wells closer to the shoreline are influenced by tides to a greater extent than inland wells. There are also some indications that water levels in glacial wells tend to be more influenced by tides than water levels in bedrock wells. This may not hold true for all wells, however, owing to local geologic controls at individual well sites.

Figure 5.

Tidal Influence on the Water Levels of Two Marrowstone Island Wells





Ground-Water Recharge

Local folklore has held, for years, that there is a major source of deep, fresh ground water that flows to Marrowstone Island, and other northern Puget Sound islands, from the high peaks of the Olympic Mountains via an under-ground river. Unfortunately, this is not true. All ground water on Marrowstone Island is derived from precipitation that falls on the island.

Water from precipitation follows many paths: a small portion flows to the Puget Sound as surface runoff; a large portion is returned to the atmosphere by evapotranspiration; a growing portion is collected by people for use; some soaks into the upper soils and moves down gradient toward the sea as underflow; and a small amount makes its way through the soil layers, past the root zone, through the unsaturated zone and becomes recharge to the island's aquifers. Ground-water on Marrowstone Island generally flows from the island's center ridge toward the Puget Sound.

As part of this study, we calculated a simple water budget for Marrowstone Island using a computer program called WATBUG (Willmott, 1977). A water budget is an accounting of the inflow to, outflow from, and storage changes in a hydrologic system. Water budgets are based on the principle that, for hydrologic systems in equilibrium, the amount of water leaving the system via discharges to springs, seeps, and other discharge pathways must equal aquifer recharge from precipitation and other sources.

This relationship can be expressed by the simple relation:

Aquifer Recharge = Aquifer Discharge.

Recharge is estimated based on the equation:

Aquifer Recharge = Precipitation - Surface Runoff - Actual Evapotranspiration.

The WATBUG program assumes surface runoff to be zero. This is not strictly true, but there are no perennial streams on Marrowstone Island and little evidence of other surface runoff. We therefore assume that, compared to the total water in Marrowstone Island's hydrologic system, surface runoff is a negligible component of the water budget.

The WATBUG program requires information about precipitation, air temperature, and soil moisture holding capacity. We used climate data from Port Townsend for both precipitation (Table 1) and air temperature. This data was obtained from National Weather Service records for most of the period from June, 1948 through February, 1991. Air temperature records for Port Townsend were used since long term air temperature data for the island is not available. WATBUG calculates potential and actual evapotranspiration, based on latitude and air temperature, using an empirical formula developed by Thornthwaite and Mather (1957). We used precipitation data for the island that was collected at six precipitation stations (Degerness, 1993; Illman, 1993; Steenrod, 1990; Stout, 1990; and VanEtten, 1993) shown on Plate 1 and Table 2.

We estimated soil-moisture-holding capacity based on information from the Jefferson County Soil Survey (McCreary, 1975). The descriptions of each soil type included an estimate of the amount of water the soil can hold for use by plants. We assumed this number to be equivalent to the soil-moisture-holding capacity. We calculated an average soil-moisture-holding capacity for all soils mapped as advance outwash (Qva) and for all soils mapped as till (Qvt) (Plate 2). Soils derived from advance outwash have an average soil-moisture-holding capacity of six inches based on an average soil thickness of 60 inches, while soils derived from till have an average soil moisture holding capacity of five inches based on an average soil thickness of 35 inches. This means that soils derived from till hold more water per foot of soil (1.7 inches per foot) than soils derived from advance outwash (1.2 inches per foot). Based on the above information, we assumed the island has an average soil-moisture-holding capacity of approximately 5.5 inches. The WATBUG program assumes that recharge to ground-water aquifers cannot occur until the soil-moisture-holding capacity is exceeded. Then surplus water (recharge) is able to flow downward through the unsaturated zone to the water table.

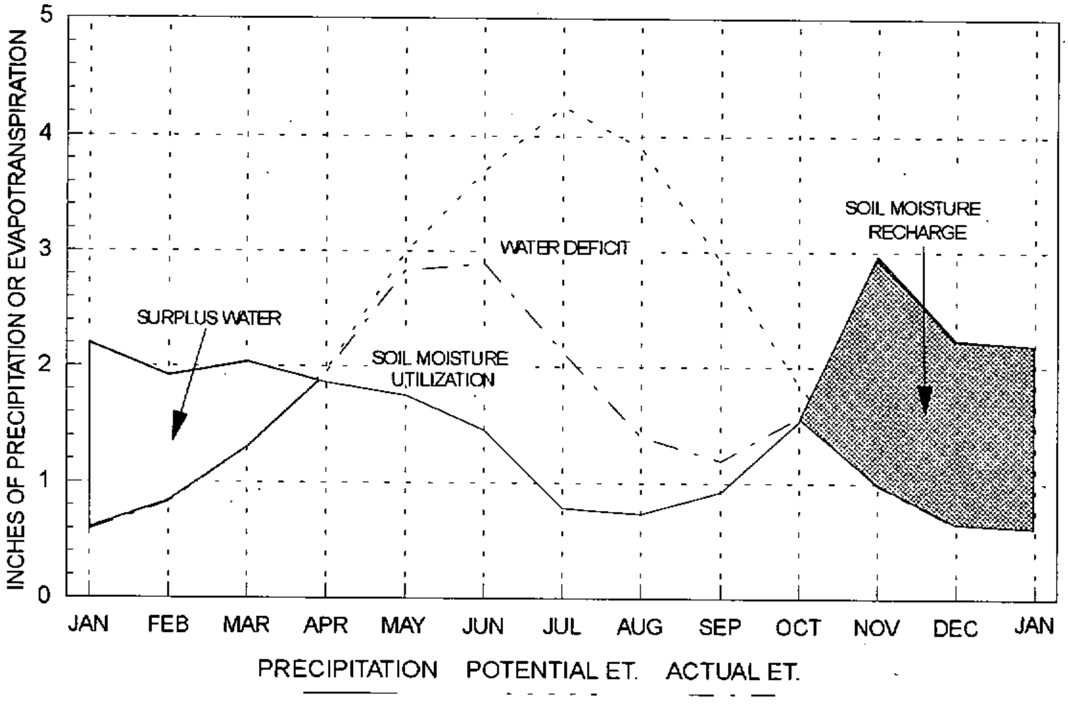
Using WATBUG, a water budget was derived for each of the six precipitation stations on the island and surplus water (recharge) values were obtained. We then averaged these six recharge values to get an estimated average annual recharge for the island.

According to our analysis, the average annual recharge to Marrowstone Island aquifers is 2.2 inches per year. The total area of Marrowstone Island is 4018 acres, including beaches, and steep slopes and cliffs along the coast. We rounded the potential recharge area for the island to 4000 acres. Recharge of 2.2 inches/year spread over 4000 acres is equivalent to an annual recharge of about 238,000,000 gallons or about 730 acre-feet per year (ac-ft/yr). This equates to a continuous recharge rate of about 450 gallons per minute.

Figure 6 shows the typical annual water budget for Marrowstone Island. The annual balance between precipitation, actual and potential evapotranspiration (AET and PET), and surplus water (recharge) is shown. On average, the island's soils are in a state of water deficit from late March through September. During this period, evapotranspiration is greater than precipitation and soil moisture is being depleted. In the fall, as rainfall increases, the precipitation and PET curves begin to converge until they cross in early October. At this point, precipitation exceeds PET and soil moisture depleted during the summer begins to be replenished. This replenishment continues until January when the soil-moisture-holding capacity is exceeded. From January to late March, surplus water is available for ground-water recharge. Recharge to Marrowstone Island's aquifers occurs only in January, February, and March of the typical year, because that is the only time of the year that enough precipitation has accumulated to exceed the soil moisture holding capacity and PET. Precipitation at other times of the year is held in the soil or lost to the atmosphere.

Figure 6.

Mean Annual Water Budget for Marrowstone Island



Recharge Through Advance Outwash, Till, and in Wetland Areas

According to Freeze and Cherry (1979, p. 29), the unconsolidated sands and gravels of advance outwash have hydraulic conductivities ranging from 10^2 to 10^5 gallons per day per square foot (gal/day/ft^2). This means that water flows easily through this material, relative to many other aquifer materials.

Till has hydraulic conductivities ranging from 10^{-5} to 1 gal/day/ft^2 (Freeze and Cherry, 1979). This means that water passes through a till aquitard at a rate many times slower than through advance outwash. However, water that becomes recharge through till probably provides a constant, long-term trickle of recharge to island aquifers.

For the most part, wetlands on Marrowstone Island are the result of ponding on near-surface till layers. Wetlands act as temporary storage reservoirs because water stays in them through the wet months of the year rather than running off to the sea. This may provide the opportunity for the water to percolate through soil and till layers in wetland areas and become recharge. Marrowstone Island wetlands may contribute significantly to the trickle recharge effect mentioned above. Artificial draining of wetlands on Marrowstone Island may have significant and even devastating effects on local ground-water levels and production capabilities.

Ground-Water Discharge

During our field investigations of the Marrowstone Island coastline, we observed many seeps, small springs, and what appeared to be large quantities of water flowing from the beaches at low tide. As mentioned above, the annual average recharge rate for the island is about 450 gpm. Given a coastline of approximately 18.4 miles, an annual average discharge of only about 24 gpm per mile is needed to discharge all of the estimated aquifer recharge of 450 gpm. Discharge rates of this magnitude are not difficult to imagine. These discharge rates would be maintained, as a matter of course, in an undisturbed hydrologic system in equilibrium.

Water Use On Marrowstone Island

Ground water on Marrowstone Island is used primarily for domestic purposes such as single household use and lawn and garden watering. There is no organized water metering program on the island with which to establish water-use information.

Because of their individual beliefs about water availability and the need for water conservation, the water use habits of Marrowstone Island residents vary widely. We estimate that average per-capita ground-water withdrawals range from about 60 gallons per day per person (gpd/person) — for the most conservation minded — to about 160 gpd/ person. Accordingly, our water-use estimates are based on the simple assumption that the average annual per-capita withdrawal is approximately 120 gpd/person. This equates to a total ground-water withdrawal in 1993 of approximately 107 acre-feet (Table 8). The population projections upon which our use estimates are based are shown on Table 8.

Consumptive Versus Non-Consumptive Use

Consumptive use refers to any loss of water, as a result of use by mankind, whether it be a loss in quantity, a decline in water quality, a change in location, or a delay in the time it takes for the water to return to the aquifer system. Non-consumptive use causes no changes in the natural balance of the ground-water flow system and therefore has no detrimental effects. Consumptive use, on the other hand, changes the natural balance of the ground-water flow system and can cause detrimental effects such as sea-water intrusion.

Essentially all of the in-house domestic water used on Marrowstone Island is disposed of through septic systems. Some unknown portion of this water is returned to the water-table aquifer through the septic system drain fields.

The following assumptions are used regularly in Colorado to calculate water use in non-sewered areas (Wood, 1993) and are essentially the same as those used by Sapik and others (1988) in their water resources study of Island County, Washington.

1. In-house use is 90% non-consumptive (returned to the water-table aquifer) and 10% consumptive.
2. Outdoor use such as lawn and garden irrigation is 10% non-consumptive and 90% consumptive.
3. Stock watering is 100% consumptive.
4. Annual non-consumptive use is 70% of the total withdrawal and 30% is consumptive.

Recharge and Water Use: Findings

The following are the conclusions we have reached about recharge and water use on Marrowstone Island.

- Based on the estimated population (Table 8) and estimated per-capita water use, the total ground-water withdrawal on Marrowstone Island, in 1993, was about 107 acre-feet and consumptive water use was about 32 ac-ft/yr (Table 8).
- Annual recharge to Marrowstone Island's aquifers is about 730 ac-ft/yr - about 23 times greater than the estimated annual consumptive use.
- Most of Marrowstone Island's annual recharge discharges to the Puget Sound. The production of fresh ground water is limited by the need to maintain sufficient fresh-water heads to keep sea-water intrusion at bay.
- Ground-water withdrawal by wells reduces the amount of discharge to the sea by the amount of consumptive use.
- On a small island like Marrowstone Island, where all recharge comes from precipitation that falls on the island, and where about 80% of the land surface is covered by till, most of the land area is potentially important for aquifer recharge.
- Particular care should be taken to protect advance outwash recharge areas, but a significant amount of the recharge to island aquifers must also come through till and from wetland areas. Therefore, it is important, on Marrowstone Island, to preserve as much land area as possible for recharge sites.
- Several physical factors combine to make ground-water withdrawals a problem on Marrowstone Island: the small size of the island; the physical limits to the size and storage capacity of the aquifers; the presence of surficial till over a large portion of the island; and the bounding of most of the aquifers by sea water — a source of water-quality degradation.
- Even though Marrowstone Island residents are using a relatively small portion of the annual recharge, sea-water intrusion is evident on most of the island, ground-water shortages are common in certain areas, and water-level declines have been a problem in some wells.
- Continued increases in consumptive water use can only exacerbate the island's water-supply and water-quality problems.

TABLE 8
Population Projections and Water Use Estimates for Marrowstone Island

Year	Approx. Population[1]	Total GW Withdrawal[2] (Ac-Ft/Yr)	Water-Use Estimates (Ac-Ft/Yr)[3]	
			Non-Consumptive	Consumptive
1990	690	93	65	28
1993	795	107	75	32
1994	830	112	78	33
1999	1058	142	100	43

1. 1990 population based on 1990 census; 1991 through 1999 populations based on projected population increases shown in Table 3 (Jefferson County Planning Department, 1993).
2. Based on the assumption that the average year-round per-capita withdrawal is 120 gallons per day per person.
3. Based on the water-use assumption in No. 2, above, and the assumption that consumptive/non-consumptive use is 70% non-consumptive and 30% consumptive use.

Water Quality

Between May 1990 and December 1992, we collected ground-water samples from 46 Marrowstone Island wells for laboratory analysis of major dissolved inorganic chemicals. We sampled for chlorides and field parameters on five separate occasions during this period, and once for major cations and anions. The results of this sampling are presented here. The first part of the discussion addresses the island's water types and water hardness, and compares the island's water quality to that required of drinking water under state and federal regulations. The second part of the discussion addresses the effects of sea-water intrusion on the island's ground-water resources.

Water Types

Water typing is an informal method of classifying water based on the relative concentrations of the cation(s) and anion(s) contained in a water sample. Waters having a single cation and anion whose concentrations exceed 50 percent of their respective totals (when expressed as milliequivalents) are classified as single water types. Such waters are designated by their dominant cation and anion names (ex., magnesium/bicarbonate). If no single cation or anion constitutes at least 50 percent of the sample total, then the water is a mixed type, with all important cations and anions being identified (Hem, 1985).

Based on our sampling of 10 wells (Appendix C, p. C-9), we identified six water types on Marrowstone Island (Table 9). For the wells sampled, the dominant cations were magnesium and sodium, while the dominant anions were bicarbonate and chloride.

Table 9
Water Types on Marrowstone Island

Well Number	Water Bearing Strata	Water Type (Dominant Cations/Anions)
AAB015	Bedrock	Sodium-Magnesium/Bicarbonate-Chloride
AAB022	Bedrock	Sodium/Chloride
AAB061	Bedrock	Sodium/Bicarbonate
AAB006	Glacial	Magnesium/Bicarbonate
AAB026	Glacial	Calcium-Sodium/Chloride
AAB038	Glacial	Magnesium/Bicarbonate
AAB042	Glacial	Sodium/Chloride
AAB046	Glacial	Magnesium-Calcium-Sodium/Bicarbonate
AAB051	Glacial	Magnesium-Calcium-Sodium/Bicarbonate
AAB069	Glacial	Magnesium-Calcium-Sodium/Bicarbonate

Water Hardness

Water hardness is a term used to describe variations in the amount of soap that is needed to produce lather, or the rate of scale build-up in low pressure boilers and water heaters. By convention, hard water requires more soap to form lather than does soft water and produces more scale in boilers and water heaters. Total hardness is usually expressed as the concentration of calcium (Ca^{2+}) and magnesium (Mg^{2+}) in mg/L, reported as an equivalent concentration of calcium carbonate ($CaCO_3$). While other cations contribute to water hardness, their concentration in fresh-ground water is generally small enough that they do not significantly affect water hardness. Hardness can be calculated from the mg/L concentrations of calcium and magnesium using the following equation:

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

Total hardness may be subdivided into two categories, namely carbonate hardness and non-carbonate hardness. Carbonate hardness is that part of total hardness that is equal in concentration to alkalinity (bicarbonate + carbonate) expressed as $CaCO_3$. Non-carbonate hardness refers to that part of total hardness that is not accounted for by alkalinity.

Several systems for classifying water by hardness content, have been proposed over the years, including the one shown below (Table 10).

TABLE 10

Water Classification by Hardness Content, (U.S. EPA, 1986)

Hardness Range (mg/L of $CaCO_3$)	Hardness Classification
0 - 75	Soft
76 -150	Moderately Hard
151 - 300	Hard
300+	Very Hard

Based on this classification, Marrowstone Island's ground water is generally hard to very hard (Table 11). Of the 10 wells we sampled for inorganic analyses, (Appendix C, p. C-9) six had hard water, two had very-hard water, and two had soft water.

TABLE 11

Ground-Water Hardness Expressed as $CaCO_3$ (mg/L)

Well Number	Water Bearing Strata	Total Hardness	Carbonate Hardness (Alkalinity)	Non-carbonate Hardness	Hardness Range
AAB015	Bedrock	219	202	17	Hard
AAB022	Bedrock	75	66	9	Soft
AAB061	Bedrock	8	8	0	Soft
AAB006	Glacial	216	192	24	Hard
AAB026	Glacial	246	130	116	Hard
AAB038	Glacial	231	224	7	Hard
AAB042	Glacial	401	274	127	Very Hard
AAB046	Glacial	627	446	181	Very Hard
AAB051	Glacial	261	226	35	Hard
AAB069	Glacial	243	188	55	Hard
Bedrock Wells	Minimum	8	8	0	
	Maximum	219	202	17	
	Median	75	66	9	
Glacial Wells	Minimum	216	130	7	
	Maximum	627	446	181	
	Median	246	224	5	

Water Quality And Drinking Water Standards

With exceptions for total dissolved solids (TDS), pH, and chloride, the wells we sampled produced water that met the water-quality standards or maximum contaminant levels (MCLs) for drinking water (Table 12 and Appendix C). Detailed discussions of the parameters that exceeded MCL criteria, along with other regulated constituents are provided below.

Total Dissolved Solids (TDS)

TDS refers to the total concentration of dissolved constituents in water. Under state and federal drinking water regulations, TDS is considered a secondary (aesthetic) contaminant at concentrations greater than 500 mg/L. Water with higher TDS concentrations can corrode pipes and plumbing fixtures, may taste bad, and can have laxative effects. In addition, some constituents of TDS, such as sodium, may pose a health threat to individuals on salt restricted diets. The primary contributors to TDS in Marrowstone Island ground water are calcium, magnesium, sodium, bicarbonate, sulfate, chloride, and silica.

TABLE 12
Statistical Summary of Ground-Water Quality
(reported in units of mg/L unless otherwise noted)

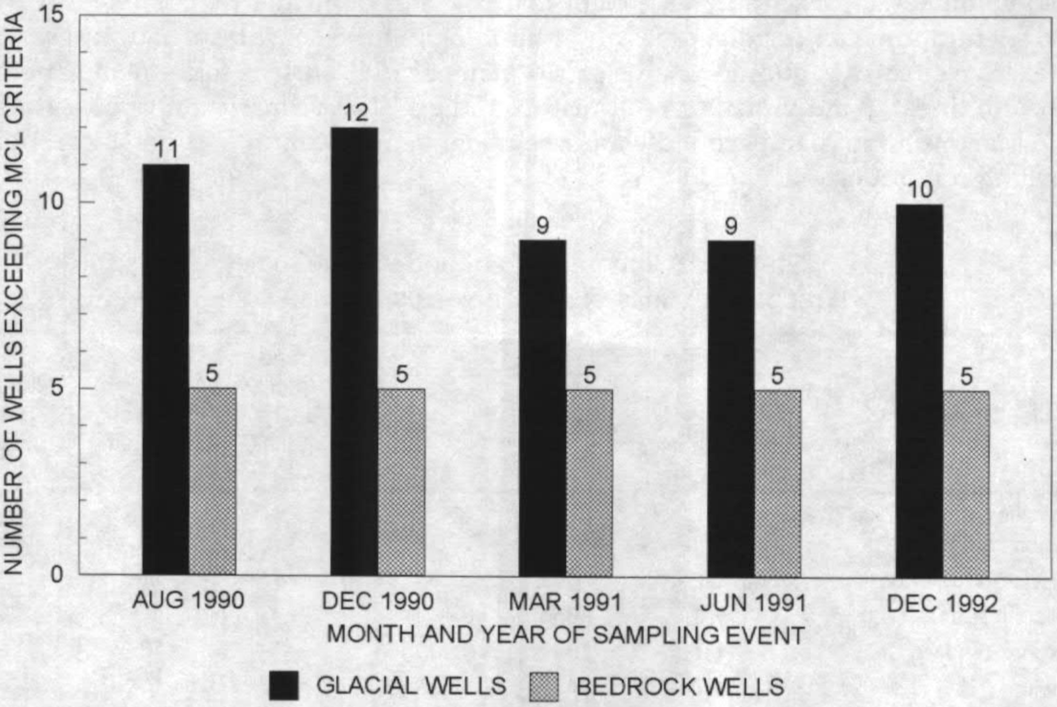
Constituent	Concentration			Ground Water Quality Criteria (MCL)[A]	Number of Wells Sampled[B]	Number of Wells Exceeding MCL[C]
	Min.	Max.	Median			
Specific Conductance (µmohs/cm at 25°C)	419	4840	719	700*	46	29
pH at 25°C (standard units)	6.2	9.5	7.3	6.5 to 8.5*	46	4
Calcium (Ca^{2+})	3.1	95.2	34	—	10	—
Magnesium (Mg^{2+})	0.1	94.8	37.35	—	10	—
Sodium (Na^+)	21.6	247	73.95	—	10	—
Potassium (K^+)	<0.3 (U)	13.4	2.65	—	10	—
Bicarbonate Alkalinity (HCO_3-)	66	446	213	—	10	—
Carbonate Alkalinity ($CO_3$2-)	48	48	48	—	10	—
Sulfate ($SO_4$2-)	11.9	148	33.8	250*	10	0
Chloride (Cl^-)	13.4	1310	59.3	250*	46	11
Silica	4.8(J)	20.2(J)	17.45(J)		10	
Total Dissolved Solids (calculated)	272	3146	467.5	500*	46	23
Nitrate + Nitrite (NO_3-+NO_2-)	<0.01(J)	8.14(J)	0.16	10	10	0
Phosphorous ($PO_4$3-)	0.02	0.43	0.045	—	10	—
Iron (Fe^{2+})	<0.02(U)	0.09(J)	<0.02(U)	0.3*	10	0

(U) Indicates the constituent was not found at the reported detection limit.
(J) The sample holding time was exceeded prior to analysis. The reported value is estimated.
(*) Washington state water quality standard for secondary contaminants.
(A) WAC 173-200.
(B) The reported value is the number of individual wells sampled during this study.
(C) The reported value is the number of individual wells that exceeded the indicated standard (MCL) during at least one sampling event.

TDS concentrations in water from 23 wells exceeded the recommended MCL during at least one sampling event. In August and December of 1990, 16 and 17 wells respectively, exceeded the drinking water standard for TDS. This value decreased to 14 wells in March and June of 1991 and then increased to 15 wells in December 1992 (Figure 7).

Figure 7

Number of Wells Exceeding the 500 mg/L MCL for Total Dissolved Solids



TDS concentrations for 26 glacial wells and eight bedrock wells sampled between August 1990 and December 1992, are shown below (Figures 8 and 9). In general, TDS concentrations are lower in the island interior and higher near the coast. The highest TDS values occurred in wells drilled east and north of Mystery Bay where the island is relatively narrow and water use is high (Plate 7).

TDS concentrations are elevated in many of the bedrock wells, especially in the Griffith's point area. With a few exceptions, the southern end of the island (south of Meade Road) has water relatively low in TDS. Only three of 20 wells there had median TDS concentrations exceeding the MCL. North of Meade Road 17 of 26 wells had median TDS concentrations greater than the MCL.

Figure 8

TDS Concentration in 26 Glacial Wells
Sampled between August 1990 and December 1992

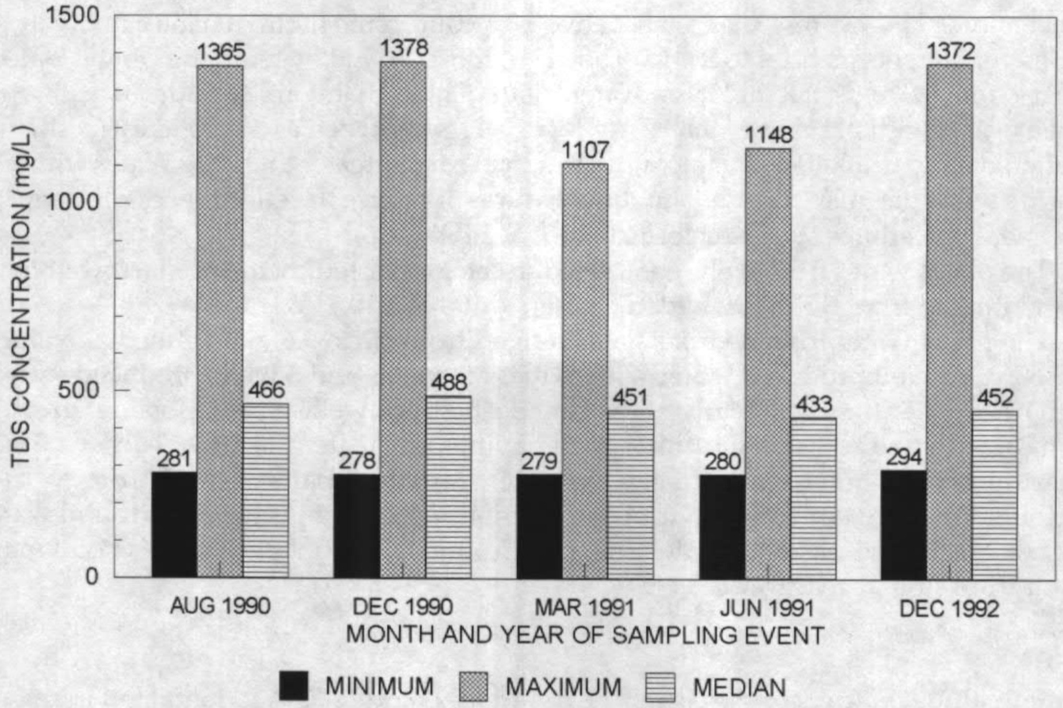
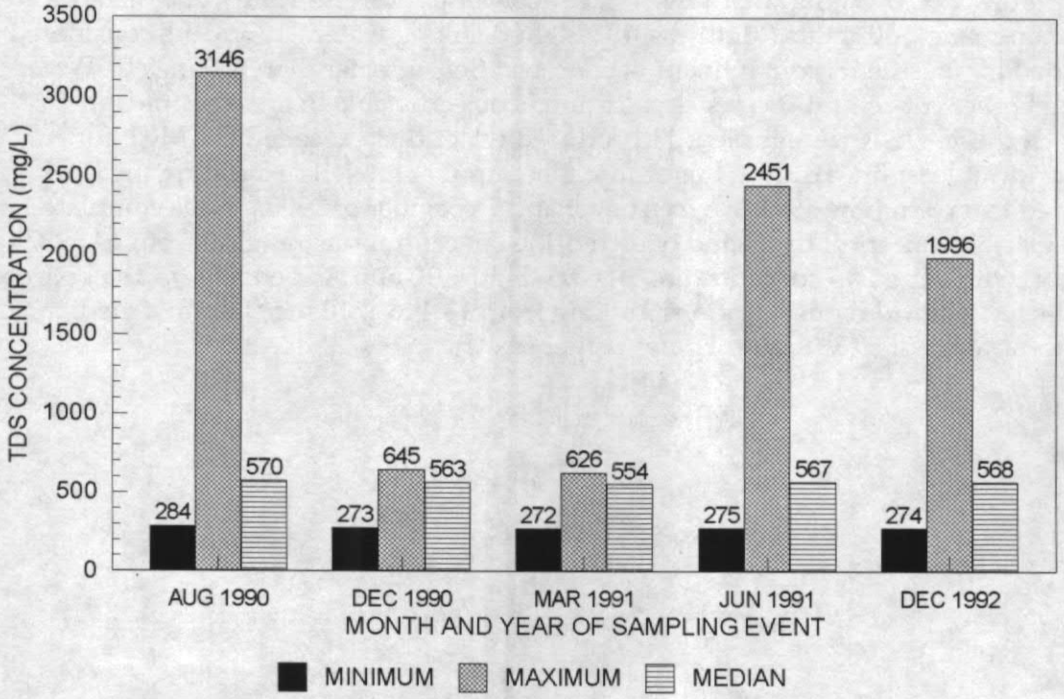


Figure 9

TDS Concentration in 8 Bedrock Wells
Sampled Between August 1990 and December 1992



pH

pH is a measure of the acid-base equilibrium of natural waters. pH plays many important roles in the biological and chemical systems of natural waters. It can control the solubility of metal compounds and the rate or magnitude of chemical reactions. By convention, pH is expressed as the negative logarithm of the hydrogen ion activity in moles per liter, normalized to 25° C. The pH of most ground water in the United States ranges from 6.0 to 8.5 (Hem, 1985). Waters with pH less than 7 are considered acidic, while waters with pH greater than 7 are basic. pH is regulated as a secondary (aesthetic) contaminant in drinking water at values less than 6.5 or greater than 8.5. Water with pH outside this range may corrode plumbing fixtures or reduce the effectiveness of water treatment procedures such as chlorination (U.S. EPA, 1986).

The pH of water from wells completed in the glacial sediments of Marrowstone Island ranged from 6.5 to 8.4, with a median value of 7.19.

The pH of water from bedrock wells ranged from 6.2 to 9.6, with a median value of 7.65. One well produced water with pH less than 6.5, and 3 wells produced water with pH greater than 8.5. Many of the Island's bedrock wells have pH values greater than 8.0 with two wells on Griffith's point having pH greater than 9.0. Turney (1990) measured pH values up to 9.5 in ground water from the basalts of Clark County. He attributed the elevated pH to hydrolysis reactions involving infiltrating ground water and the area's sodium-rich basalt. The high ground water pH of Griffith's Point may result from similar reactions.

Chloride

Roughly three quarters of the earth's near-surface chloride (Cl^-) is contained in sea water, which has an average chloride concentration of approximately 19,000 mg/L (Hem, 1985). Much of this chloride probably originated by outgassing from the earth's crust during volcanic eruptions, with additional input from the weathering of igneous rocks (Matthess, 1982). In fresh ground water, chloride usually occurs at concentrations of 30 mg/L or less. Higher concentrations indicate mineralized waters or man-made pollutants (Matthess, 1982). In drinking water, chloride is considered a secondary (aesthetic) contaminant at concentrations greater than 250 mg/L. Water with higher concentrations tastes salty and is objectionable to most people.

Of the 46 wells we sampled, 11 produced water that exceeded the MCL for chloride at least once during this study. The number of wells exceeding the MCL varied from 3 in June 1991 to 6 in August and December of 1990. Wells completed in the glacial aquifers of the island had chloride concentrations ranging from 19 to 874 mg/L with a median concentration of 60.8 (Figure 10 and Appendix C). The bedrock wells had chloride concentrations ranging from 13.4 to 1310 mg/L with a median concentration of 59.3 (Figure 11 and Appendix C).

Figure 10

Chloride Concentration in 26 Glacial Wells
Sampled Between August 1990 and December 1992

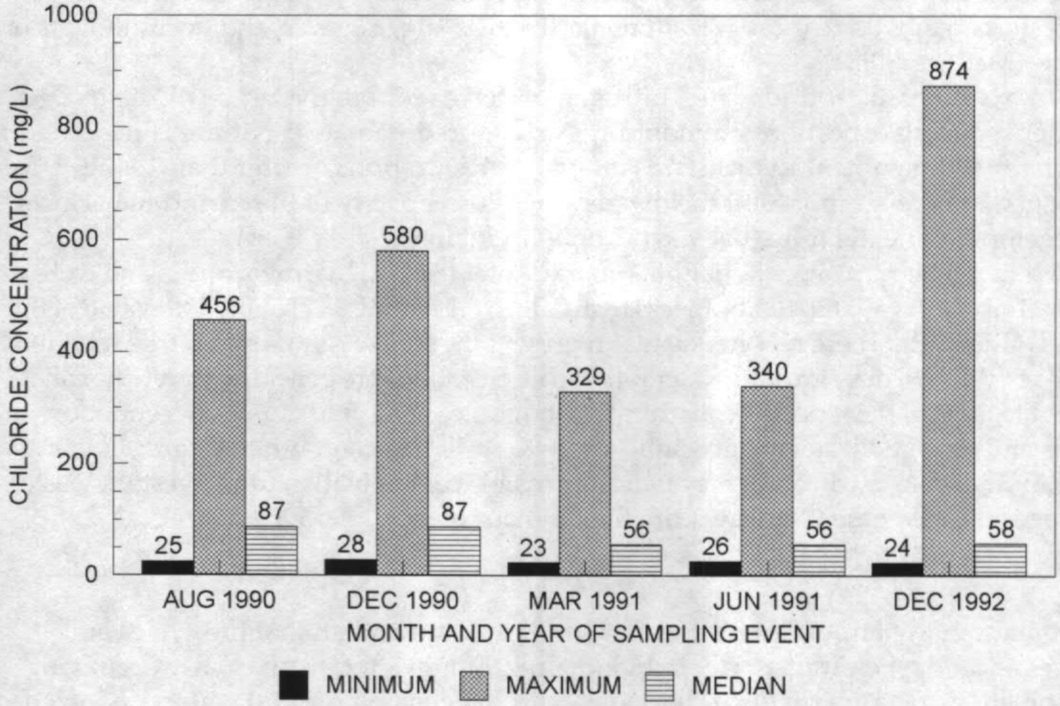
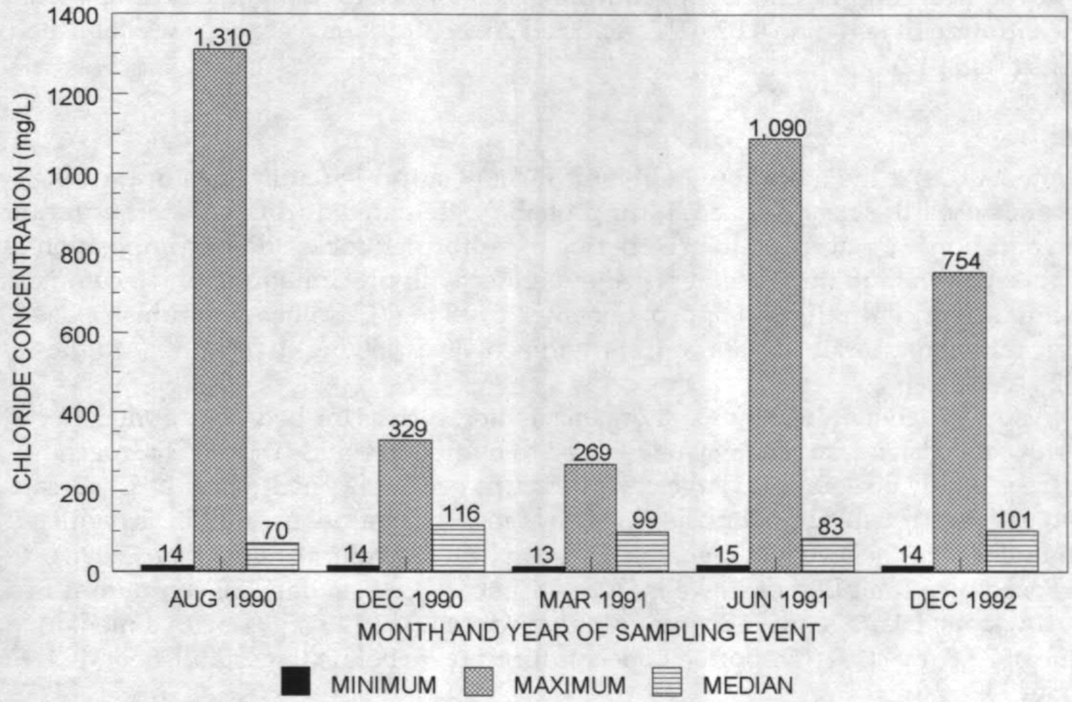


Figure 11

Chloride Concentration in 8 Bedrock Wells
Sampled Between August 1990 and December 1992



Nitrate + Nitrite

Nitrogen-based compounds such as nitrate and nitrite are important nutrients that are used by plants or bacteria. High concentrations of these compounds in ground water may indicate contamination by sewage or animal waste, industrial waste, or nitrogen-rich fertilizers. Nitrogen compounds can also enter ground water with precipitation, which typically contains 0.1 to 0.2 mg/L ammonia, 0.3 to 2.5 mg/L nitrate, and trace amounts of nitrite (Matthess, 1982).

In oxygenated ground water, nitrogen occurs as nitrate (NO_3-) or nitrite (NO_2-). Under reducing conditions ammonium (NH_4+) predominates. Nitrate is regulated as a primary contaminant in drinking water at concentrations greater than 10 mg/L as nitrogen, where it can inhibit the oxygen-carrying capacity of blood and may cause methemoglobinemia (blue-baby syndrome) in infants.

Nitrate + Nitrite concentrations in ground water from 10 Marrowstone Island wells (Appendix C, p. C-9) ranged from less than 0.01 to 8.14 mg/L, with a median value of 0.16 mg/L (Table 12). These reported values represent the sum of nitrate and nitrite reported as nitrogen (N). Because ground-water nitrite concentrations are generally small one can attribute most of the reported concentration to nitrate. Although nitrate concentrations in the island's ground water are generally low, two wells had concentrations greater than 1 mg/L. These elevated values may indicate possible contamination from livestock waste, sewage, nitrogen-based fertilizers, or other human sources.

Iron

Iron plays many important biochemical roles in plant and animal life cycles and serves as an oxygen transporter in blood. In ground water, iron usually occurs in dissolved form as the divalent cation Fe^{2+}. In oxygenated ground water, dissolved iron is generally present only in trace amounts. Under reducing conditions, it is more prevalent and often reaches concentrations of 1 to 10 mg/L as Fe^{2+}. Iron is regulated as a secondary (aesthetic) contaminant in drinking water at concentrations greater than 0.3 mg/L, where it can stain laundry or encrust plumbing fixtures.

Based on a sampling of 10 Marrowstone Island wells (Appendix C, p. C-9), dissolved iron concentrations ranged from less than 0.02 to 0.09 mg/L, with a median concentration of less than 0.02. The reported concentrations were below established MCLs (Table 12).

Sulfate

Sulfate ($SO_4$2-) is the most abundant ionic form of sulfur in natural ground water. Most of the earth's near-surface sulfur probably originated during volcanic eruptions with additional input from the weathering of sulfur rich rocks and decomposition of organic matter. Sulfate also enters ground water with precipitation, which commonly has sulfate concentrations of approximately 1 to 15 mg/L. In heavily industrialized areas, rain may contain sulfate concentrations of 30 to 450 mg/L or more (Matthess, 1982).

In aquifers containing abundant organic matter, such as the bedrock aquifers of Marrowstone Island, sulfate may be reduced to hydrogen sulfide (H_2S). Hydrogen sulfide is highly poisonous in large concentrations but rarely poses a health risk, because people find its rotten-egg odor objectionable at low concentrations. Sulfate is regulated as a secondary (aesthetic) contaminant in drinking water at values greater than 250 mg/L.

Based on a sampling of 10 wells (Appendix C, p. C-9), sulfate concentrations in Marrowstone Island's ground water ranged from 11.9 to 148 mg/L with a median value of 33.8 mg/L. All reported concentrations were below the established MCL for sulfate.

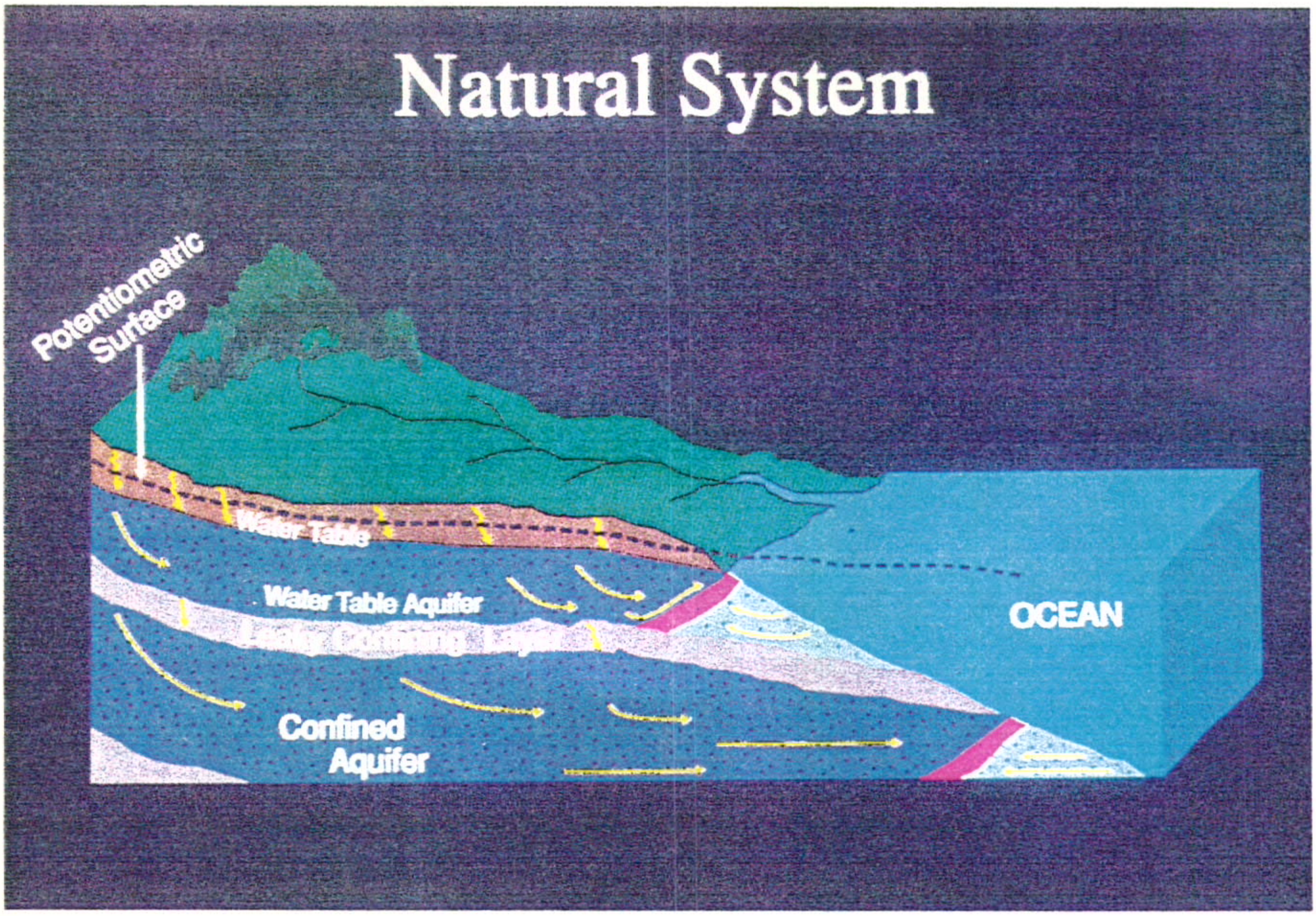
Water Quality and Sea-Water Intrusion

In coastal aquifers that are hydraulically connected to the sea, the boundary between fresh-ground water and sea water is marked by a transition zone of increasing salinity toward the sea (Figure 12A). This area of transition is known as the zone of diffusion (shown as bright pink on Figures 12A - 12D). Within the zone of diffusion, fresh-ground water from coastal aquifers mixes with slightly diluted, upwelling sea water. In a typical coastal aquifer, the zone of diffusion dips landward, with lighter fresh water overlying denser sea water. The location of the zone of diffusion is controlled largely by the volume of freshwater discharged by an aquifer. All other factors being equal, aquifers that discharge large volumes of water to the sea have diffusion zones farther seaward than aquifers of lesser discharge.

Under natural conditions, aquifer recharge from precipitation or other sources is balanced, over time, by ground-water discharge (Figure 12A). This equilibrium enables the zone of diffusion to maintain a position of relative stability, shifting landward or seaward in response to seasonal changes in discharge, recharge, or other natural climatic factors.

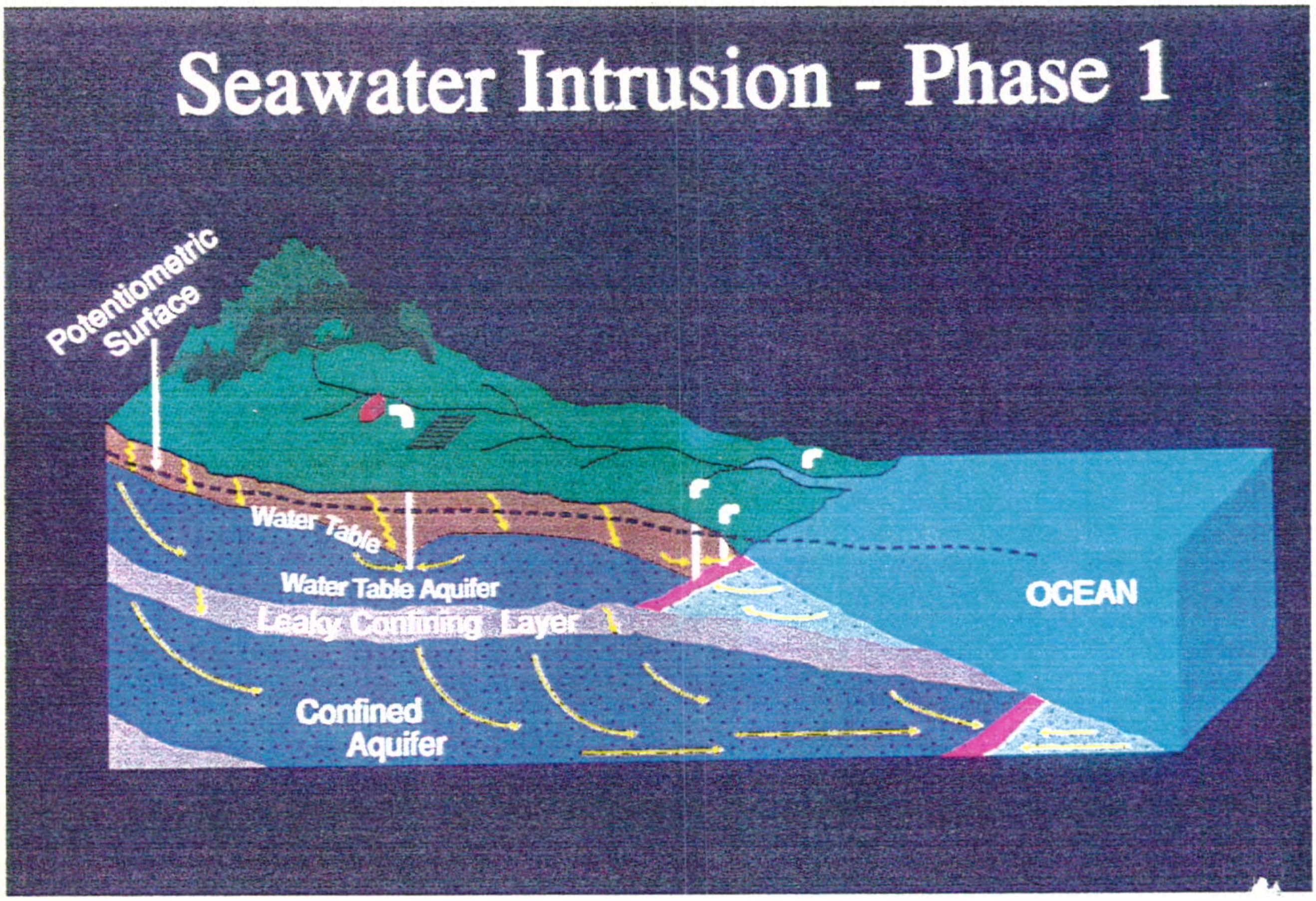
When ground water is pumped from coastal aquifers, fresh water that would normally discharge to the sea is intercepted, thereby disrupting the equilibrium that existed prior to the start of pumping (Figure 12B). With reduced fresh-water discharge, the zone of diffusion migrates inland until equilibrium is re-established. This incremental shifting of the interface, in response to ground-water development, is called passive sea-water intrusion (Fetter, 1988). With passive intrusion, the seaward- sloping hydraulic gradient is maintained, despite the reduction in natural aquifer discharge. Passive intrusion is a common consequence of water-supply development in coastal aquifers, and with time, can cause wide-spread degradation of water quality.

During advanced stages of ground-water development, ground-water quality may be degraded by both passive and active sea-water intrusion (Figure 12D). Active intrusion occurs when the volume of ground-water withdrawn from an aquifer is sufficient to cause a reversal of the seaward sloping hydraulic gradient (Fetter, 1988). Fresh water on the seaward side of pumping wells flows from the zone of diffusion toward the area of ground-water withdrawal (Figure 12D). Active intrusion occurs much more rapidly than passive intrusion and may have more severe consequences for the well or wells that caused it.



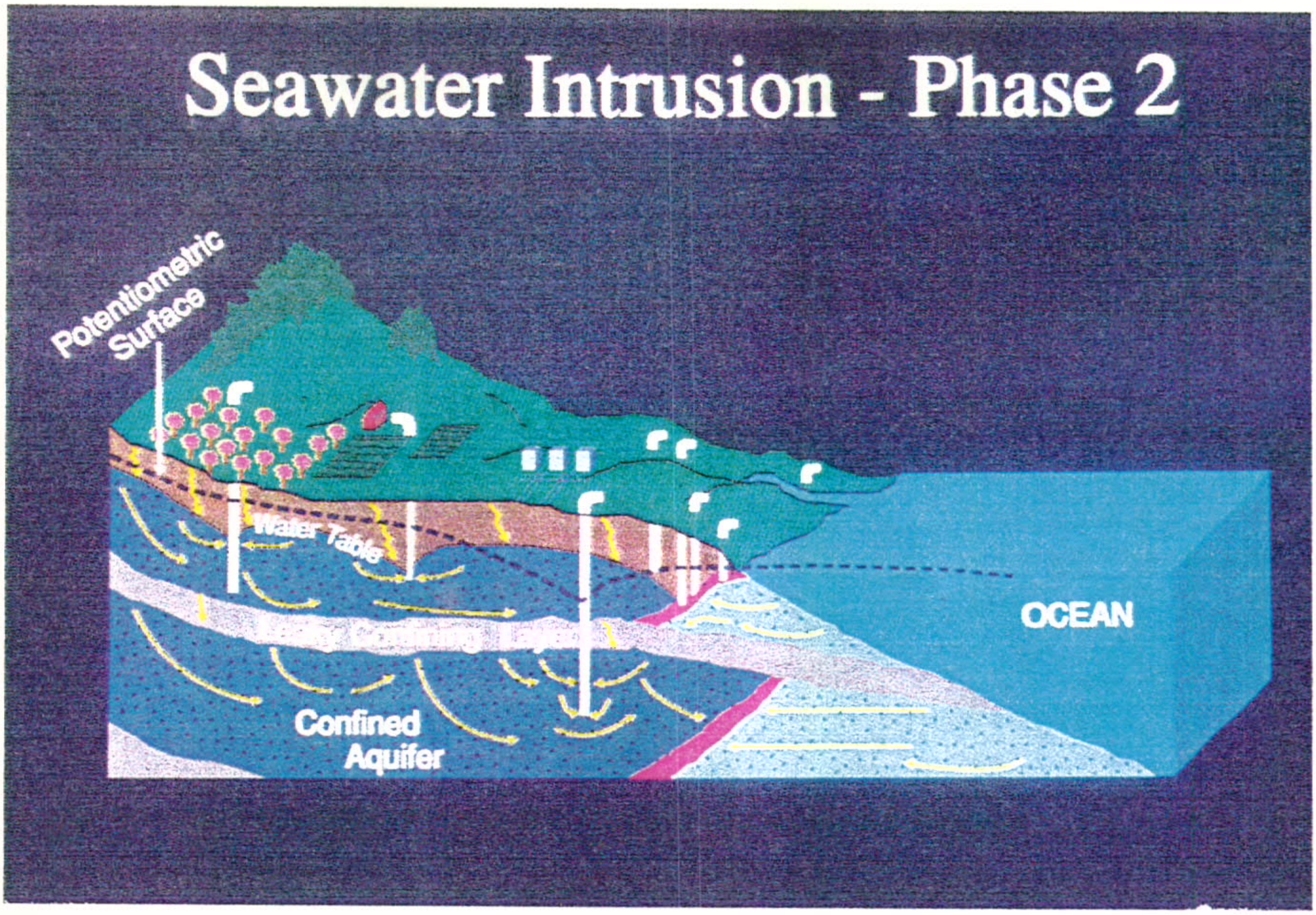
Natural System

Figure 12A - Hydrologic System in Natural Equilibrium Before Development



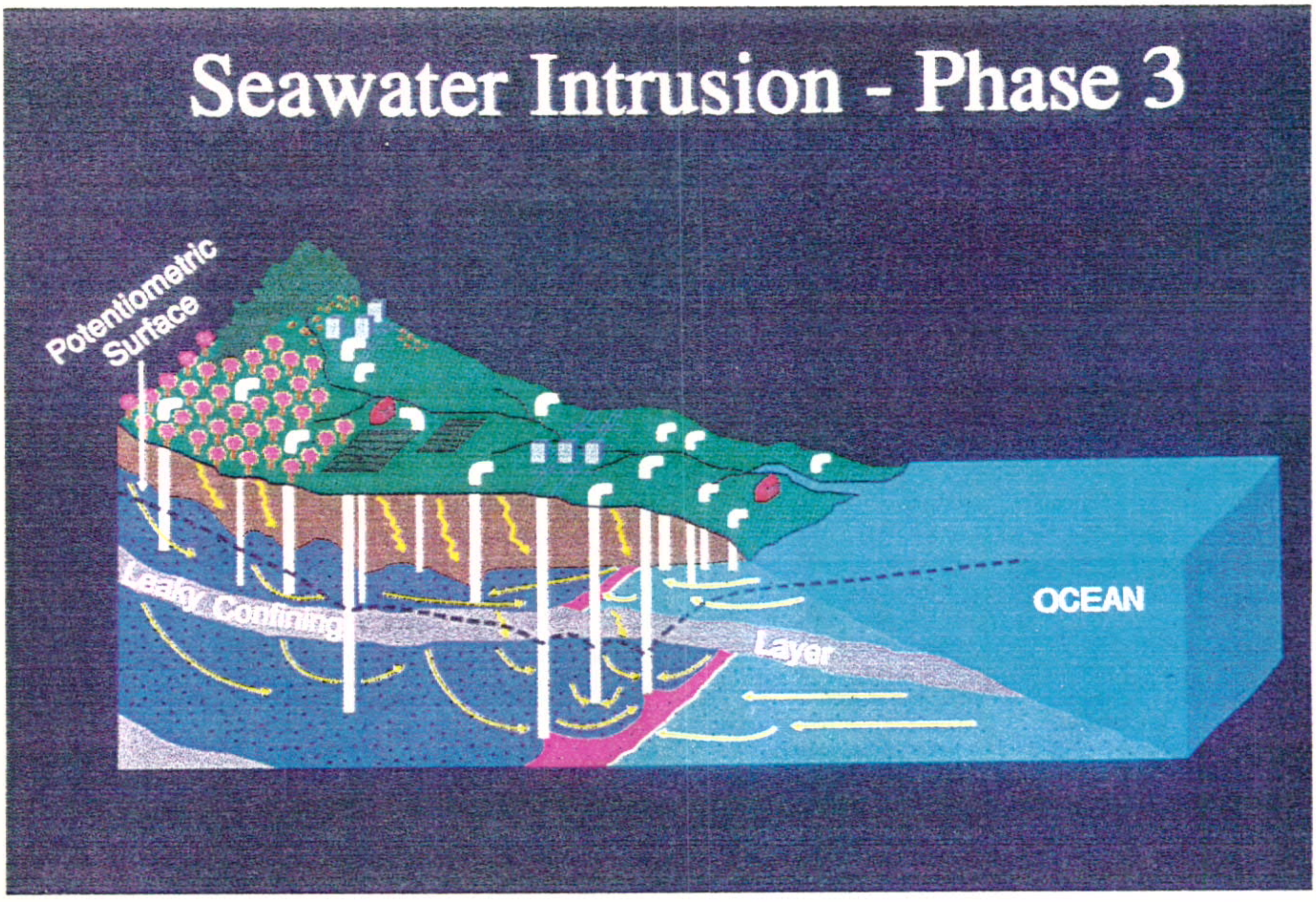
Seawater Intrusion - Phase 1

Figure 12B - Hydrologic System in Early Stage of Adjustment to Development Stress



Seawater Intrusion - Phase 2

Figure 12C - Hydrologic System Adjusting to Moderate Development Stress



Seawater Intrusion - Phase 3

Figure 12D - Hydrologic System Adjusting to Extreme Development Stress

Methods of Identifying Sea-water Intrusion

Perhaps the simplest method for defining sea-water intrusion is the 100 mg/L chloride concentration threshold proposed by Dion and Sumioka (1984). The empirically derived value of 100 mg/L represents a natural break in inland and near-shore chloride concentrations. Dissolved chloride usually travels unhindered with ground water and analysis of chloride concentration is a convenient and inexpensive means of distinguishing between intruded and non-intruded ground water. Non-intruded ground water generally has chloride concentrations of 30 mg/L or less, while highly-intruded ground water can have chloride concentrations approaching that of sea water, which averages about 19,000 mg/L chloride (Hem, 1985).

There are several additional analytical and graphical techniques one can use to evaluate water quality data for evidence of sea-water intrusion. Some of the common methods include ion ratios, theoretical mixing diagrams, cumulative percentage plots, and trilinear diagrams. These methods are especially useful for determining whether elevated chloride concentrations originated from sea-water intrusion or some other chloride source.

In the sections that follow, we evaluate several of these methods using water chemistry data from Marrowstone Island. The intent of this discussion is to define in detail, the severity and extent of sea-water intrusion on Marrowstone Island, and to illustrate the utility of these methods for future applications.

Chloride Concentrations in Marrowstone Island Ground Water

Chloride concentrations in Marrowstone Island's ground water have been measured formally on at least three occasions prior to this investigation. Based on a sampling of 12 Marrowstone Island wells in 1968, Walters (1971) identified four wells that exceeded the 100 mg/L chloride concentration threshold and three wells that produced water exceeding the drinking water standard for chloride (Table 13). During a follow up study in 1978, Dion and Sumioka (1984) revisited six of the wells sampled by Walters, plus seven additional wells (Table 13 and Plate 7). Five of the wells produced water that equaled or exceeded the sea-water intrusion threshold, while four exceeded the drinking water standard for chloride. Chloride concentrations increased in three of six wells sampled during both studies, but decreased in the three remaining wells.

TABLE 13
Marrowstone Island Wells Sampled in 1968 and 1978
(after Dion and Sumioka, 1984)

Well Number	Location	Latitude	Longitude	Sampling Date	Specific Conductance (µm/cm @ 25°C)	Chloride Concentration (mg/L)
—	29N/01E-04G1	—	—	07/24/68	453	22
AAB009	29N/01E-04L1	480153	1224103	06/29/78	705	91
—	29N/01E-05H1	480206	1224132	07/24/68	367	11
				06/29/78	390	18
AAB015	29N/01E-05H2	480211	1224143	07/24/68	4090	1150
				06/29/78	1520	360
—	29N/01E-08J1	480106	1224140	06/27/78	596	23
—	29N/01E-08Q2	—	—	07/24/68	425	44
—	29N/01E-09J1	—	—	07/24/68	488	56
—	30N/01E-20P1	480427	1224217	06/28/78	1340	240
—	30N/01E-28E1	—	—	07/11/68	1790	357
—	30N/01E-28L1	480340	1224103	07/11/68	609	55
				06/28/78	516	47
—	30N/01E-28L2	480344	1224106	07/11/68	599	46
				06/28/78	646	58
—	30N/01E-29A1	480405	1224127	06/28/78	2420	610
—	30N/01E-29C1	480405	1224206	07/11/68	1680	358
				06/28/78	911	100
—	30N/01E-29K1	—	—	07/11/68	834	141
—	30N/01E-32A1	480312	1224135	06/28/78	2220	610
—	30N/01E-32B1	480514	1224156	06/28/78	1970	47
—	30N/01E-32G1	480506	1224205	06/28/78	996	63
—	30N/01E-33C1	—	—	07/24/68	496	51
—	30N/01E-33E1	480305	1224120	07/24/68	790	66
				06/28/78	816	73

In March 1984, several residents of Marrowstone Island began monitoring a network of 29 wells (VanEtten and others, 1986). The group sampled periodically, up through August 1986, for chloride and nitrate. The field test kits used for the analytical deter- minations have purported accuracies of 30 mg/L for chloride and 1.0 mg/L for nitrate. Nitrate concentrations for the 29 wells monitored varied from less than 1 to 8.5 mg/L. Chloride concentrations varied from less that 30 mg/L to 1550+ mg/L. Seven of the wells sampled, produced water that exceeded the MCL for chloride, while 13 exceeded the sea-water intrusion threshold, at least once during the sampling (VanEtten and others, 1986).

During this study we sampled 46 wells for chlorides, on five occasions, between May 1990 and December 1992 (Appendix C and Plate 7). Twenty-one wells produced water that exceeded the sea-water intrusion threshold, while 11 wells exceeded the MCL for chloride. The number of wells exceeding the intrusion threshold varied from 11 wells in June 1991 to 15 wells in December of 1990 and 1992.

Chloride concentrations in ground water tend to be lowest in the island interior and increase toward the coast (Plate 7). South of Meade Road, chloride concentrations are generally low, with 17 of 20 wells sampled having median chloride concentrations less than 100 mg/L. North of Meade Road, concentrations are generally higher, with 16 of 26 wells sampled having median chloride values greater than 100 mg/L. For the area north of Meade Road, chlorides tend to be highest in wells that are completed below sea level, and have specific capacities of 5 gpm/ft or more (Plates 6 and 7). The relationship between well specific capacity and chloride concentration does not appear to be significant for wells South of Meade Road. There, well completion relative to sea level and proximity to the coast appear to have a greater bearing on chloride concentrations.

One additional factor that appears to significantly affect chloride concentrations is the degree to which a well is used. Wells that are heavily pumped for residential, irrigation, or other uses tend to have higher chloride concentrations than adjacent lesser used wells of comparable construction. This pattern is readily apparent north of Mystery Bay, and at various locations along the island perimeter, where heavy water use by some property owners has caused sea-water contamination of their wells. Such contamination probably results from sea-water upconing, since nearby, lesser-used wells often have lower chloride concentrations.

Two of the wells we sampled (AAB009 and AAB015) were also monitored by the USGS in 1978 (Dion and Sumioka, 1984). Between June 1978 and August 1990, chloride concentrations in well AAB009 increased from 91 to 141 mg/L, a difference of 65 percent. Chloride concentrations in well AAB015 increased from 360 to 1310 mg/L, a difference of about 360 percent.

We compared the overall results of the 1978 USGS study to ours by superimposing the earlier data on our chloride concentration map (Plate 7). The distribution and range of chloride values measured during the two studies are generally consistent, with a few notable exceptions. One area where chlorides appear to have increased is the narrow part of the Island east of Mystery Bay. In 1978, samples from three wells within Township 30N., Range 1E. Sections 28 and 33, yielded chloride concentrations ranging from 47 to 73 mg/L. Our sampling of 8 wells within these same sections yielded chloride concentrations ranging from 45 to 462 mg/L, with 5 wells having median chloride concentrations exceeding 100 mg/L. The high incidence of sea-water intrusion in this area is probably a function of heavy water use and limited ground-water recharge owing to the narrowness of the island at this location.

Together, these investigations indicate that elevated chloride concentrations are a pervasive problem on Marrowstone Island. Approximately 33 to 46 percent of the wells sampled during these studies exceeded the sea-water intrusion threshold for chloride, while 24 to 31 percent exceeded the MCL for chloride. On a percentage basis, the number of intruded wells increased from 33 percent of wells sampled in 1968, to 46 percent of wells sampled in 1990-1992. There was no appreciable difference in the number of wells exceeding the MCL for chloride during this same period.

Ion Ratios

Ion ratios have been used extensively in prior studies to define similarities or differences in water samples from disparate sources (Hem, 1985). The method requires a complete inorganic water analysis and is based on the assumption that intruded ground water contains essentially the same types of dissolved inorganic constituents as sea water, but at lesser concentrations. If one normalizes dissolved constituent concentrations by converting them to milliequivalents per liter (MEQ), similarities or differences between samples should be evident when one compares the ratios of selected constituents.

The ion-ratio method may be particularly appropriate for evaluating sites where historic chloride data are lacking or where chloride concentrations are not yet elevated to the 100 mg/L sea-water intrusion threshold.

Tables 14 and 15 are a listing of milliequivalent concentrations and ion ratios for 10 Marrowstone Island wells, and a sea water sample from Admiralty Bay (Culhane, 1993).

TABLE 14
Constituents Expressed in Milliequivalents per Liter (meq/L) for Ground Water Samples Collected in May, 1990 (Appendix C, p. C-9)

Well or Source	Chloride (Cl^-)	Sulfate (SO_4-2)	Alkalinity ($CaCO_3$)	Calcium (Ca^{+2})	Magnesium(Mg^{+2})	Potassium (K^+)	Sodium (Na^+)
Sea water	496.50	47.91	1.80	17.71	91.34	8.72	391.50
AAB006	0.70	0.40	3.15	1.57	2.76	0.08	0.94
AAB015	2.82	0.62	3.31	1.15	3.24	0.14	3.95
AAB022	7.17	0.25	1.08	1.49	0.01	0.01	7.09
AAB026	4.71	0.71	2.13	3.81	1.10	0.00	3.01
AAB038	1.22	0.54	3.67	1.12	3.51	0.04	2.16
AAB042	11.06	1.92	4.49	2.60	5.43	0.34	10.40
AAB046	5.22	1.05	7.31	4.75	7.80	0.26	3.43
AAB051	1.52	0.70	3.70	1.83	3.40	0.11	1.67
AAB061	1.41	3.08	6.38	0.15	0.01	0.02	10.74
AAB069	1.06	1.25	3.08	1.97	2.90	0.05	1.31

TABLE 15
Ion Ratios Calculated from MEQ Concentrations of Selected Constituents

Well or Source	Aquifer Type	CONSTITUENT RATIOS			
		Na/Cl	Ca/Mg	Cl/SO4	Cl/Alk
Sea water	—	0.79	0.19	10.36	275.83
AAB015	Bedrock	1.40	0.35	4.55	0.85
AAB022	Bedrock	0.99	149	28.68	6.64
AAB061	Bedrock	9.42	15	0.46	0.22
AAB006	Glacial	1.34	0.57	1.75	0.22
AAB026	Glacial	0.64	3.46	6.63	2.21
AAB038	Glacial	1.77	0.32	2.26	0.33
AAB042	Glacial	0.94	0.48	5.76	2.46
AAB046	Glacial	0.66	0.61	4.97	0.71
AAB051	Glacial	1.10	0.54	2.17	0.41
AAB069	Glacial	1.24	0.68	0.85	0.34

Incipient intrusion often results in the exchange of sodium for calcium in calcium-rich clays contained within the zone of diffusion (Hem, 1985, and Richter and Kreitler, 1991). This exchange process results in waters that are deficient in sodium (relative to chloride) and enriched in calcium. The Admiralty Bay sea water sample has a sodium-to-chloride ratio of 0.79. Ratios for these constituents in our samples varied from 0.64 to 9.42. Based on our sampling, four wells (AAB022, AAB026, AAB042, and AAB046) show a deficit of sodium relative to chloride and have sodium-to-chloride ratios similar to that of sea water. Three wells (AAB022, AAB026, and AAB061) have elevated calcium concen- trations relative to other island wells. Wells AAB022 and AAB026 both have elevated calcium and reduced sodium concentrations.

In sea water, sulfate accounts for about nine percent of the total anion concentration, expressed as MEQ. The chloride-to-sulfate ratio for Admiralty Bay sea water is 10.36. Ratios for these constituents in our samples varied from 0.46 to 28.68, with five wells (AAB015, AAB022, AAB026, AAB042, and AAB046) producing water having chloride-to- sulfate ratios significantly larger than the other wells. The chloride-to-sulfate ratio for these wells ranged from 4.55 to 28.68. The remaining wells had chloride-to-sulfate ratios ranging from 0.46 to 2.26. The break between the two groups is not distinctive, however.

In sea water, alkalinity accounts for less than one percent of the total anion concentration expressed as MEQ. The chloride-to-alkalinity ratio for Admiralty Bay sea water was 275.36, reflecting the large chloride concentration relative to alkalinity. This ratio for our samples varied from 0.22 to 6.64. Three wells (AAB022, AAB026, and AAB042) produced water with elevated chloride-to-alkalinity ratios relative to other wells. The chloride-to-alkalinity ratios for these wells varied from 2.21 to 6.64. The remaining wells had chloride-to-alkalinity ratios ranging from 0.22 to 0.85.

Potassium is a major component of Admiralty Bay sea water where it reaches a concentration of 341 mg/L (8.72 MEQ). Potassium concentrations in Marrowstone Island ground water varied from 0 to 13.4 mg/L (0 to 0.34 MEQ). Three wells (AAB015, AAB042, and AAB046) produced water with potassium concentrations significantly higher than other wells. Based on ion ratios for other constituents, the elevated potassium concentrations noted for these wells is most likely attributable to sea-water intrusion.

Our evaluation of ion ratios suggests that 6 of the ten wells we sampled (AAB015, AAB022, AAB026, AAB042, AAB046, and AAB061) are influenced by sea-water intrusion.

Graphical Analysis Methods

Several graphical methods for evaluating water quality data have been proposed including those by Collins (1923), Piper (1944), and Stiff (1951). Zaporozec (1972), Hem (1985), and Richter and Kreitler (1991), contain fairly complete discussions of the commonly used graphical analysis methods. As with the ion-ratio method, these procedures require a complete inorganic analysis for each well or sampling site. Graphical methods are a useful tool for identifying waters of common origin, because waters having similar proportions of dissolved constituents (expressed as percentages) display approximately the same graphical pattern, when plotted.

Figures 13A and 13B are examples of one graphical method where sample constituents are plotted as cumulative percentages of total dissolved solids (Table 16) (Hem, 1985). The upper portion of these figures is a graphic representation of the cumulative percentage of dissolved solids as defined in the table below each graph. As an example, SiO_2 accounts for 5.02 percent of the TDS concentration for sample AAB006. Together, SiO_2 and Ca^{+2}, account for 14.13 percent of the samples TDS concentration, and so on.

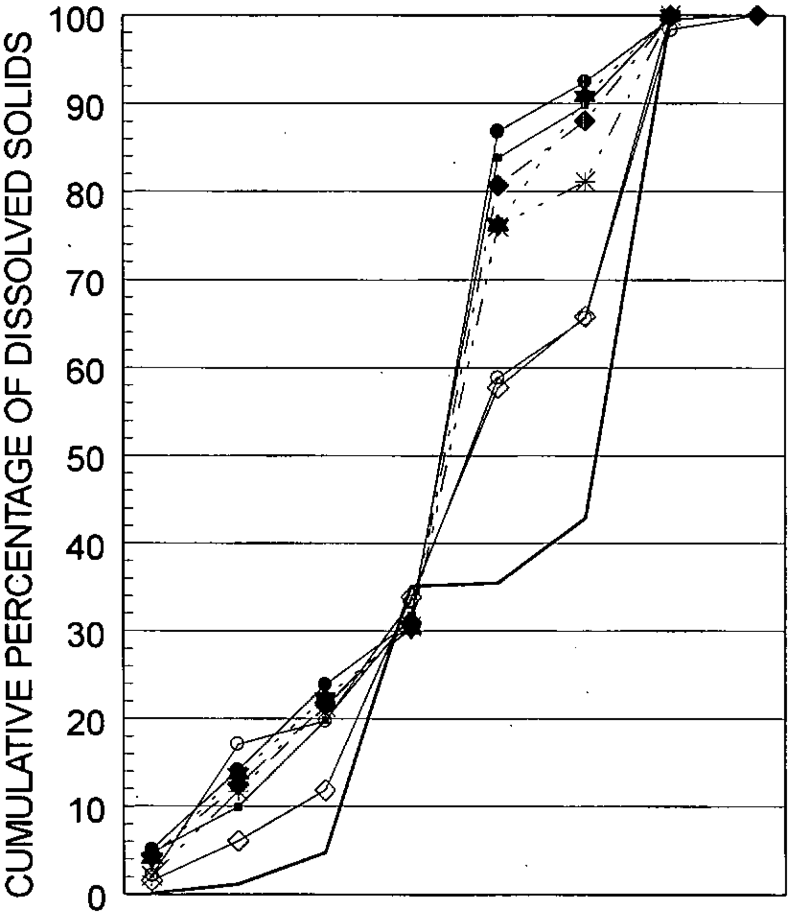
Visual evaluation of these figures indicates that most of the water samples probably represent mixtures of magnesium-bicarbonate and sodium-chloride water types. These end-member water types are best represented on the graphs by well AAB006 and sea water. The graphical signatures of the remaining wells generally lie between these end-member water types. The severity of intrusion can be inferred from the plot of each water sample relative to that of the end members. At the time of this sampling, wells AAB022, AAB026, and AAB042 were the most influenced by sea-water intrusion, although the other wells have graphical patterns that indicate various degrees of intrusion as well.

TABLE 16
Percentage of Total Dissolved Solids (TDS) by Well and Constituent

Well #	Source	SiO2	Ca	Mg	Na+K	CaCO3	SO4	Cl	NO3+NO2
AAB015	Bedrock	3.46	4.55	7.75	18.93	39.75	5.88	19.68	0.00
AAB022	Bedrock	0.91	5.64	0.02	30.81	12.45	2.25	47.92	0.00
AAB061	Bedrock	1.61	0.39	0.01	30.90	42.40	18.46	6.22	0.00
AAB006	Glacial	5.02	9.11	9.72	7.23	55.72	5.63	7.17	0.39
AAB026	Glacial	2.06	15.00	2.63	13.59	25.56	6.71	32.84	1.60
AAB038	Glacial	4.70	5.23	9.90	11.92	52.07	6.02	10.09	0.07
AAB042	Glacial	1.54	4.55	5.75	22.00	23.89	8.06	34.18	0.03
AAB046	Glacial	2.03	9.71	9.67	9.07	45.50	5.15	18.87	0.00
AAB051	Glacial	4.40	8.05	9.08	9.43	49.70	7.37	11.85	0.11
AAB069	Glacial	4.11	9.63	8.63	7.85	45.96	14.67	9.14	0.00
	Seawater	0.02	1.15	3.60	30.32	0.35	7.43	57.12	0.00

Figure 13A

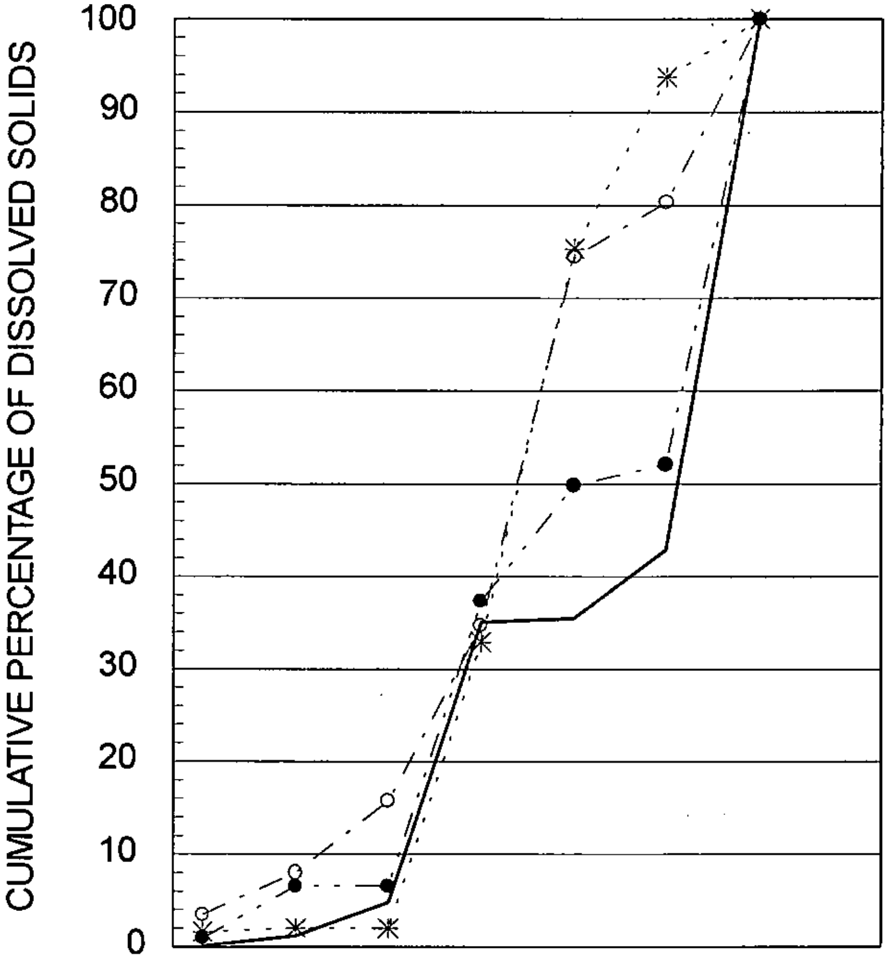
Cumulative Percentage Composition of Marrowstone Island Ground Water From Wells Completed in Glacial Sediments



	SiO_2	Ca	Mg	Na+K	$CaCO_3$	SO_4	Cl	NO_3+NO_2
SEAWATER —	0.02	1.17	4.78	35.09	35.44	42.88	100.00	
AAB006 ●	5.02	14.13	23.86	31.08	86.81	92.44	99.61	100.00
AAB026 ⊖	2.06	17.07	19.70	33.29	58.85	65.56	98.40	100.00
AAB038 -▪-	4.70	9.93	19.83	31.75	83.82	89.84	99.93	100.00
AAB042 ◇	1.54	6.09	11.85	33.85	57.74	65.80	99.97	100.00
AAB046 ✳	2.03	11.74	21.41	30.48	75.98	81.13	100.00	
AAB051 ◆	4.40	12.45	21.53	30.97	80.67	88.04	99.89	100.00
AAB069 ✶	4.11	13.74	22.37	30.22	76.18	90.85	100.00	

Figure 13B

Cumulative Percentage Composition of Marrowstone Island Ground Water From Wells Completed in Bedrock



	SiO2	Ca	Mg	Na+K	CaCO3	SO4	Cl	NO3+NO2
AAB015 ○	3.46	8.01	15.76	34.69	74.44	80.32	100.00	
AAB022 ●	0.91	6.55	6.57	37.38	49.83	52.08	100.00	
AAB061 ✳	1.61	2.00	2.01	32.91	75.32	93.77	100.00	
SEAWATER —	0.02	1.17	4.78	35.09	35.44	42.88	100.00	

Mixing Diagrams

The process of sea-water intrusion causes freshwater to mix with sea water within the advancing zone of diffusion. If one knows the chemical composition of the end member water types (non-intruded fresh water and sea water) one can, through use of the following equation, predict the theoretical composition of water derived by mixing various percentages of each end member (Richter and Kreitler, 1991).

$$CM = X*CF+(1-X)*CS \rightarrow X=(CS-CM)/(CS-CF)$$

Where
CM = Constituent concentration in mixed water,
CF = Constituent concentration in fresh water,
CS = Constituent concentration in sea water,
X = Fraction of fresh water in the mixture, and
1-X = Fraction of sea water in the mixture.

The mixing lines shown in Figure 14 represent the theoretical constituent concentrations one would expect if various proportions of non-intruded ground water and sea water from Admiralty Bay were mixed, and no other chemical reactions occurred (Tables 17 and 18). We selected the sample from well AAB006 to represent the non-intruded ground-water composition, based on its relatively low chloride and TDS concentrations.

TABLE 17
Constituent Concentrations (mg/L) in Water from
Well AAB006 and Admiralty Bay (Culhane, 1993)

	Constituent					
Source	Cl	SO4	Ca	Mg	K	Na
AAB006	24.7	19.4	31.4	33.5	3.3	21.6
Ad. Bay Seawater	17600	2290	355	1110	341	9000

TABLE 18
Theoretical Mixing Concentrations by Constituent for Well AAB006 and Admiralty Bay Seawater

Percent Freshwater	Percent Seawater	Constituent Concentration (mg/L)					
		Cl	SO4	Ca	Mg	K	Na
100	0	24.7	19.4	31.4	33.5	3.3	21.6
99.9	0.1	42.27	21.67	31.72	34.58	3.64	30.58
99.8	0.2	58.85	23.94	32.05	35.65	3.97	39.56
99.7	0.3	77.42	26.21	32.37	36.73	4.31	48.53
99.6	0.4	95	28.48	32.69	37.8	4.65	57.51
99.5	0.5	112.6	30.75	33.02	38.88	4.98	66.5
99	1.0	200	42.1	34.64	44.26	6.67	111.4
98.5	1.5	288	53.46	36.25	49.65	8.35	156.3
98	2	376	64.81	37.87	55.03	10.03	201.2
97	3	552	87.52	41.11	65.79	13.4	290.9
96	4	728	110	44.34	76.56	16.77	380.7
95	5	903	132.9	47.58	87.33	20.13	470.5
94	6	1079	155.6	50.82	98.09	23.5	560.3
93	7	1255	178.3	54.05	108.85	26.87	650.1
92	8	1431	201	57.29	119.62	30.24	739.9
91	9	1606	223.8	60.52	130.39	33.6	829.7
90	10	1782	246.5	63.76	141.15	36.97	919.4

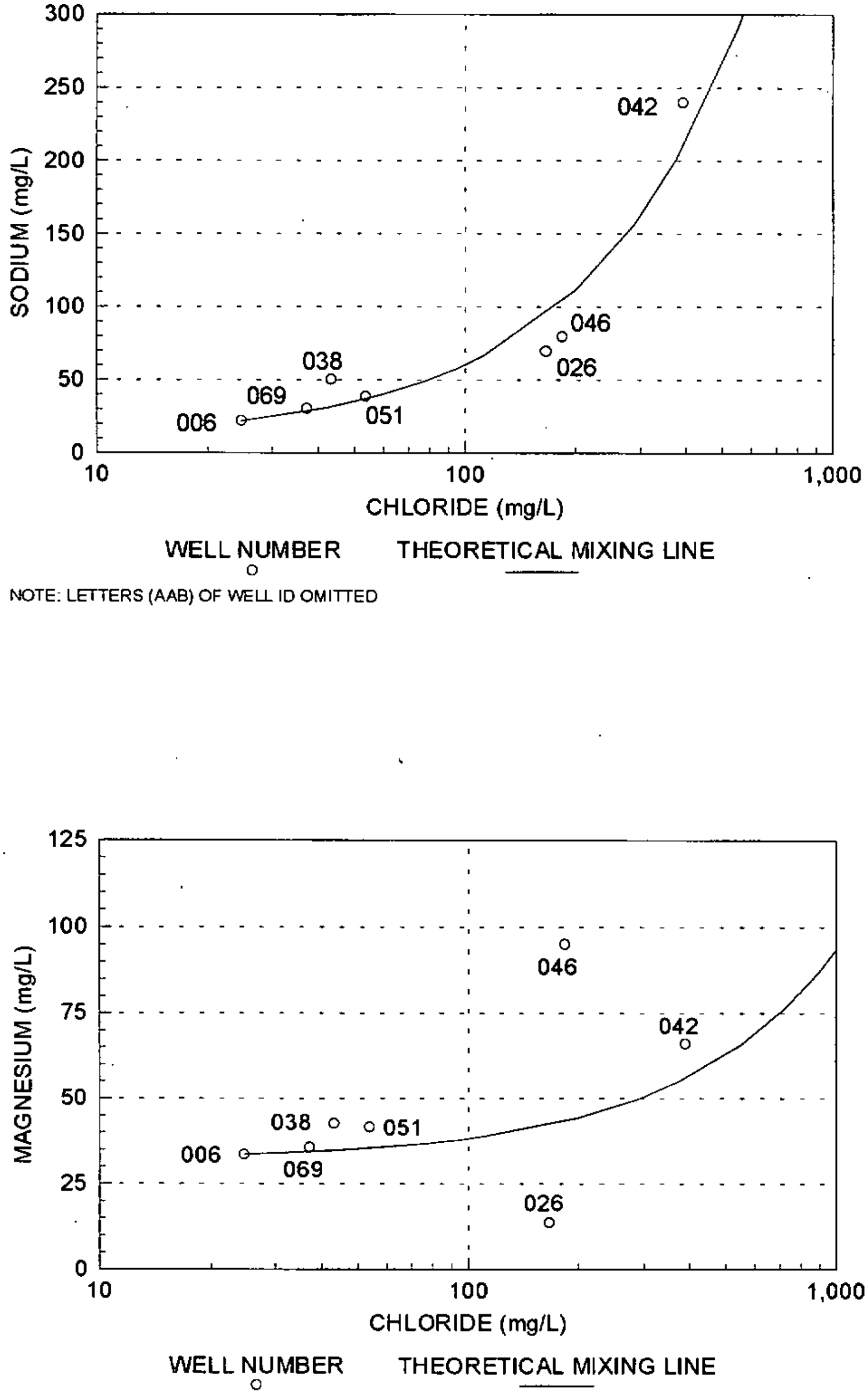
The numbered samples plotted adjacent to the theoretical mixing lines on Figure 14 are the actual constituent concentrations determined from our May, 1990 sampling of 7 glacial wells (Appendix C, p. C-9). Large sample deviations from the theoretical mixing line, as seen for calcium in wells AAB026 and AAB046, may be explained by ionic exchange processes, where by the excess or deficit of one cation/anion is balanced by the deficit or excess of another.

These figures reveal that constituent concentrations for the sampled wells generally follow the theoretical mixing line. This substantiates our initial assumption that elevated chloride concentrations in the island's ground water result from sea-water intrusion. Further, all wells included in this analysis (with the exception of well AAB006 which defined our fresh-water end member) are effected by sea-water intrusion to some extent.

The amount of sea water required to produce the sample compositions of the seven wells used in this example is quite small. The sample from well AAB042, the most highly intruded of those depicted in Figure 14, probably consists of about 98 percent fresh water and two percent sea water. The remaining samples probably contain less than one percent sea water.

Figure 14

Mixing Diagrams

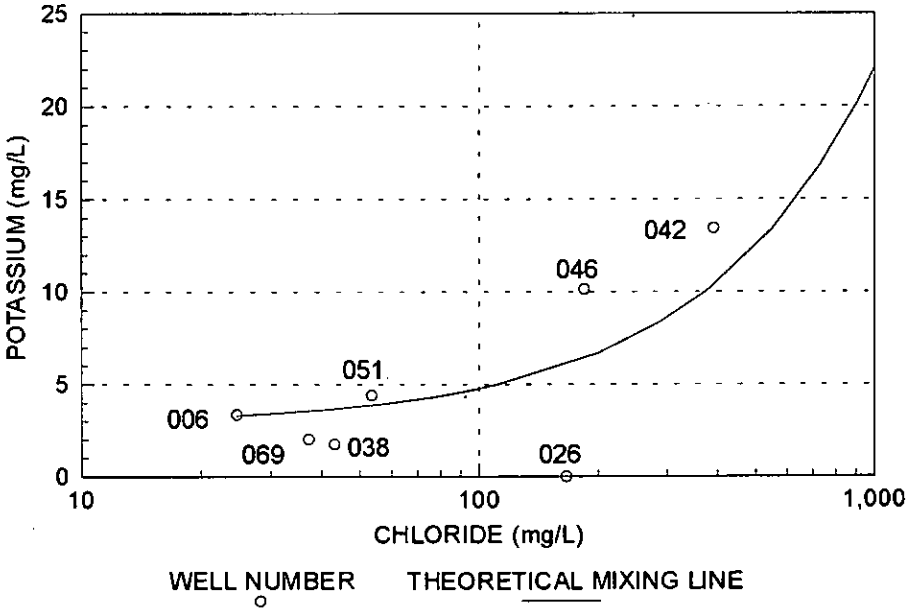


NOTE: LETTERS (AAB) OF WELL ID OMITTED

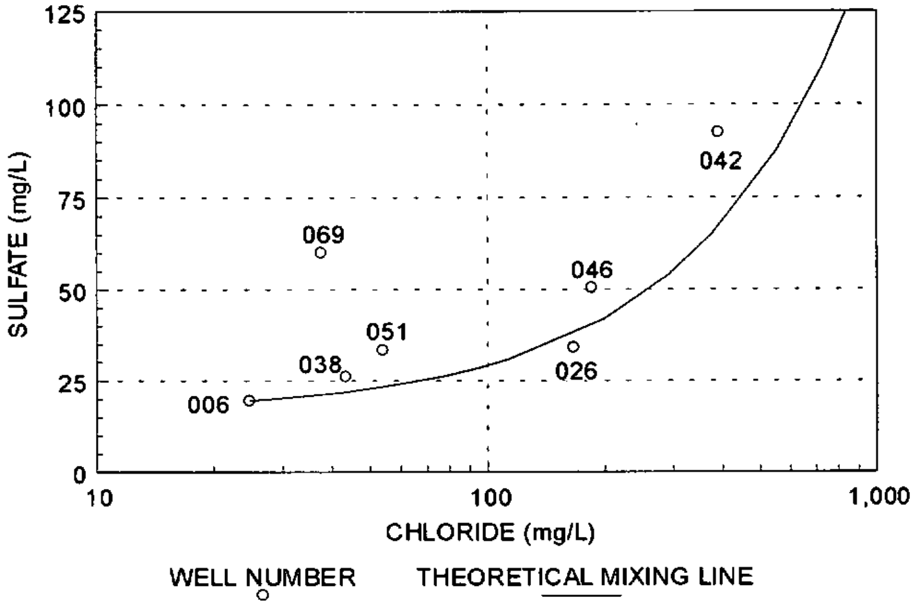
NOTE: LETTERS (AAB) OF WELL ID OMITTED

Figure 14 (continued)

Mixing Diagrams



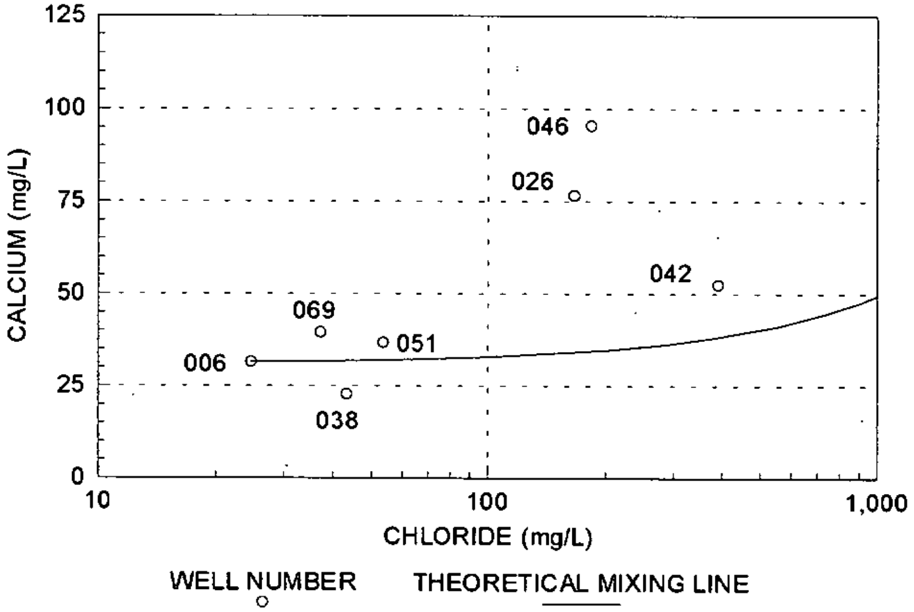
NOTE: LETTERS (AAB) OF WELL ID OMITTED



NOTE: LETTERS (AAB) OF WELL ID OMITTED

Figure 14. (continued)

Mixing Diagrams



NOTE: LETTERS (AAB) OF WELL ID OMITTED

Trilinear Diagrams

Trilinear diagrams are another means of conveniently representing the chemical composition of several samples on a single graph, thereby enabling one to identify data groupings or trends (Piper, 1944). Trilinear diagrams are constructed by plotting the percentage composition (expressed in milliequivalents) of major cations and anions on triangular graphs. The major cations (calcium, magnesium, and the sum of sodium and potassium) are plotted on one triangle, while the major anions (chloride, sulfate, and the sum of carbonate and bicarbonate) are plotted on a second triangle (Figure 15). Each of the triangle apexes represents a 100 percent concentration of one of the represented ions. The triangle sides represent a zero percent concentration. Samples containing only two of the represented ions in a triangle will plot along the line connecting the apexes for these ions. Samples containing three or more of the represented ions will plot in the triangle interior.

The diamond area between the triangles represents the total sample composition with respect to cations and anions. Sample compositions here are derived by projection. From the cation point for a sample, an imaginary line is projected into the diamond interior parallel to the magnesium axis. There it intersects another line projected parallel to the sulfate axis from the anion point. The point defined by the intersection of these projections represents the total sample composition.

Mixed waters comprised of two different water types, such as fresh-ground water and sea water, plot roughly in a line on these diagrams, with each of the pure non-mixed water types defining one of the line ends. Highly-intruded ground water plots near the sea water end member, while less intruded ground water plots near the non-intruded fresh-water end member.

The sample plots for Marrowstone Island demonstrate this (Figure 15). Chloride concentrations for both the glacial and bedrock wells plot in a linear pattern characteristic of sea-water intrusion. The fresh-water end members are best defined by samples AAB006 (glacial wells) and AAB061 (bedrock wells) with Admiralty Bay sea water defining the other pure end member for each graph. The remaining mixed-water types plot between the end-member water types, based on the relative proportions of the end members which comprise them.

The distribution of sample points on the graphs indicates that all the glacial wells evaluated, with the exception of AAB006, are affected by sea-water intrusion. Like the other graphical methods, this analysis indicates that the elevated chlorides in Marrowstone Island ground water originated from the mixing of fresh-ground water and sea water.

Figure 15

Trilinear Diagram Showing Percentages of Major Ions in Water From Glacial Wells

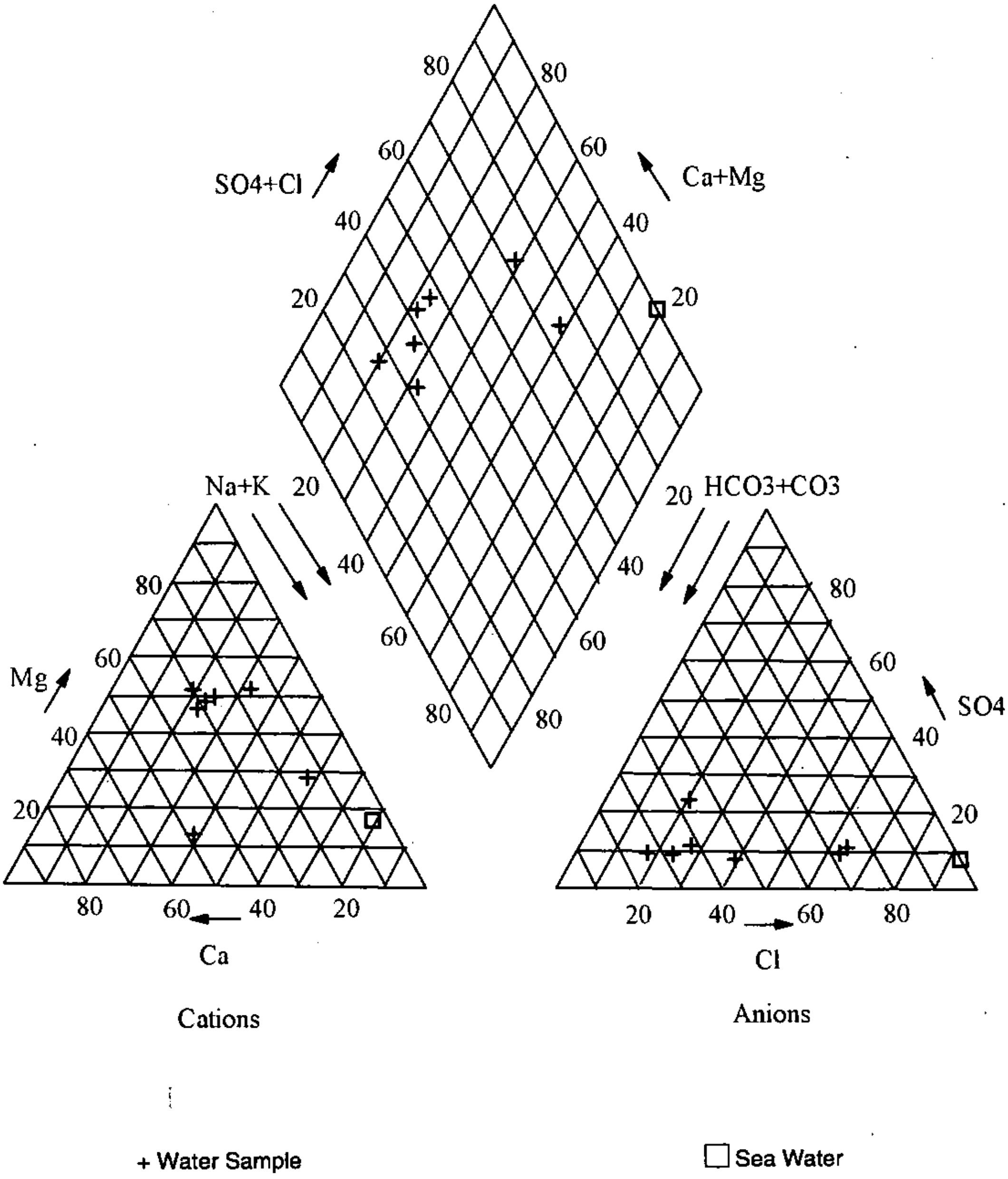
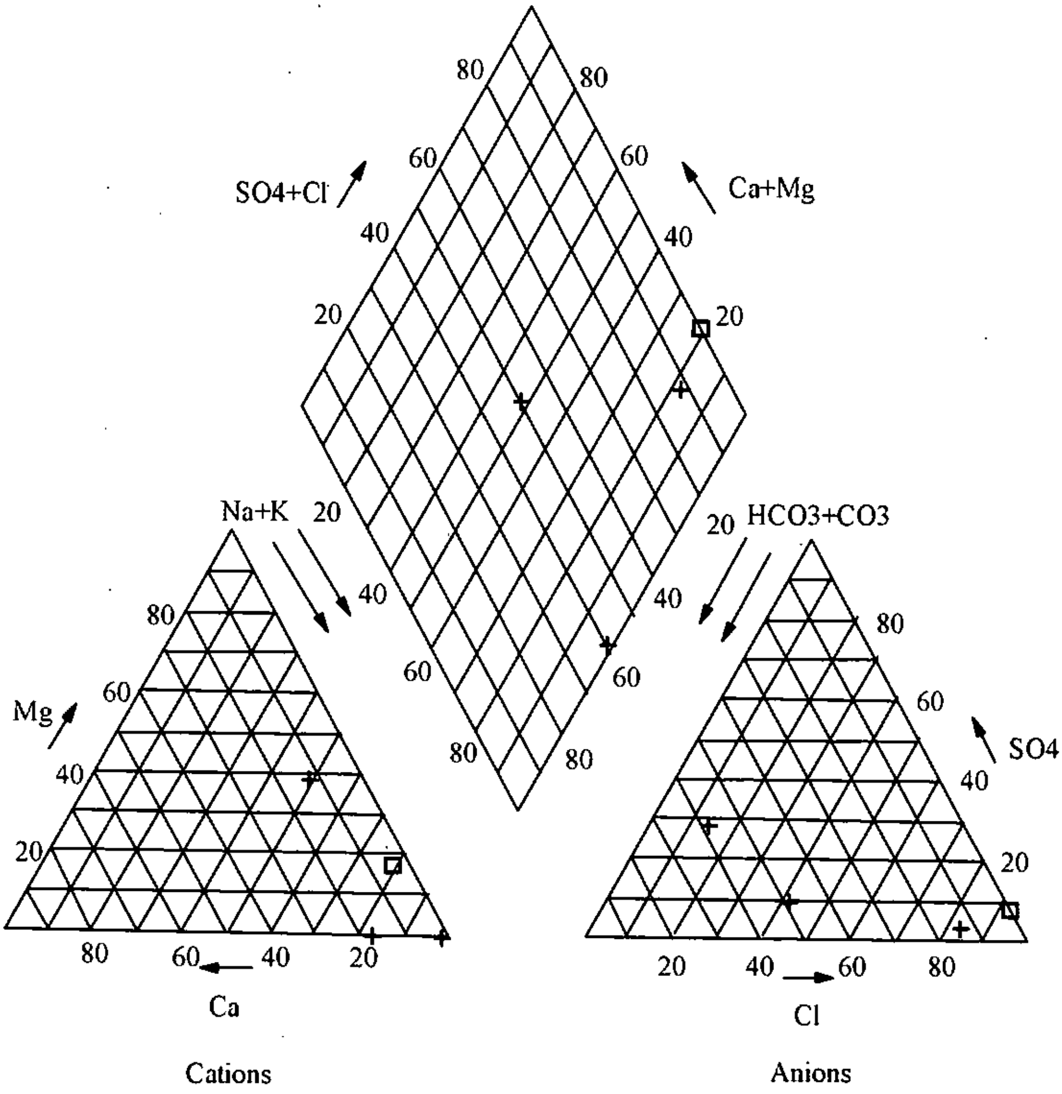


Figure 15. (continued)

Trilinear Diagram Showing Percentages of Major Ions in Water From Bedrock Wells



+ Water Sample

☐ Sea Water

Summary and Conclusions

Ground-Water Hydrology

Marrowstone Island's ground water is contained within two distinct hydrogeologic units: 1) Eocene bedrock consisting of fractured sandstone and shale and 2) the overlying Pleistocene glacial drift composed of sand, gravel, silt, and minor clay. The drift deposits contain the most productive aquifers on the island.

Wells completed in the glacial sediments have specific capacities ranging from less than 0.01 to more than 30 gpm/ft of drawdown, with an average about 7.2 gpm/ft of drawdown (Plate 6 and Table 7). The bedrock aquifers are generally less productive and have specific capacities ranging from less than 0.01 to 1.5 gpm/ft of drawdown, with an average of about 0.19 gpm/ft of drawdown (Plate 6 and Table 7).

The island's aquifers are recharged by local precipitation which averages approximately 20.4 inches per year. Based on a mean annual water-budget analysis for the island, approximately 2.2 inches or 11 percent of total precipitation, is available for ground-water recharge during the period January-March. Precipitation variations between the north and south ends of the island have noticeable affects on the island's hydrology, particularly ground-water recharge. Ground-water heads in the drift aquifer are lower (closer to sea level) at the north end of the Island than at the southern end where precipitation, hence recharge, is higher.

Water Quality

Marrowstone Island's ground water is generally acceptable for drinking water. With exceptions for chloride, TDS, and pH, the inorganic constituents we evaluated were within acceptable MCL ranges. The ground water is generally hard to very hard. Total hardness ranged from 8 to 627 mg/L (expressed as $CaCO^3$) with a median concentration of 237 mg/L. The ground water consists largely of mixed water types derived from sodium-chloride and magnesium-bicarbonate end members.

Eleven wells, or about 24 percent of those sampled, had chloride concentrations in excess of the MCL of 250mg/L, while 21 wells, or 46 percent, had concentrations in excess of the chloride concentration threshold of 100 mg/L which indicates sea-water intrusion (Dion and Sumioka, 1984). Twenty-three wells, or 50 percent of those sampled, exceeded the MCL for TDS, while 4 wells (8.6 percent) exceeded the MCL for pH.

Chloride concentrations tend to be lower in the island interior than they are near the coast. Chloride concentrations tend to be highest in wells that are completed below sea level.

South of Meade Road, chloride and TDS concentrations are generally low, where most wells have median chloride values less than 50 mg/L. Wells there withdraw water primarily from the glacial-drift aquifer which lies at elevations slightly above to slightly below sea level.

North of Meade Road, chloride and TDS concentrations are typically higher, with 16 of 26 wells sampled having median chloride values greater than 100 mg/L.

Wells that withdraw water from the bedrock aquifers of Griffith's Point and Nodule Point generally have median chloride concentrations less than 100 mg/L.

Exceptions to these general trends occur throughout the island where localized instances of high water use in areas of generally good quality cause elevated chloride values and vice versa.

Sea-Water Intrusion

We used five analytical methods, with varying degrees of success, to identify sea-water intrusion on Marrowstone Island: (1) chloride concentrations compared to the 100 mg/L threshold; (2) ion ratios and grouping by water types; (3) graphic data plots including cumulative percentages of TDS, mixing diagrams, and trilinear diagrams. Sea-water intrusion was indicated by all five methods (Table 19). Perhaps the agreement of results between multiple methods as applied to a single sample, provides the best approach for reliably detecting sea-water intrusion.

TABLE 19
The Analytical Methods Used:
In Which Wells Did They Indicate Sea-Water Intrusion?

Well Number	Analytical Methods				
	100 mg/L Chloride Standard	Ion Ratios	Cumulative % of TDS	Mixing Diagrams	Trilinear Diagrams
AAB006	No	No	No	No	No
AAB026	Yes	Yes	Yes	Yes	Yes
AAB038	No	No	Yes	Yes	Yes
AAB042	Yes	Yes	Yes	Yes	Yes
AAB046	Yes	Yes	Yes	Yes	Yes
AAB051	No	No	Yes	Yes	Yes
AAB069	No	No	Yes	Yes	Yes
AAB015	No	Yes	Yes	---	Yes
AAB022	Yes	Yes	Yes	---	---
AAB061	No	Yes	Yes	---	---

The oft-used 100 mg/L chloride concentration threshold is a reliable indicator of intrusion, but, by definition, sea-water intrusion is already a problem by the time it is identified. Analysis of major dissolved ions makes it possible to identify incipient sea-water intrusion while chloride concentrations are relatively low. The use of ion ratios and water typing (trilinear diagrams) appear to provide reliable mechanisms for identifying sea-water intrusion.

Sea-water intrusion has been a problem on Marrowstone Island since people first settled there (Russell and Bean, 1978). The early problems were site-specific and were mostly caused by wells being located too close to the shoreline. As the island population increased, sea-water intrusion problems became more widespread. The cause of the problem gradually changed from one of poor well siting to one of pumping stress on the aquifers. Annual recharge from precipitation is a finite resource and the amount stored in the small aquifers changes greatly with pumping. Although annual consumptive use of ground-water is only about five percent of the annual recharge, this is enough to significantly affect the already small ground-water flux through the island's aquifers. On such a small island, minor reductions in the hydraulic head can cause what seem like inordinately high incidence of sea-water intrusion.

Recommendations for Marrowstone Island

Ground water, and to some extent rainfall-catchment systems, provide the only affordable and reliable source of fresh water on Marrowstone Island. Water conservation provides the best (and, essentially, only) means of preventing additional intrusion on the Island. Some measures that would help to decrease or prevent the spread of sea-water intrusion on the island are:

- Continue educating residents about the importance of efficient water use;
- Require that water-conserving devices such as low-volume toilets and plumbing fixtures be installed during construction of new residences, or during ownership changes of existing residences;
- Condition building permits for new residential construction to limit ground-water use to potable in-house uses only. Encourage residents to use alternative water sources such as rainfall collection systems and cisterns to supplement water needs;
- Through the building permit process, require that existing residences be retrofitted with water conserving toilets and fixtures when they are remodeled;
- Develop incentive programs to encourage residents to retrofit established residences with water conserving toilets and fixtures and to redesign outdoor watering systems to minimize water use;
- Educate residents about methods to eliminate waste of potential ground-water recharge. For example, currently there are numerous pipes that divert roof runoff or wetland waters directly to the sea. Roof runoff could possibly be piped to inland detention basins or dry wells to supplement recharge;
- Wetlands should not be drained since they may play an important role in the recharge of Marrowstone Island aquifers;
- Require full inorganic analyses of water samples from newly constructed wells. This information will reveal areas of incipient intrusion where chloride concentrations may still be relatively low;
- Enlist a group of Island residents to periodically monitor water levels in selected wells, to gain more data on the island's seasonal and long-term ground-water-level fluctuations. The wells should be equipped with totalizing flow meters to enable concurrent tracking of water use. In selecting wells for monitoring, care should be taken to choose wells that show little tidal influence. Tidal influence on each monitoring well should be carefully quantified so correction factors can be developed. Long-term water-level and water-use monitoring will help to detect whether ground-water use is exceeding recharge. If possible, the land-surface elevations for these wells should be surveyed to allow one to interpret the direction of ground-water flow and the relative distribution of head in the island's aquifers;
- Enlist a group of island residents to expand the precipitation monitoring network. Such information is necessary to better define aquifer recharge patterns and to interpret ground-water level information;
- Re-sample the wells monitored during this and previous USGS studies at least once every 2-3 years for chlorides. We recommend that the sampling be done during June to be comparable to previously collected data for these wells.

Recommendations for Other Sea-Water Intrusion Studies

Our work on Marrowstone Island has made it clear that there are common factors that should be considered in all sea-water intrusion studies. These factors include (not in order of preference or importance):

- Establish a ground-water-level and water-quality monitoring network:
  - In designing a network for long-term water quality monitoring, it is important to obtain a representative sampling of the major aquifers and formations within the area of concern. Wells should be selected with this in mind. Wells used for water-level monitoring may also serve as water-quality monitoring wells. Water levels should be measured as part of each sampling event.
  - Water-level monitoring wells should be selected with the goal of establishing a monitoring network that will define ground-water heads and gradients in each aquifer of interest. Both up-gradient and near-shore wells should be used and all should be available for collection of base-line as well as long-term data.
  - Whenever possible, non-pumping wells dedicated only to monitoring should be used to avoid unpredictable pumping effects. If non-pumping wells are not available, wells with predictable pumping schedules, such as single-domestic wells at part-time homes for the owners, should be sought out. If full-time residential wells are used, they should, as much as possible, be wells with high specific capacities that have relatively low draw down and quick recovery from pumping.
  - Tidal influence on each monitoring well should be carefully quantified so correction factors can be calculated.
  - Well logs with lithology and well-construction information is essential for each monitoring well.
  - The well-head elevation should be accurately established for each monitoring well.
  - Each monitoring well should be tagged with a Washington Dept. of Ecology Unique Well Number to facilitate data tracking and manipulation.
- Establish base-line water-level and water-quality data sets:
  - Up-gradient control wells should be used to help define base-line regional gradients.
  - All wells included in the monitoring network should be sampled initially for field parameters (temperature, conductivity, and pH) and common inorganic constituents to define a base line data set, and to define areas that initially have sea-water intrusion problems.
  - Up-gradient control wells that are not significantly affected by intrusion should be monitored to define base-line end-member water types for each aquifer.
- Identify established precipitation stations in the area of interest.
  - Official stations such as those at airports, cities, Coast Guard stations, and National Weather Service locations are important in that they provide reliable, long-term data.
  - Precipitation stations run by private citizens (HAM radio operators can be an excellent precipitation data source) can provide valuable local precipitation data.

- Set up a regular schedule of more frequent monitoring for at least one year to determine seasonal effects on ground-water levels and water quality.
  - Following the initial baseline sampling, quarterly monitoring of field parameters (temperature, pH, and specific conductance) should be initiated for those wells that are intruded, or appear to be at particular risk of intrusion. If conductivity values vary significantly, during subsequent monitoring events, from those determined during the initial base line sampling, a sample should be collected for laboratory analysis of chloride concentrations. Maintain a graph of specific conductance versus chloride concentration.
  - Monitor water levels to observe seasonal changes in local and regional heads and gradients. Monthly water-level monitoring is the preferred frequency or, failing that, quarterly measurements are the minimum frequency.
  - After the base-line chloride concentration data has been established and sea-water intruded areas have been identified, areas deemed at risk of intrusion should be sampled and analyzed for major anion and cation concentrations. As explained in our water quality discussion, the cation/anion balance analysis can be used to detect incipient sea-water intrusion.
- Design and implement a long-term monitoring program to detect changes, over time, in regional ground-water gradients and water quality.
  - Long-term monitoring of ground-water levels, plus collection of ground-water samples, and precipitation data can be capably handled by citizen volunteers - if they are available.
  - Initiate long-term precipitation data collection if such data is not available through conventional public sources.
  - Long-term monitoring of water levels should be conducted to monitor local and regional heads and gradients. This should be used to assure that ground-water development is not reducing regional or local heads and inducing passive sea-water intrusion.
  - Re-sample the same chloride sampling wells for chloride analysis at least once every 2-3 years. The sampling should be done during the same month of each year to be comparable to previously collected data.
  - Re-sample the same wells for cation/anion balance every 2 to 3 years. These analyses will provide a means of early detection of incipient sea-water intrusion.

Glossary

advance outwash: Sediments deposited by glacial melt-water streams in front of and along the margins of a glacier as it advances.

anion: A negatively charged ion.

aquiclude: A geologic formation, group of formations, or part of a formation through which virtually no water moves. (Driscoll, 1986)

aquifer: The water saturated portions of a formation or group of formations that are capable of yielding water to a well in useful quantities.

aquifer test: A test designed to determine the hydraulic characteristics of an aquifer. This is accomplished by pumping a well and monitoring the resultant drawdown with respect to time, in the pumping well and nearby observation wells.

aquitard: A formation, group of formations, or part of a formation of lower hydraulic conductivity than surrounding aquifers. Aquitards may or may not be saturated and tend to inhibit the movement of water between aquifers.

bailer test: A method, used by cable tool drillers, to determine the yield of a well. This method consists of bailing the well and recording the rate at which the water is removed. The drawdown is also noted as the well is bailed. After bailing at a more or less constant rate for some period of time the drawdown will stabilize somewhat. In this way a rough measure of the well's potential yield can be obtained (Driscoll, 1986).

calcite: A common rock forming mineral composed of calcium carbonate ($CaCO^3$).

cation: A positively charged ion.

clastic: A rock or sediment composed principally of broken fragments from preexisting rocks or minerals (Gary and others, 1974).

concretion: A hard, normally sub-spherical mass or aggregate of mineral matter, contained within the pores of a sedimentary or fragmental volcanic rock. Concretions are generally formed by localized precipitation of minerals from an aqueous solution. (Gary and others, 1974)

cone of depression: The decline in total head around a well resulting from withdrawal of water from an aquifer.

confined aquifer: An aquifer contained between two confining layers. The water level in wells completed in confined aquifers rises above the top of the aquifer.

confining layer: A relatively impermeable geologic formation that isolates an aquifer from the atmosphere or other aquifers. Synonyms: aquitard and aquiclude.

cross-stratified sets: See "cross-stratum."

cross-stratum: a single layer of homogeneous or gradational lithology deposited at an angle to the original dip of the formation and separated from adjacent layers by surfaces of erosion, non-deposition, or abrupt change in character. A *set* is a group of essentially conformable strata or cross-strata, separated from other sedimentary units by surfaces of erosion, non-deposition, or abrupt change in character (McKee and Weir, 1953).

data logger: An instrument used in conjunction with a transducer to automatically collect, record, and store electronic water-level data at specific pre-determined time intervals.

diagenesis: Physical, chemical, or biologic rock-forming processes which, at low temperature and pressure, lead to sediment compaction, consolidation, and cementation.

dike: A tabular intrusion that cuts across the planar structures of the surrounding rock (Gary and others, 1974).

depositional environment: The environment that existed during the deposition of the sediments.

detritus: A collective term for loose rock and mineral material that is worn off or removed directly by mechanical means; esp. fragmental material, such as sand, silt, and clay, derived from older rocks and moved from its place of origin (Gary and others, 1974).

discharge 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, seep, or baseflow, or by evaporation and transpiration (Fetter, 1980).

drawdown: Pumpage induced water level decline in a well.

drift: A general term applied to glacially transported rock material (clay, sand, gravel, or boulders) deposited by or from glacial ice, or by water emanating from a glacier (Gary and others, 1974).

effective porosity: The interconnected spaces between particles in a porous medium through which water can move. Effective porosity is expressed as a percentage of total bulk volume.

epoch: A term used to designate a length of geologic time; e.g. glacial epoch (Gary and others, 1974).

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

evapotranspiration, actual: The evapotranspiration that actually occurs under given climatic and soil-moisture conditions (Fetter, 1988).

evapotranspiration, potential: The evapotranspiration that would occur under given climatic conditions if there were unlimited soil moisture (Fetter, 1988).

feldspathic: Said of a mineral aggregate containing feldspar. A feldspathic sandstone is a feldspar-rich sandstone.

fissile: A term used to describe rocks which are easily split into thin sheets or layers along closely spaced bedding or cleavage planes (Gary and others, 1974).

flux: Rate of flow.

fluvial: A sedimentary deposit consisting of material transported by, suspended in, or laid down by a river or stream (Gary and others, 1974).

formation: The basic or fundamental rock-stratigraphic unit in the local classification of rocks, consisting of a body of rock generally characterized by some degree of internal lithologic homogeneity or distinctive geologic features, by a prevailing but not necessarily tabular shape, and by mappability at the Earth's surface or traceability in the subsurface. (Gary and others, 1974)

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

glaciomarine: A term that refers to marine sediments which contain glacially derived materials (Gary and others, 1974).

heterogeneous: A term used to describe a substance comprised of different materials, or to describe a material, such as an aquifer, whose properties (i.e. porosity, hydraulic conductivity, etc.) are not uniformly distributed with respect to location.

homogeneous: Uniform in structure and composition throughout.

hydraulic conductivity: An aquifers ability 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 head in an aquifer with respect to horizontal distance. Expressed as h/d where h is the difference in total measured head between two points in an aquifer that are separated by horizontal distance, d.

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

head: The pressure exerted by a water mass at any given point. Total head is the sum of elevation head, pressure head, and velocity head.

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

ion: An electrically charged atom or group of atoms.

interglacial deposits: Material or sediment deposited between two successive glacial epochs or stages.

leaky confining layer: A geologic formation that transmits water at significantly lower rates than adjacent aquifer materials, but through which water still flows. Synonym: aquitard.

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

lithosphere: 1. The solid part of the earth. 2. The earth's rocky crust. 3. The silicate shell of the Earth which includes the mantle and crust and is part of the classification lithosphere, hydrosphere, atmosphere, and biosphere (Dennis and Atwater, 1974).

milliequivalents per liter: A method of reporting water chemistry data as equivalent units, there by accounting for differences in the weight and charge of dissolved ionic constituents. The concentration of dissolved ionic constituents, expressed in units of mg/L, can be converted to milliequivalents per liter by dividing the formula weight of the constituent by its ionic charge, and then multiplying the reciprocal of this result by the constituent concentration.

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

outwash: Stratified detritus (chiefly sand and gravel) removed or "washed out" from a glacier by meltwater streams and deposited in front of or beyond the terminal moraine or along the margin of an active glacier. Outwash deposited during glacial advance is called advance outwash, while outwash deposited during glacial retreat is referred to as recessional outwash. (Gary and others, 1974)

paleosol: A buried soil horizon of the geologic past. (Gary and others, 1974)

piezometer: A well with a short screened interval installed to measure total head at a specific location and depth.

plate tectonics: A theory of global tectonics in which the Earth's lithosphere is divided into a number of plates whose pattern of horizontal movement is that of rigid bodies which interact with one another at their boundaries, causing seismic and tectonic activity along these boundaries (Dennis and Atwater, 1974)

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: An imaginary surface defined by plotting the measured head of wells completed in a confined aquifer. This concept is valid only for those aquifers that do not have large vertical gradients.

primary porosity: See "porosity."

recharge 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 melt-water streams in front of and along the margins of a glacier as it retreats.

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

secondary porosity: See "porosity".

semi-confined aquifer: A formation 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 water table aquifers. Semi-confined conditions are caused by a local lens of impermeable material overlying a portion of a larger aquifer system or by a leaky confining layer.

soil moisture holding capacity: The maximum amount of water that the unsaturated zone of a soil can hold against the pull of gravity - also known as "field capacity."

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: The ability of water to conduct electricity. Measured in µmohs/cm at 25° C. Synonym: conductivity.

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.

stade: A climatic episode within a glacial stage during which a secondary advance of glaciers occurred (Gary and 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.

subduction: The process of one lithospheric plate descending beneath another (Dennis and Atwater, 1974).

subduction zone: An elongate region along which one of the earths crustal blocks descends beneath another by folding, faulting, or both, (e.g. the decent of the Farallon plate beneath the North American plate off the Washington coast).

tectonism: A term used to describe all movement of the Earth's crust produced by Earth forces, including the formation of ocean basins, continents, plateaus, and mountain ranges. Synonym: diastrophism (Gary and others, 1974).

thermal metamorhism: A type of metamorphism resulting in chemical reconstitution controlled by temperature and influenced to a lesser extent by the confining pressure (as a function of depth): there is no simultaneous deformation (Gary and others, 1974).

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

tombolo: A sand or gravel bar (or spit) that connects an island with the mainland or another island (Gary and others, 1974).

transducer: An instrument that, when placed below water level in a well, measures water level changes based on the change in pressure induced by the height of the water column standing above the instrument.

transgression: The spread or extension of the sea over land areas, resulting from a rise in sea level or land subsidence.

transmissivity: The rate that water of prevailing kinematic viscosity is transmitted through a unit width of aquifer under a unit hydraulic gradient. Transmissivity is equal to the aquifer hydraulic conductivity multiplied by aquifer thickness.

transpiration: Water vapor transferred to the air through plants.

type section: The original sequence of strata as described for a given locality or area (Gary and others, 1974).

unconfined aquifer: An aquifer that is not separated from land surface by an intervening confining layer.

unconformity: A substantial break or gap in the geologic record where a rock unit is overlain by another that is not next in stratigraphic succession.

underflow: Water that infiltrates into the soil on a slope and moves down slope as lateral unsaturated flow in the soil zone, also referred to as "throughflow."

unsaturated zone: That portion of the earth's subsurface which contains both air and water. Synonym: Vadose zone.

upconing: When fresh-water head is lowered sufficiently and sea water rises as a cone and moves toward a well from underneath (see figue 12-D)

vadose zone. See "unsaturated zone."

water budget: A conceptual evaluation of water movement in an aquifer or drainage basin with respect to water input versus water discharged from the system.

water table: That level in the saturated zone where pressure is equal to atmospheric pressure.

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.

well interference: The unacceptable water level decline in a well, as a result of pumping another well.

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Appendix A
Ground-Water Level Information

Unique Well Number	Well Location	Latitude	Longitude	Land Surface Elevation (Ft msl)	Drilled Depth (Ft)	Cased/ Lined Depth (Ft)	Open/Screened Interval (Feet Below Land Surface)	Source Aquifer	Water Level Measurement Date	Water Level (Feet Below Land Surface)	Measurement Method	Well Status
AAB004	29N/01E-09R	48°00'58"	122°40'20"	74	---	---	---	B	02/26/1990	80.4	T	
									05/25/1990	75.9	T	
									08/07/1990	135.9	T	P
									12/05/1990	72.0	T	
									03/20/1991	79.7	T	
									06/05/1991	73.4	T	
									04/21/1992	74.7	T	R
									12/08/1992	70.1	T	
AAB005	29N/01E-09G	48°01'15"	122°40'45"	118	143	141	141	G	12/17/1975	112	R	
									05/25/1990	111.4	T	
									08/07/1990	111.3	T	
									12/05/1990	111.6	T	
									03/18/1991	111.1	T	
									06/05/1991	111.3	T	
									04/21/1992	110.7	T	
									12/08/1992	110.8	T	
AAB006	29N/01E-09B	48°01'29"	122°40'43"	94	114	109	109-114	G	10/17/1989	94	R	
									02/27/1990	90.2	T	
									05/25/1990	90.4	T	
									08/07/1990	90.3	T	
									03/19/1991	90.0	T	
									06/04/1991	90.4	T	
									04/21/1992	89.7	T	
									12/08/1992	90.0	T	
AAB007	29N/01E-09A	48°01'32"	122°40'11"	70	105	100	100-105	G	02/10/1981	76	R	
									02/27/1990	75.5	T	
									05/25/1990	76.7	T	
									08/09/1990	79.4	T	
									12/06/1990	75.3	T	
									03/19/1991	76.5	T	
									06/04/1991	77.0	T	
									04/21/1992	76.4	T	
									12/08/1992	74.9	T	

Unique Well Number	Well Location	Latitude	Longitude	Land Surface Elevation (Ft msl)	Drilled Depth (Ft)	Cased/ Lined Depth (Ft)	Open/Screened Interval (Feet Below Land Surface)	Source Aquifer	Water Level Measurement Date	Water Level (Feet Below Land Surface)	Measurement Method	Well Status
AAB009	29N/01E-04L	48°01'53"	122°41'03"	113	250	120	120-250	B	10/22/1974	118	R	
									02/27/1990	116.6	T	
									05/24/1990	116.7	T	
									08/08/1990	116.8	T	
									12/05/1990	116.7	T	
									03/19/1991	116.1	T	
									06/05/1991	116.5	T	
									04/26/1992	116.2	T	
									12/07/1992	116.1	T	
									12/06/1990	122.6	T	
AAB010	29N/01E-09D	48°01'35"	122°41'10"	113	134	129	129-134	G	01/15/1983	120	R	
									02/27/1990	122.6	T	
									05/25/1990	122.6	T	
									08/08/1990	122.9	T	R
									03/20/1991	122.8	T	
									06/05/1991	122.6	T	
									04/22/1992	122.3	T	
									12/09/1992	122.6	T	
AAB011	29N/01E-09C	48°01'38"	122°40'58"	102	116	110	110-115	G	05/12/1989	104	R	
									02/27/1990	102.5	T	
									05/25/1990	102.6	T	
									08/09/1990	102.7	T	
									12/06/1990	102.7	T	
									03/19/1991	102.3	T	
									06/05/1991	102.5	T	
									04/21/1992	102.0	T	
									12/08/1992	102.3	T	
AAB012	29N/01E-08A	48°01'36"	122°41'34"	25	50	49	39-44	G	03/07/1986	31.5	R	
									02/27/1990	33.4	T	
									05/24/1990	33.0	T	
									08/08/1990	33.0	T	
									12/05/1990	31.8	T	
									03/18/1991	33.4	T	
									06/05/1991	33.5	T	
									04/22/1992	32.9	T	
									12/09/1992	31.5	T	

Unique Well Number	Well Location	Latitude	Longitude	Land Surface Elevation (Ft msl)	Drilled Depth (Ft)	Cased/ Lined Depth (Ft)	Open/Screened Interval (Feet Below Land Surface)	Source Aquifer	Water Level Measurement Date	Water Level (Feet Below Land Surface)	Measurement Method	Well Status
AAB013	29N/01E-08K	48°01'04"	122°41'48"	15	---	---	---	?	04/19/1990	20.3	T	
									05/24/1990	20.3	T	
									08/07/1990	21.0	T	
									12/05/1990	20.4	T	
									03/18/1991	23.3	T	
									06/05/1991	20.4	T	
									04/22/1992	19.8	T	
									12/07/1992	20.0	T	
AAB015	29N/01E-05H	48°02'11"	122°41'43"	10	80	24	24-80	B	02/27/1990	9.5	T	
									03/14/1990	10.0	T	
									03/15/1990	8.5	T	
									04/20/1990	9.7	T	
									05/24/1990	24.0	T	R
									07/26/1990	37.5	T	R
									08/08/1990	21.8	T	R
									12/05/1990	9.6	T	
									03/18/1991	8.4	T	
									04/22/1992	8.0	T	
									12/07/1992	11.0	T	
AAB017	29N/01E-04E	48°02'13"	122°41'20"	112	---	---	---	?	02/27/1990	119.6	T	
									05/24/1990	118.2	T	
									08/08/1990	121.9	T	
									12/06/1990	115.8	T	
									03/19/1991	117.4	T	
									06/05/1991	117.3	T	
									04/22/1992	117.9	T	
									12/10/1992	119.4	T	
AAB019	29N/01E-04J	48°01'53"	122°40'07"	65	49	45.5	43.5-49	G	06/07/1984	40	R	
									02/27/1990	41.3	T	
									05/24/1990	41.5	T	
									08/08/1990	41.7	T	
									12/07/1990	41.7	T	
									03/19/1991	41.4	T	
									06/04/1991	41.4	T	
									04/22/1992	41.0	T	
									12/08/1992	40.9	T	

Unique Well Number	Well Location	Latitude	Longitude	Land Surface Elevation (Ft msl)	Drilled Depth (Ft)	Cased/ Lined Depth (Ft)	Open/Screened Interval (Feet Below Land Surface)	Source Aquifer	Water Level Measurement Date	Water Level (Feet Below Land Surface)	Measurement Method	Well Status
AAB020	29N/01E-04E	48°02'10"	122°41'08"	165	340	130	115-120	BG	02/07/1980	105	R	
									03/16/1990	103.8	T	
									04/19/1990	103.7	T	
									05/24/1990	104.1	T	
									08/08/1990	104.5	T	
									12/05/1990	104.8	T	
									03/19/1991	103.4	T	
									06/05/1991	103.6	T	
									04/22/1992	104.2	T	
									12/11/1992	103.1	T	
AAB021	29N/01E-04E	48°02'10"	122°41'11"	140	205	94	94-205	B	04/21/1978	127	R	
									04/19/1990	154.9	T	R
									05/24/1990	182.1	T	R
									08/09/1990	131.7	T	
									12/05/1990	124.9	T	
									03/19/1991	122.8	T	
									06/05/1991	182.8	T	R
									04/22/1992	186.0	T	R
									12/09/1992	178.5	T	R
AAB022	29N/01E-04C	48°02'29"	122°40'57"	100	244	96	96-244	B	04/01/1983	105	R	
									03/16/1990	135.3	T	
									04/19/1990	138.3	T	
									08/08/1990	152.3	T	R
									12/05/1990	139.6	T	
									03/19/1991	138.9	T	
									06/04/1991	142.4	T	
									04/22/1992	142.5	T	
									12/08/1992	144.5	T	
AAB023	29N/01E-04C	48°02'31"	122°41'03"	90	344	69	69-344	B	03/28/1983	86	R	
									05/16/1990	94.2	T	
									05/24/1990	93.9	T	
									12/05/1990	91.7	T	
									03/19/1991	91.6	T	
									06/04/1991	93.2	T	
									04/22/1992	92.8	T	
									12/08/1992	93.9	T	

Unique Well Number	Well Location	Latitude	Longitude	Land Surface Elevation (Ft msl)	Drilled Depth (Ft)	Cased/ Lined Depth (Ft)	Open/Screened Interval (Feet Below Land Surface)	Source Aquifer	Water Level Measurement Date	Water Level (Feet Below Land Surface)	Measurement Method	Well Status
AAB024	30N/01E-33M	48°02'59"	122°41'08"	50	58	56	48-52	G	03/25/1984	51	R	
									03/16/1990	51.1	T	
									05/24/1990	51.4	T	
									08/08/1990	51.5	T	
									12/05/1990	50.1	T	
									03/19/1991	51.1	T	
									06/04/1991	51.7	T	
									04/22/1992	50.6	T	
									12/09/1992	50.1	T	
AAB025	30N/01E-33F	48°03'05"	122°41'03"	75	70	69	56-61	G	11/08/1982	59	R	
									03/16/1990	59.0	T	
									04/19/1990	59.3	T	
									05/24/1990	59.2	T	
									08/08/1990	59.3	T	
									12/05/1990	53.2	T	
									03/19/1991	58.9	T	
									06/04/1991	59.5	T	
									04/22/1992	58.4	T	
									12/09/1992	58.2	T	
AAB026	30N/01E-33C	48°03'20"	122°41'01"	40	53	42	42-47	G	05/23/1977	39	R	
									03/15/1990	38.7	S	
									04/18/1990	43.3	S	R
									04/19/1990	38.8	S	
									05/24/1990	38.4	S	
									08/08/1990	39.3	S	
									12/07/1990	39.8	S	
									03/19/1991	38.4	S	
									06/06/1991	38.2	S	R
									04/21/1992	37.2	S	
									12/09/1992	37.6	S	

Unique Well Number	Well Location	Latitude	Longitude	Land Surface Elevation (Ft msl)	Drilled Depth (Ft)	Cased/ Lined Depth (Ft)	Open/Screened Interval (Feet Below Land Surface)	Source Aquifer	Water Level Measurement Date	Water Level (Feet Below Land Surface)	Measurement Method	Well Status
AAB028	30N/01E-33D	48°03'24"	122°41'05"	45	48	43	43-48	G	05/18/1976	38	R	
									03/14/1990	37.7	T	
									04/19/1990	37.8	T	
									05/24/1990	37.9	T	
									08/08/1990	37.9	T	
									12/07/1990	37.1	T	
									03/20/1991	37.5	T	
									06/06/1991	38.1	T	
									04/22/1992	37.2	T	
									12/09/1992	37.2	T	
AAB030	30N/01E-28L	48°03'40"	122°41'04"	35	46	42	42-46	G	09/09/1977	37.5	R	
									03/15/1990	36.5	T	
									05/23/1990	36.5	T	
									08/08/1990	36.8	T	
									12/07/1990	35.8	T	
									03/20/1991	36.2	T	
									06/05/1991	36.9	T	
									04/22/1992	35.9	T	
									12/09/1992	35.2	T	
AAB031	30N/01E-28F	48°03'53"	122°41'03"	60	80	72.6	62.3-67.6	G	11/26/1986	60	R	
									05/23/1990	58.5	T	
									08/09/1990	59.2	T	
									12/06/1990	58.3	T	
									03/20/1991	58.8	T	
									06/05/1991	59.9	T	
									04/23/1992	58.9	T	
AAB032	30N/01E-28L	48°03'55"	122°41'07"	64	71	66	66-71	G	05/19/1973	60	R	
									03/16/1990	60.6	T	
									05/23/1990	61.0	T	
									08/09/1990	61.0	T	
									12/06/1990	60.1	T	
									03/20/1991	60.5	T	
									06/05/1991	61.8	T	P
									04/23/1992	60.6	T	
									12/09/1992	59.9	T	

Unique Well Number	Well Location	Latitude	Longitude	Land Surface Elevation (Ft msl)	Drilled Depth (Ft)	Cased/ Lined Depth (Ft)	Open/Screened Interval (Feet Below Land Surface)	Source Aquifer	Water Level Measurement Date	Water Level (Feet Below Land Surface)	Measurement Method	Well Status
AAB034	30N/01E-28E	48°04'00"	122°41'23"	105	111	111	99.5-105	G	02/24/1981	99	R	
									05/23/1990	99.6	T	
									08/09/1990	99.8	T	
									12/06/1990	100.0	T	
									03/20/1991	99.2	T	
									06/05/1991	99.7	T	
									04/23/1992	99.6	T	
AAB036	30N/01E-29J	48°03'50"	122°41'27"	89	120	115	114.5-119.5	G	07/12/1982	91	R	
									05/23/1990	89.8	T	
									08/08/1990	88.9	T	
									12/06/1990	90.5	T	R
									03/20/1991	89.7	T	
									06/05/1991	88.9	T	
									04/23/1992	93.2	T	R
									12/08/1992	90.1	T	R
AAB037	30N/01E-29A	48°04'06"	122°41'29"	106	125	119	119-124	G	10/21/1981	109	R	
									05/23/1990	107.1	T	
									08/08/1990	106.9	T	
									12/06/1990	106.5	T	
									03/20/1991	106.5	T	
									06/05/1991	107.0	T	
									04/23/1992	106.7	T	
									12/09/1992	107.0	T	
AAB038	30N/01E-29R	48°03'33"	122°41'33"	20	60	60	39.5-42.5	G	11/29/1977	17	R	
									04/19/1990	17.9	T	
									05/23/1990	21.1	T	R
									07/25/1990	23.5	T	R
									07/26/1990	20.2	T	R
									08/07/1990	17.6	T	
									12/06/1990	17.4	T	
									03/19/1991	18.2	T	
									06/05/1991	17.3	T	
									04/09/1992	16.9	T	
									12/07/1992	17.1	T	

Unique Well Number	Well Location	Latitude	Longitude	Land Surface Elevation (Ft msl)	Drilled Depth (Ft)	Cased/ Lined Depth (Ft)	Open/Screened Interval (Feet Below Land Surface)	Source Aquifer	Water Level Measurement Date	Water Level (Feet Below Land Surface)	Measurement Method	Well Status
AAB039	30N/01E-29R	48°03'37"	122°41'42"	22	60	41.6	26.3-31.6	G	12/27/1977	22.5	R	
									04/19/1990	22.2	T	
									05/23/1990	22.2	T	
									08/07/1990	22.1	T	
									12/06/1990	21.6	S	
									03/19/1991	22.8	S	
									06/05/1991	22.3	S	
									04/09/1992	21.7	S	
									12/07/1992	21.8	S	
AAB041	30N/01E-29K	48°03'44"	122°41'46"	38	61	61	45.5-50.5	G	10/17/1978	43	R	
									03/15/1990	41.2	T	
									05/23/1990	41.4	T	
									08/07/1990	41.3	T	R
									12/06/1990	40.8	T	
									03/19/1991	41.0	T	R
									06/05/1991	41.5	T	R
									04/23/1992	40.9	T	
									12/07/1992	40.9	S	
AAB042	30N/01E-29C	48°04'07"	122°42'03"	50	64	59	59-64	G	08/02/1985	50	R	
									03/15/1990	50.0	T	
									04/19/1990	50.1	T	
									05/23/1990	50.1	T	
									05/24/1990	49.4	T	
									08/07/1990	49.9	T	
									12/06/1990	49.3	T	
									03/19/1991	49.6	T	R
									06/05/1991	50.1	T	
									04/09/1992	49.1	T	
									12/08/1992	49.0	T	
AAB043	30N/01E-20P	48°04'20"	122°42'05"	104	121	109	109.5-114.8	G	03/15/1990	105.6	T	
									05/23/1990	105.8	T	
									08/07/1990	105.5	T	
									12/05/1990	105.0	T	
									03/19/1991	105.4	T	
									06/04/1991	106.1	T	
									04/09/1992	105.0	T	
									12/08/1992	104.8	T	

Unique Well Number	Well Location	Latitude	Longitude	Land Surface Elevation (Ft msl)	Drilled Depth (Ft)	Cased/ Lined Depth (Ft)	Open/Screened Interval (Feet Below Land Surface)	Source Aquifer	Water Level Measurement Date	Water Level (Feet Below Land Surface)	Measurement Method	Well Status
AAB044	30N/01E-20Q	48°04'21"	122°41'49"	94	117	114	114-117	G	08/14/1985	97	R	
									03/15/1990	94.4	T	
									05/23/1990	94.4	T	
									08/08/1990	94.3	T	R
									12/05/1990	94.4	T	
									03/19/1991	93.7	T	
									06/04/1991	94.5	T	
									04/09/1992	93.7	T	
									12/08/1992	93.7	T	
AAB045	30N/01E-20Q	48°04'31"	122°41'43"	104	125	120	109-114	G	05/04/1983	103	R	
									04/20/1990	104.3	T	
									05/23/1990	103.8	T	
									07/25/1990	103.7	T	
									08/07/1990	103.8	T	
									12/05/1990	103.9	T	
									03/19/1991	103.1	T	
									06/04/1991	104.0	T	
									04/09/1992	103.1	T	
									12/08/1992	103.1	T	
AAB047	30N/01E-20M	48°04'38"	122°42'28"	35	44.5	40	40-44.5	G	09/13/1977	36	R	
									05/23/1990	35.1	T	
									08/08/1990	34.9	T	
									12/05/1990	33.6	T	
									03/19/1991	34.7	T	
									06/04/1991	35.3	T	
									04/09/1992	34.4	T	
									12/08/1992	33.1	T	
AAB049	30N/01E-20D	48°05'01"	122°42'35"	35	50	45	45-49.5	G	05/20/1969	39	R	
									03/15/1990	36.4	T	
									05/23/1990	36.6	T	
									08/08/1990	36.5	T	
									12/05/1990	35.9	T	
									03/19/1991	36.1	T	
									06/04/1991	36.7	T	
									04/22/1992	36.1	T	

Unique Well Number	Well Location	Latitude	Longitude	Land Surface Elevation (Ft msl)	Drilled Depth (Ft)	Cased/ Lined Depth (Ft)	Open/Screened Interval (Feet Below Land Surface)	Source Aquifer	WaterLevel Measurement Date	WaterLevel (Feet Below Land Surface)	Measurement Method	Well Status
AAB050	30N/01E-20D	48°05'03"	122°42'38"	43	60	53	53-58	G	07/05/1979	47	R	
									03/15/1990	42.9	T	
									05/23/1990	42.9	T	
									08/08/1990	42.9	T	
									12/05/1990	42.2	T	
									03/19/1991	42.6	T	
									06/04/1991	43.2	T	
									04/23/1992	42.5	T	
AAB051	30N/01E-18R	48°05'12"	122°42'44"	85	105	91	91-96	G	04/--/1982	83	R	
									04/20/1990	83.5	T	
									05/23/1990	83.5	T	
									08/08/1990	83.3	T	
									12/05/1990	82.7	T	
									03/19/1991	82.9	T	
									06/04/1991	83.6	T	
									04/22/1992	83.1	T	
									12/08/1992	82.5	T	
AAB052	30N/01E-32Q	48°02'33"	122°41'55"	20	55	20	20-55	B	05/23/1974	5	R	
									05/25/1990	5.1	T	
									08/09/1990	50.4	T	R
									12/07/1990	47.6	T	R
									03/20/1991	45.9	T	R
									06/05/1991	48.7	T	R
									04/22/1992	50.3	T	R
AAB053	30N/01E-32Q	48°02'35"	122°41'55"	25	209	209	141-181,201-209	B	08/03/1989	28	R	
									12/07/1990	23.0	T	
									03/20/1991	21.3	T	
									06/05/1991	21.8	T	
									04/22/1992	21.7	T	
									12/10/1992	22.3	T	

Unique Well Number	Well Location	Latitude	Longitude	Land Surface Elevation (Ft msl)	Drilled Depth (Ft)	Cased/ Lined Depth (Ft)	Open/Screened Interval (Feet Below Land Surface)	Source Aquifer	Water Level Measurement Date	Water Level (Feet Below Land Surface)	Measurement Method	Well Status
AAB054	30N/01E-32K	48°02'45"	122°42'01"	30	235	22	22-235	B	10/20/1974	20	R	
									03/14/1990	8.6	T	
									05/25/1990	7.8	T	
									08/09/1990	8.9	T	
									12/07/1990	8.1	T	
									03/20/1991	6.6	T	
									06/05/1991	9.3	T	
									04/22/1992	10.2	T	
									12/10/1992	8.1	T	
AAB056	30N/01E-32K	48°02'53"	122°42'01"	35	160	28	28-160	B	06/25/1984	7	R	
									03/14/1990	16.1	T	
									05/25/1990	17.0	T	R
									08/09/1990	17.8	T	
									12/07/1990	16.4	T	
									06/05/1991	15.6	T	
									04/22/1992	15.8	T	
									12/10/1992	16.1	T	
AAB061	30N/01E-32G	48°03'11"	122°41'55"	48	240	20	20-240	B	10/26/1976	20	R	
									03/14/1990	60.3	T	
									05/25/1990	79.7	T	R
									08/09/1990	58.5	T	
									06/06/1991	52.5	T	
									04/22/1992	58.1	T	
									12/10/1992	61.7	T	
AAB065	30N/01E-32H	48°03'05"	122°41'34"	49	180	21	21-180	B	07/18/1977	24	R	
									03/14/1990	31.4	S	
									05/25/1990	73.7	S	R
									08/09/1990	98.0	S	
									12/07/1990	84.9	S	R
									03/21/1991	91.2	S	
									06/06/1991	108.2	S	R
									04/09/1992	86.0	S	
									12/09/1992	75.3	S	

Unique Well Number	Well Location	Latitude	Longitude	Land Surface Elevation (Ft msl)	Drilled Depth (Ft)	Cased/ Lined Depth (Ft)	Open/Screened Interval (Feet Below Land Surface)	Source Aquifer	Water Level Measurement Date	Water Level (Feet Below Land Surface)	Measurement Method	Well Status
AAB068	30N/01E-29K	48°03'42"	122°41'46"	40	46	47	37-42	G	09/25/1986	37.4	R	
									05/23/1990	37.7	T	
									08/07/1990	37.6	T	
									12/06/1990	37.1	T	
									03/19/1991	37.3	T	
									06/05/1991	37.8	T	
									04/09/1992	37.2	T	
									12/08/1992	37.3	T	
AAB069	29N/01E-08R	48°00'48"	122°41'31"	60	108	---	---	G	12/09/1970	27	R	
									02/26/1990	35.2	T	
									03/19/1990	34.2	T	
									06/05/1990	34.2	T	
									08/07/1990	37.4	T	
									12/08/1992	34.0	T	
AAB070	29N/01E-09P	48°00'47"	122°40'53"	90	78	73	73-78	G	10/24/1977	63	R	
									02/26/1990	63.5	T	
									05/25/1990	63.4	T	
									08/07/1990	63.4	T	
									12/05/1990	63.7	T	
									03/18/1991	63.4	T	
AAB070	29N/01E-09P	48°00'47"	122°40'53"	90	78	73	73-78	G	06/05/1991	63.1	T	
									04/21/1992	63.3	T	
									12/08/1992	63.4	T	
AAB071	29N/01E-09L	48°01'01"	122°40'59"	150	153	---	---	G	02/26/1990	127.5	T	
									05/25/1990	127.4	T	R
									08/07/1990	127.5	T	
									12/05/1990	123.0	T	
									03/18/1991	127.4	T	
									06/06/1991	127.4	T	
									04/21/1992	127.3	T	
									12/07/1992	127.2	T	

Unique Well Number	Well Location	Latitude	Longitude	Land Surface Elevation (Ft msl)	Drilled Depth (Ft)	Cased/ Lined Depth (Ft)	Open/Screened Interval (Feet Below Land Surface)	Source Aquifer	Water Level Measurement Date	Water Level (Feet Below Land Surface)	Measurement Method	Well Status
AAB073	29N/01E-09P	48°00'56"	122°41'06"	125	240	235	37-40,124-130	G	06/13/1978	102	R	
									04/19/1990	101.3	T	
									05/25/1990	101.4	T	
									08/07/1990	101.5	T	
									12/05/1990	102.2	T	
									03/18/1991	101.4	T	
									06/05/1991	101.6	T	
									04/19/1992	101.3	T	
									12/07/1992	101.1	T	R
AAB074	29N/01E-09P	48°00'55"	122°40'49"	90	72	64	64-69	G	10/--/1972	57	R	
									05/25/1990	56.2	T	
									08/07/1990	56.3	T	
									12/05/1990	56.6	T	
									03/18/1991	56.1	T	
									06/05/1991	56.9	T	P
									04/21/1992	56.0	T	
									12/07/1992	56.3	T	
AAB078	29N/01E-04Q	48°01'47"	122°40'45"	103	112	112	94-112	G	05/23/1978	90	R	
									04/19/1990	91.2	T	
									05/24/1990	91.2	T	
									08/08/1990	91.4	T	
									12/06/1990	91.3	T	
									03/19/1991	90.9	T	
									06/04/1991	90.9	T	
									04/21/1992	90.7	T	
									12/08/1992	90.9	T	
AAB079	29N/01E-04R	48°01'40"	122°40'14"	64	130	110	110-130	B	03/31/1981	70	R	
									05/25/1990	91.4	T	R
									08/08/1990	92.7	T	
									12/07/1990	82.7	T	
									03/20/1991	85.7	T	

Unique Well Number	Well Location	Latitude	Longitude	Land Surface Elevation (Ft msl)	Drilled Depth (Ft)	Cased/ Lined Depth (Ft)	Open/Screened Interval (Feet Below Land Surface)	Source Aquifer	Water Level Measurement Date	Water Level (Feet Below Land Surface)	Measurement Method	Well Status
AAB080	29N/01E-04F	48°02'06"	122°40'47"	110	220	220	200-220	B	09/26/1973	108	R	
									04/19/1990	104.8	T	
									05/24/1990	104.7	T	
									08/08/1990	105.0	T	
									12/06/1990	104.6	T	
									06/04/1991	105.2	T	
									04/21/1992	104.6	T	
									12/08/1992	99.9	T	
AAB081	29N/01E-04G	48°02'09"	122°40'39"	75	195	57	57-195	B	09/12/1976	81	R	
									04/19/1990	83.2	T	
									05/24/1990	84.0	T	
									08/08/1990	108.8	T	R
									12/07/1990	84.6	T	
									03/19/1991	83.2	T	
									06/04/1991	91.9	T	
									04/21/1992	96.9	T	R
									12/08/1992	91.8	T	
AAB083	30N/01E-33E	48°03'05"	122°41'12"	35	62	60	60-62	B	06/15/1988	57	R	
									04/19/1990	34.2	T	
									05/16/1990	34.0	T	
									05/24/1990	34.0	T	
									07/26/1990	32.8	T	
									08/09/1990	32.7	T	
									12/07/1990	32.6	T	
									06/05/1991	31.7	T	
									04/22/1992	33.0	T	
AAB084	30N/01E-29R	48°03'27"	122°41'25"	30	65	55	55-60	G	11/04/1985	28	R	
									05/23/1990	37.9	T	R
									08/07/1990	33.9	T	
									12/06/1990	31.9	T	
									06/05/1991	40.6	T	R
									04/23/1992	28.3	T	
									12/10/1992	28.2	T	

Unique Well Number	Well Location	Latitude	Longitude	Land Surface Elevation (Ft msl)	Drilled Depth (Ft)	Cased/ Lined Depth (Ft)	Open/Screened Interval (Feet Below Land Surface)	Source Aquifer	Water Level Measurement Date	Water Level (Feet Below Land Surface)	Measurement Method	Well Status
AAB085	30N/01E-28D	48°04'10"	122°41'16"	120	140	140	130-135	G	05/24/1990	121	R	
									08/09/1990	121.6	T	
									12/06/1990	120.4	T	
									03/20/1991	120.1	T	
									06/05/1991	120.7	T	
									04/23/1992	120.5	T	
									12/09/1992	120.7	T	
AAB087	30N/01E-21E	48°04'44"	122°41'24"	118	---	---	---	G	04/18/1990	120.2	T	
									05/24/1990	120.8	T	
									08/09/1990	120.1	T	
									12/07/1990	119.2	T	
									03/20/1991	119.1	T	
									06/05/1991	120.2	T	
									04/23/1992	119.7	T	
									12/09/1992	119.1	T	
GC008	29N/01E-04G			50	201	201	201	G	06/24/1986	47.5	R	
GC018	29N/01E-05J			12	200	200	60-200	B	01/30/1978	30	R	
GC048	30N/01E-20D			25	33	28	28-33	G	01/12/1981	23	R	
GC058	30N/01E-32G			40	185	14	14-185	B	03/--/1972	18	R	
GC063	30N/01E-32H			45	225	18	18-225	B	07/07/1986	17	R	
GC072	29N/01E-08R			35	157	157	157	B	12/12/1975	57	R	
GC075	29N/01E-09J			65	151	151	151	B	11/09/1988	61	R	
GC076	29N/01E-09A			90	108	98	98-103	G	01/06/1984	95	R	
GC077	29N/01E-09A			90	111	102	102-111	G	11/24/1986	100	R	
GC082	30N/01E-33L			50	60	5	249-54	G	07/14/1986	51.6	R	
GC088	30N/01E-33P			80	470		Well Abandoned	?				

Measurement Method Codes:
(T) Electric tape
(S) Steel tape
(R) Reported by well driller at time of construction

Well Status Codes:
(P) Pumping
(R) Recently pumped

Source Aquifer Codes:
(G) Water source - glacial sediments
(B) Water source - bedrock
(BG) Water source - glacial sediments and bedrock

Appendix B
Quality Assurance Review

Quality Assurance

A number of quality control procedures or measures were followed during this study. Quality-control procedures related to ground-water sampling and water-level measurements were discussed in the Methods Section of this report and will not be discussed here. This section discusses the use of quality-control samples as a means of evaluating the accuracy and precision of laboratory analyses.

In addition to the internal quality-control checks conducted by the laboratory, we submitted a number of blind, duplicate samples and blind sample blanks and conducted internal sample checks for those sites where complete inorganic analyses were made. Based on this information, the quality of the data obtained during this study appears to be good by all measures. The constituent concentration of blank samples fell within acceptable limits, with most analytes being undetectable in blank samples. All duplicate sample analyses yielded acceptable results with the exception of nitrate + nitrite, where errors of 143 percent occurred. The internal sample checks yielded percentage errors in the cation/anion balance of approximately 1-11 percent.

Sample Duplicates

Blind, duplicate samples were submitted to the laboratory during most of this study's six sampling events. The term "blind" refers to 'identical' samples that are submitted to the laboratory with different identification numbers. In principal the reported constituent concentrations for duplicate sample pairs should be nearly identical. For this study duplicate sample determinations were considered acceptable if the difference in reported concentrations varied by 10 percent or less of the average concentration of the pair. The results of the duplicate sample analyses are shown below in Table B-1. The constituent concentrations of duplicate samples are presented with the other analyses in Appendix C.

For the most part, the duplicate sample analyses were within the target precision criteria. The single exception was for the nitrate + nitrite analyses where the difference was 143 percent. While the percentage difference for the nitrate + nitrite pair was large, it is not considered significant because the reported concentrations are low and do not significantly affect data interpretation.

TABLE B-1

Constituent	Number of Duplicate Pairs	Total Number of Samples	Average Difference in Percent	Pairs Exceeding Difference Criteria
Chloride	13	224	2.5	0
Sulfate	1	10	0.5	0
Total Phosphate	1	10	0	0
Nitrate + Nitrite	1	10	143	1
Total Alkalinity	1	10	4.5	0
Calcium	1	10	1.5	0
Iron	1	10	0	0
Magnesium	1	10	0.8	0
Potassium	1	10	3.7	0
Silica	1	10	0	0
Sodium	1	10	6.1	0

Sample Blanks

We prepared blank samples, using deionized water, for several of this study's six sampling events. The blanks were prepared and shipped to the laboratory blind, in the same manor as actual ground-water samples. In all cases, constituent concentrations for blank analyses fell below the detection limit for target analytes. The absence of detectable target analytes in blank samples indicates careful field and laboratory handling of samples.

Internal Sample Checks

In order to evaluate the gross accuracy of the water analysis conducted during this study we evaluated the cation-anion balance in those cases where major cation-anion determinations had been made. We calculated the cation-anion balance as a percent difference using the following equation.

$$\frac{\Sigma \text{ cations} - \text{ anions}}{\Sigma \text{ cations} + \text{ anions}}$$

Where

Σ cations = the sum of cation concentrations, in milliequivalents per liter and

Σ anions = the sum of anion concentrations, in milliequivalents per liter.

In principal the cation-anion balance should be zero, although errors in analysis or missing determinations for major ions will introduce discrepancies. Assuming careful analytical work, the difference between the cation and anion sums should not exceed 1-2 percent for water of moderate concentration where the sum of cations and anions is in the range of 250-1,000 mg/L (Hem, 1985). Water with dissolved solids concentrations in excess of 1,000 mg/L generally have high concentrations of a few constituents. Accordingly, the cation-anion balance may not be sufficient to evaluate the accuracy of determinations for lesser constituents (Hem, 1985).

The results of the cation-anion balance for 10 water samples collected during this study are shown in Table B-2. Three samples had errors of 3.6 percent or less, with the remaining seven samples having errors in the range of 7.2 to 11.3 percent. Evaluation of the data shows a systematic deficit of anions relative to cations. This may be explained in part by the absence of analyses for bromide, fluoride, or other anions that may contribute to total anion concentrations. A more complete cation-anion sampling should yield better balances than we obtained with this limited sampling.

While the error range noted for the latter seven samples is higher than recommended, the results are not unacceptable and have been used throughout this study without further qualification.

TABLE B-2
Sample Constituents Expressed in Milliequivalents per Liter (meq/L)

Well Number	Sampling Date	Chloride (Cl^-)	Sulfate $(SO_4{-}^{2})$	Phosphate $(PO_4{-}^{3})$	Nitrate + Nitrite $(NO_3{-}{+}NO_2{-})$	Alkalinity $(CaCO_3)$	Calcium (Ca^{+2})
AAB006	05/24/90	0.70	0.40	0.001	0.02	3.15	1.57
AAB015	05/24/90	2.82	0.62	0.001	0.00	3.31	1.15
AAB022	05/24/90	7.17	0.25	0.001	0.00	1.08	1.49
AAB026	05/24/90	4.71	0.71	0.001	0.13	2.13	3.81
AAB038	05/24/90	1.22	0.54	0.002	0.01	3.67	1.12
AAB042	05/24/90	11.06	1.92	0.002	0.01	4.49	2.60
AAB046	05/24/90	5.22	1.05	0.004	0.00	7.31	4.75
AAB051	05/24/90	1.52	0.70	0.001	0.01	3.70	1.83
AAB061	05/24/90	1.41	3.08	0.002	0.00	6.38	0.15
AAB069	05/24/90	1.06	1.25	0.01	0.00	3.08	1.97

Well Number	Sampling Date	Magnesium (Mg^{+2})	Potassium (K^+)	Sodium (Na^+)	Sum Anions	Sum Cations	Percent Error
AAB006	05/24/90	2.76	0.08	0.94	4.27	5.35	11.2
AAB015	05/24/90	3.24	0.14	3.95	6.76	8.48	11.3
AAB022	05/24/90	0.01	0.01	7.09	8.50	8.60	0.6
AAB026	05/24/90	1.10	0.00	3.01	7.68	7.92	1.5
AAB038	05/24/90	3.51	0.04	2.16	5.44	6.83	11.3
AAB042	05/24/90	5.43	0.34	10.40	17.48	18.78	3.6
AAB046	05/24/90	7.80	0.26	3.43	13.58	16.24	8.9
AAB051	05/24/90	3.40	0.11	1.67	5.93	7.01	8.4
AAB061	05/24/90	0.01	0.02	10.74	10.88	10.93	0.2
AAB069	05/24/90	2.90	0.05	1.31	5.40	6.23	7.2

Appendix C
Ground-Water Quality Data by Well and Sampling Date

Well Number	Site Location	Source Aquifer	Sampling Date	Time Sampled	Temperature (°C)	Conductance (µmhos/cm)	pH	TDS (mg/L) (Calculated)	Chloride (mg/L)
AAB004	29N/01E-09R	(B)	05/25/90	14:10	11.0	850	8.0	553	165(J)
			08/07/90	17:30	12.9	849	7.4	552	143(H)
			12/06/90	10:15	10.1	826	7.7	537	181
			03/20/91	13:15	10.3	831	7.4	540	152
			06/05/91	15:40	10.9	824	---	536	122
			12/08/92	10:45	9.2	845	8.4	549	156
			12/08/92	---	---	---	---	---	151(D)
AAB005	29N/01E-09G	(G)	08/07/90	18:00	11.1	721	7.0	469	34.2(H)
			12/06/90	10:34	10.6	706	7.0	459	53.6
			03/18/91	15:05	10.7	704	7.1	458	35.0
			06/05/91	15:15	10.8	708	---	460	32.6
			12/08/92	11:20	10.5	702	7.8	456	31.4
AAB006	29N/01E-09B	(G)	05/24/90	17:05	11.2	492	7.4	345	24.7
			08/07/90	18:40	11.7	486	6.9	316	23.9(H)
			12/06/90	10:45	10.6	478	6.9	311	29
			03/19/91	10:30	10.4	483	7.1	314	25.1
			06/04/91	17:25	11.1	482	---	313	28.6
AAB007	29N/01E-09A	(G)	05/25/90	15:35	11.3	523	7.5	340	40(J)
			08/09/90	---	12.1	524	7.1	341	53.4(H)
			12/06/90	12:00	10.4	518	6.7	337	60.8
			12/06/90	---	---	---	---	---	63.9(D)
			03/19/91	11:30	10.4	517	6.9	336	51.9
			03/19/91	---	---	---	---	---	49.6(D)
			06/04/91	16:55	11.1	509	---	331	58.2
			12/08/92	16:20	10.4	521	7.6	339	47
AAB009	29N/01E-04L	(B)	08/09/90	13:55	---	831	7.9	540	141(H)
			12/06/90	14:30	7.8	837	7.6	544	---

Well Number	Site Location	Source Aquifer	Sampling Date	Time Sampled	Temperature (°C)	Conductance (µmhos/cm)	pH	TDS (mg/L) (Calculated)	Chloride (mg/L)
AAB010	29N/01E-09D	(G)	05/25/90	12:00	11.7	481	7.6	313	19(J)
			08/08/90	---	11.9	453	6.8	294	25.3(H)
			12/06/90	15:10	9.8	464	6.9	302	28.1
			03/20/91	14:35	10.2	469	6.8	305	23.0
			06/05/91	12:25	11.4	468	---	304	25.5
			12/09/92	10:10	9.5	492	7.7	320	23.8
AAB011	29N/01E-09C	(G)	05/25/90	15:14	11.2	599	7.3	389	19(J)
			08/09/90	11:10	11.2	599	6.7	389	28.5(H)
			12/06/90	11:15	11.1	598	6.7	389	31.1
			03/19/91	11:10	10.7	598	7.0	389	26.4
			06/05/91	14:45	12.0	580	---	377	30.1
			12/08/92	12:00	11.6	608	7.6	395	27.5
AAB012	29N/01E-08A	(G)	08/08/90	10:00	10.6	630	7.0	410	37.7(H)
			12/06/90	14:45	10.5	771	6.9	501	74.8
			03/18/91	15:45	10.6	579	6.9	376	32.0
			06/05/91	11:55	10.7	568	---	369	38.6
			12/09/92	09:40	10.4	686	7.8	446	50.7
			12/09/92	---	---	---	---	---	48.4(D)
AAB015	29N/01E-05H	(B)	05/24/90	16:15	11.6	765	7.3	508	100
			08/08/90	11:15	11.9	4840	7.0	3146	1310(H)
			12/06/90	14:00	10.9	993	7.1	645	192
			03/18/91	16:05	11.1	873	7.1	567	169
			06/05/91	13:00	11.6	3770	---	2451	1090
			12/07/92	13:40	11.2	3070	7.4	1996	754
			12/07/92	---	---	---	---	---	749(D)
AAB017	29N/01E-04E	(?)	08/08/90	11:45	11.4	494	7.3	321	22.6(H)
			12/06/90	15:40	10.9	551	7.1	358	27.9
			03/19/91	13:50	11.1	483	7.3	314	24.0
			06/05/91	16:40	11.3	481	---	313	25.8
			12/10/92	14:30	10.9	499	8.3	324	24.3
			12/10/92	---	---	---	---	---	24.4(D)

Well Number	Site Location	Source Aquifer	Sampling Date	Time Sampled	Temperature (°C)	Conductance (µmhos/cm)	pH	TDS (mg/L) (Calculated)	Chloride (mg/L)
AAB019	29N/01E-04J	(G)	08/08/90	13:45	13.7	614	6.6	399	73.1(H)
			12/07/90	09:25	8.5	656	6.6	426	87.6
			03/19/91	---	7.3	665	6.5	432	73.0
			06/04/91	16:00	10.8	652	---	424	74.8
			12/08/92	15:25	8.1	658	7.6	428	71.9
AAB020	29N/01E-04E	(BG)	08/08/90	12:20	13.0	606	7.3	394	28.2(H)
			12/06/90	16:00	10.1	599	7.4	389	31.2
			03/19/91	13:10	10.2	593	7.3	385	28.5
			06/05/91	16:00	11.8	589	---	383	28.6
			12/09/92	11:45	9.6	609	7.9	396	26.6
AAB022	29N/01E-04C	(B)	05/24/90	11:50	13.1	983	6.2	530	254
			08/08/90	16:45	16.3	1036	7.9	673	59.3(H)
			12/06/90	13:00	11.2	975	7.6	634	329
			03/19/91	15:00	10.4	965	7.7	627	269
			06/04/91	14:50	12.9	939	---	610	229
			12/08/92	13:55	12.1	1141	8.3	742	304
AAB024	30N/01E-33M	(G)	08/08/90	15:55	16.0	1633	7.1	1061	360(H)
			03/19/91	16:10	8.8	1085	7.0	705	220
			06/04/91	14:15	12.7	1128	---	733	193
			12/09/92	11:15	8.0	2008	7.6	1305	462
AAB025	30N/01E-33F	(G)	08/08/90	---	---	1969	7.2	1280	456(H)
			12/05/90	14:30	9.0	1441	7.6	937	374
			03/19/91	16:50	8.8	1294	7.5	841	247
			06/04/91	13:45	12.1	1294	---	841	228
			12/09/92	15:30	8.1	1228	8.4	798	218
AAB026	30N/01E-33C	(G)	05/24/90	16:40	11.2	939	7.3	509	167
			08/08/90	15:15	12.6	1289	6.9	838	295(H)
			12/07/90	12:09	10.3	950	7.0	617	199
			03/19/91	17:30	10.3	824	6.6	536	140
			06/06/91	10:37	11.4	591	6.6	384	80.9
			12/09/92	12:20	8.2	684	7.4	445	104

Well Number	Site Location	Source Aquifer	Sampling Date	Time Sampled	Temperature (°C)	Conductance (µmhos/cm)	pH	TDS (mg/L) (Calculated)	Chloride (mg/L)
AAB028	30N/01E-33D	(G)	08/08/90	16:18	12.4	773	7.0	502	99.7(H)
			12/07/90	11:18	11.0	802	7.2	521	157
			03/20/91	15:57	11.4	708	6.8	460	114
			06/06/91	11:27	12.0	683	6.7	444	98.4
			12/09/92	14:50	10.4	728	7.5	473	105
AAB030	30N/01E-28L	(G)	08/08/90	---	12.2	895	7.0	582	109(H)
			12/07/90	10:35	10.6	783	---	509	121
			03/20/91	15:29	10.7	636	6.7	413	63.5
			06/05/91	12:52	11.7	781	6.6	508	92
			12/09/92	14:25	10.4	903	7.4	587	126
AAB032	30N/01E-28L	(G)	03/20/91	11:35	10.0	666	7.4	433	63.4
			12/09/92	10:15	10.3	718	---	46771	
			12/09/92	---	---	---	---	---	73.3(D)
AAB034	30N/01E-28E	(G)	06/05/91	16:55	12.9	748	7.0	486	72.6
AAB036	30N/01E-29J	(G)	08/08/90	17:50	12.0	606	8.1	394	47.8(H)
			12/06/90	14:10	10.9	637	7.8	414	98.4
			03/20/91	12:10	10.9	622	7.4	404	48.3
			06/05/91	18:03	11.2	609	7.4	396	49
			12/08/92	16:10	10.5	640	8.1	416	47.1
AAB037	30N/01E-29A	(G)	08/08/90	18:35	11.1	992	7.8	645	122(H)
			12/06/90	16:17	10.3	1099	7.8	714	205
			03/20/91	10:55	10.4	1045	7.3	679	150
			03/20/91	---	---	---	---	---	150(D)
			06/05/91	15:53	10.8	1076	7.1	699	152
			12/09/92	11:45	10.2	1028	---	668	137
AAB038	30N/01E-29R	(G)	05/24/90	15:00	12.5	618	7.5	430	43.4
			08/07/90	13:59	---	---	7.8	---	32.8(H)
			12/06/90	12:22	10.4	599	8.0	389	58.9
			03/21/91	11:10	11.1	617	7.6	401	45.4
			12/07/92	15:00	10.6	660	8.0	429	41.1
			12/07/92	---	---	---	---	---	41.2(D)

Well Number	Site Location	Source Aquifer	Sampling Date	Time Sampled	Temperature (°C)	Conductance (µmhos/cm)	pH	TDS (mg/L) (Calculated)	Chloride (mg/L)
AAB039	30N/01E-29R	(G)	08/07/90	15:01	15.3	1231	7.3	800	261(H)
			06/05/91	11:53	12.2	984	6.7	640	197
AAB041	30N/01E-29K	(G)	12/06/90	11:10	10.8	1109	7.1	721	290
			03/21/91	11:35	11.0	1265	6.9	822	286
			06/05/91	11:16	11.0	1208	6.6	785	237
			12/07/92	16:46	10.0	1291	7.5	839	273
AAB042	30N/01E-29C	(G)	11/21/88	---	---	1950	---	1170	455
			05/24/90	13:30	11.4	1991	6.8	1135	392
			05/24/90	---	---	---	---	---	391(D)
			08/07/90	17:45	11.5	2100	7.4	1365	411(H)
			12/06/90	09:40	11.0	2120	7.7	1378	473
			03/21/91	09:40	10.7	1567	7.2	1019	286
			06/05/91	10:05	11.5	994	6.7	646	112
			12/08/92	10:50	11.2	1082	7.8	703	137
			12/08/92	---	---	---	---	---	138(D)
AAB043	30N/01E-20P	(G)	08/07/90	18:35	11.4	657	7.5	427	206(H)
			12/05/90	17:40	11.1	749	7.6	487	86.3
			03/21/91	10:45	11.1	681	7.3	443	47.4
			06/04/91	17:32	11.3	445	7.1	289	33.8
			12/08/92	11:36	10.8	647	7.4	421	41.8
AAB044	30N/01E-20Q	(G)	08/08/90	---	11.1	1455	7.5	946	238(H)
			12/05/90	17:15	10.6	1472	7.5	957	294
			03/21/91	10:36	10.5	1305	7.3	848	200
			06/04/91	16:27	11.1	1342	7.2	872	207
			12/08/92	13:45	10.4	1331	7.8	865	193
AAB045	30N/01E-20Q	(G)	08/07/90	12:35	11.6	1743	6.9	1133	99.9(H)
			12/05/90	16:30	10.5	1768	7.3	1149	134
			03/21/91	10:05	10.5	1703	7.2	1107	120
			06/04/91	15:47	10.8	1766	6.9	1148	100
			12/08/92	14:20	10.3	1806	7.4	1174	113

Well Number	Site Location	Source Aquifer	Sampling Date	Time Sampled	Temperature (°C)	Conductance (µmhos/cm)	pH	TDS (mg/L) (Calculated)	Chloride (mg/L)
AAB046	30N/01E-21E	(G)	05/24/90	12:30	10.7	1466	6.5	980	185
			08/09/90	12:30	10.8	1959	7.4	127	335(H)
			12/07/90	09:57	10.5	1656	7.3	1076	285
			03/20/91	10:10	10.6	1611	7.1	1047	253
			06/05/91	14:48	10.7	1519	6.9	987	285
			12/09/92	13:55	10.1	2020	7.8	1313	360
AAB047	30N/01E-20M	(G)	08/08/90	11:40	11.8	1798	7.2	1169	402(H)
			12/05/90	15:30	11.3	1856	7.4	1206	580
			03/20/91	18:00	11.1	1472	6.9	957	329
			06/04/91	14:55	11.8	1605	6.8	1043	340
			12/08/92	12:21	11.1	2110	7.3	1372	874
AAB051	30N/01E-18R	(G)	05/24/90	14:20	12.5	651	6.9	454	53.9
			08/08/90	13:00	16.0	708	7.3	460	72.3(H)
			12/05/90	14:00	10.2	608	7.4	395	55.3
			03/20/91	17:38	10.3	638	7.0	415	59.3
			06/04/91	13:35	12.7	646	6.6	420	53.6
			12/08/92	14:55	8.7	687	7.6	447	64
AAB056	30N/01E-32K	(B)	05/25/90	10:35	12.2	964	6.9	627	40(J)
			08/09/90	14:10	16.8	931	7.3	605	80(H)
			12/07/90	12:35	8.2	930	7.4	605	50.9
			12/07/90	---	---	---	---	---	55.9(D)
			03/20/91	17:03	7.9	908	7.0	590	45.2
			06/05/91	17:30	11.4	954	---	620	43.9
			12/10/92	12:30	8.9	971	7.9	631	46.1
AAB061	30N/01E-32G	(B)	05/24/90	15:30	11.4	1106	9.4	802	49.9
			12/07/90	---	11.3	1118	8.9	727	62.5
			03/21/91	13:50	11.2	1176	8.4	764	27.5
			06/06/91	11:30	11.4	1139	---	740	42.7
			12/10/92	13:00	11.0	1106	9.1	719	48.3
AAB065	30N/01E-32H	(B)	05/25/90	11:25	11.0	929	9.3	604	175(J)
			08/09/90	14:55	---	905	8.8	588	140(H)
			12/07/90	11:20	10.6	905	8.8	588	192
			03/21/91	13:05	10.8	945	8.4	614	155
			06/06/91	12:16	11.0	918	9.5	597	157
			12/09/92	16:25	10.3	901	9.6	586	181

Well Number	Site Location	Source Aquifer	Sampling Date	Time Sampled	Temperature (°C)	Conductance (µmhos/cm)	pH	TDS (mg/L) (Calculated)	Chloride (mg/L)
AAB068	30N/01E-29K	(G)	08/07/90	15:50	17.0	1033	7.0	671	184(H)
			12/06/90	10:33	8.7	1048	7.6	681	225
			03/21/91	12:10	9.1	1004	6.9	653	182
			06/05/91	10:51	12.7	1095	6.5	712	182
			12/08/92	10:05	10.5	1042	7.3	677	195
AAB069	29N/01E-08R	(G)	05/24/90	17:30	11.4	593	7.3	409	37.4
			08/07/90	13:45	12.7	597	6.7	388	34.9(H)
			03/19/91	10:10	10.8	572	6.9	372	36.4
			06/05/91	09:35	11.2	552	---	359	36.9
			12/08/92	09:35	11.4	580	7.6	377	40.6
AAB070	29N/01E-09P	(G)	05/25/90	13:15	13.1	448	7.5	291	26(J)
			08/07/90	16:15	---	562	6.7	365	38.0(H)
			12/06/90	09:15	10.4	563	6.6	366	44.9
			03/18/91	13:20	10.6	571	6.8	371	43.1
			06/05/91	10:35	11.4	554	---	360	38.7
			12/08/92	10:20	10.6	573	7.7	372	41.9
AAB071	29N/01E-09L	(G)	08/07/90	14:55	10.9	497	6.8	323	27.3(H)
			12/06/90	09:55	10.6	492	6.8	320	39.0
			03/18/91	14:00	10.6	492	6.9	320	28.0
			06/06/91	10:20	10.8	488	---	317	31.3
			12/07/92	15:40	10.6	498	7.7	324	28.8
AAB073	29N/01E-09P	(G)	05/25/90	12:25	10.7	431	7.8	280	19(J)
			08/07/90	14:40	10.8	433	7.0	281	25.3(H)
			12/06/90	09:35	10.4	428	7.0	278	28.6
			03/18/91	14:25	10.5	429	7.1	279	25.3
			03/18/91	---	---	---	---	---	25.4(D)
			06/05/91	11:20	10.8	430	---	280	26.2
			12/07/92	15:05	9.4	453	8.0	294	24.9
AAB074	29N/01E-09P	(G)	05/25/90	13:35	11.0	763	7.3	496	29(J)
			08/07/90	15:50	10.9	769	6.7	500	43.6(H)
			12/06/90	08:40	10.7	751	6.7	488	41.6
			03/18/91	12:50	10.7	743	6.9	483	40.0
			06/05/91	10:15	10.9	754	---	490	38.2
			12/07/92	16:10	8.4	774	7.6	503	40.7

Well Number	Site Location	Source Aquifer	Sampling Date	Time Sampled	Temperature (°C)	Conductance (µmhos/cm)	pH	TDS (mg/L) (Calculated)	Chloride (mg/L)
AAB078	29N/01E-04Q	(G)	08/08/90	---	12.3	710	6.7	462	51.5(H)
			12/06/90	12:25	10.0	720	6.8	468	61.2
			03/19/91	12:10	9.3	713	6.9	463	51.1
			06/04/91	16:30	10.5	680	---	442	43.2
			12/08/92	15:55	9.3	725	7.6	471	50.1
AAB080	29N/01E-04F	(B)	08/08/90	17:25	11.2	549	7.5	357	61.9(H)
			12/06/90	16:30	10.0	534	8.0	347	55.6
			06/04/91	15:40	11.0	530	---	345	43.2
			12/08/92	14:55	9.4	550	8.6	357	41.8
AAB081	29N/01E-04G	(B)	08/08/90	12:40	12.1	437	7.1	284	14.2(H)
			12/07/90	10:15	9.7	420	7.4	273	14.0
			03/21/91	12:45	9.6	419	7.4	272	13.4
			06/04/91	15:15	11.2	423	---	275	15.1
			12/08/92	14:20	9.1	422	8.1	274	14.4
AAB084	30N/01E-29R	(G)	03/21/91	12:30	9.3	580	7.6	377	29.8
AAB085	30N/01E-28D	(G)	08/09/90	11:55	10.4	586	7.8	38	214(H)
			12/06/90	16:50	10.0	601	7.8	391	50.0
			03/20/91	10:30	10.0	605	7.5	393	47.0
			06/05/91	15:17	10.3	594	6.9	386	44.8
			12/09/92	12:23	9.4	611	---	397	44.8

(D) Indicates duplicate sample analyses.
(U) No analyte was detected. The method detection limit reported by the laboratory is given.
(H) The sample holding time was exceeded prior to completing sample analysis.
(J) The reported value is estimated.
(G) Water source - glacial sediments
(B) Water source - bedrock
(BG)Water source - both glacial sediments and bedrock

Ground-Water Quality Data by Well and Sampling Date (in mg/L)

Well Number	Sampling Date	Chloride (Cl^-)	Total Sulfate (SO_4-2)	Nitrate+ Phosphate (PO_4-3)	Total Nitrite (NO_3^-+NO_2^-)	Alkalinity ($CaCO_3$)	Calcium (Ca^{+2})	Iron (Fe^{+2})	Magnesium (Mg^{+2})	Potassium (K^+)	Silica (SiO_2)	Sodium (Na^+)
AAB006	05/24/90	24.7	19.4	0.03	1.35(H)	192	31.4	0.09(J)	33.5	3.3	17.3(J)	21.6
AAB015	05/24/90	100	29.9	0.02	<0.01(H)	202	23.1	0.02(U)	39.4	5.3	17.6(J)	90.9
AAB022	05/24/90	254	11.9	0.02	<0.01(H)	66	29.9	0.02(U)	0.1	0.3	4.8(J)	163
AAB026	05/24/90	167	34.1	0.02	8.14(H)	130	76.3	0.02(U)	13.4	0.3(U)	10.5(J)	69.1
AAB038	05/24/90	43.4	25.9	0.07	0.30(H)	224	22.5	0.02(U)	42.6	1.72	0.2(J)	49.6
AAB042	05/24/90	392	92.4	0.07	0.32(H)	274	52.2	0.02(U)	66.0	13.4	17.7(J)	239
	05/24/90	391(D)	91.9(D)	0.07(D)	0.05(H,D)	262(D)	51.4(D)	0.02(U,D)	65.5(D)	13.9(D)	17.7(J,D)	254(D)
AAB046	05/24/90	185	50.5	0.13	<0.01(H)	446	95.2	0.02(U)	94.8	10.1	19.9(J)	78.8
AAB051	05/24/90	53.9	33.5	0.04	0.50(H)	226	36.6	0.02(U)	41.3	4.4	20.0(J)	38.5
AAB061	05/24/90	49.9	148	0.05	0.02(H)	340	3.1	0.02(U)	0.1	0.8	12.9(J)	247
AAB069	05/24/90	37.4	60.0	0.43	0.02(H)	188	39.4	0.02(U)	35.3	2.0	16.8(J)	30.1

(D) Indicates duplicate sample analyses.
(U) No analyte was detected. The method detection limit reported by the laboratory is given.
(H) The sample holding time was exceeded prior to completing sample analysis.
(J) The reported value is estimated.

Appendix D
Materials Penetrated by Representative Wells

T29N, R01E, Sec. 4

Well AAB009, 29N/01E-04L
Domestic well, altitude 113 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Surface soil	0	1	
Brown sand	1	19	Qvt
Blue clay	19	34	
Brown dry sand	34	111	Qva, sand & sandy clay
Shale sandstone	111	190	
Shattered shale, coal, water bearing	190	250	Bedrock, Tsb

Casing 6-inch to 120 feet. Yield 2 gallons per minute with 80 feet of drawdown after 2 hours (bailer test). Static water level 118 feet on 10/22/1974.

Well AAB019, 29N/01E-04J
Domestic well, altitude 65 feet

Top soil, brown	0	3	
Brown clay	3	12	
Brown sandy clay	12	32	
Brown sand and gravel, water bearing	32	49	

Casing 6-inch to 45.5 feet. Screened slot size 16 from 43.5 to 49 feet. Yield 20 gallons per minute with 2 feet of drawdown (bailer test). Static water level 40 feet on 06/07/1984.

Well AAB020, 29N/01E-04E
Domestic well, altitude 165 feet

Brown sandy clay	0	6	
Blue clay, cemented gravel	6	48	Qvt
Brown clay, sand	48	85	
Blue clay	85	95	Qva, sand & sandy clay
Brown clay, sand	95	110	
Clay blue, sand, gravel	110	119	Qva, sand & gravel
Blue sandstone	119	275	
Blue shale	275	285	Bedrock, Tsb
Blue sandstone	285	340	

Casing 6-inch to 130 feet, perforated from 115 to 120 feet. Yield 1.5 gallons per minute with 240 feet of drawdown. Static water level 105 feet on 02/07/1980.

T29N, R01E, Sec. 4

Well AAB021, 29N/01E-04E
Domestic well, altitude 140 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Top soil	0	5	
Sandy hardpan	5	10	Qvt
Sandstone	10	37	
Brown clay	37	50	
Brown sandy clay	50	82	Qva, sand, gravel, sandy clay, & clay
Gravel	82	85	
Hardpan	85	95	Qva, sand & gravel
Sandstone	95	135	
Shale, water bearing at 190 feet	135	190	Bedrock, Tsb
Sandstone	190	205	

Casing 6-inch to 94 feet. Yield 1.5 gallons per minute, drawdown not specified. Static water level 127 feet on 04/21/1978.

Well AAB022, 29N/01E-04C
Domestic well, altitude 100 feet

Brown top soil	0	3	
Gray cemented gravel and cobbles	3	28	
Brown sandy clay	28	52	
Brown fine sand	52	80	
Brown Gravel, loose	80	95	
Gray sandstone	95	225	
Gray shale, water bearing at 225 feet	225	244	

Casing 6-inch to 96 feet. Yield 4 gallons per minute with total drawdown after one hour (bailer test). Static water level 105 feet on 04/01/1983.

Well AAB023, 29N/01E-04C
Domestic well, altitude 90 feet

Brown surface soil	0	3	
Brown sand	3	7	Qvt at top, Qva beneath
Brown sandy clay and gravel	7	15	contact unknown
Brown sandy clay	15	37	sand & sandy clay
Brown loose sand, medium	37	69	
Gray sandstone, water bearing at 225 feet	69	301	
Gray shale	301	344	Bedrock, Tsb

Casing 6-inch to 69 feet. Yield 1.5 gallons per minute with complete drawdown after 2 hours (bailer test). Static water level 86 feet on 03/28/1983.

T29N, R01E, Sec. 4

Well AAB078, 29N/01E-04Q
Domestic well, altitude 103 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Sandy clay	0	68	
Sandy clay, hard	68	93	Qvt
Basalt	93	97	
Gravel hardpan, water bearing at 106 feet	97	106	Qva, gravel
Sandstone	106	112	Bedrock, Tsb

Casing 6-inch to 94 feet. Perforated liner 5-inch from 94 to 112 feet. Yield 5 gallons per minute with little drawdown (bailer test). Static water level 90 feet on 05/23/1978.

Well AAB079, 29N/01E-04R
Domestic well, altitude 64 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Brown sandy topsoil	0	3	
Gray sandy clay	3	55	Qvt
Gray sandy shale	55	80	
Interbeded sandstone and shale, water bearing	80	130	Bedrock, Tsb

Casing 6-inch to 110 feet. Yield 25 gallons per hour (bailer test). Static water level 70 feet on 03/31/1981.

Well AAB080, 29N/01E-04F
Domestic well, altitude 110 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Top soil	0	1	
Brown sand, gravel, rocks	1	24	Qvt
Packed gray sand and pea gravel	24	54	Qva, sand, gravel, sandy clay, & clay
Sandstone and gray clay	54	68	
Stratified gray shale, clay, sandstone	68	87	
Stratified gray shale	87	155	
Light gray shale and clay	155	166	Bedrock, Tsb
Shale and sandstone	166	181	
Sandstone	181	208	
Sandstone, hard, water bearing	208	220	

Casing 6-inch to 78 feet. PVC liner from 72 to 220 feet. Liner perforated from 200 to 220 feet. Yield 30 gallons per minute with 20 feet of drawdown after 2.5 hours. Static water level 108 feet on 09/26/1973.

Well AAB081, 29N/01E-04G
Domestic well, altitude 75 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Top soil	0	1	
Sandy hardpan	1	53	Qvt at top, Qva beneath - contact unknown
Gray sandstone, water bearing @ 160 feet	53	195	Bedrock, Tsb

Casing 6-inch to 57 feet. Yield 1 gallon per minute (bailer test).
Static water level 81 feet on 09/12/1976.

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections

T29N, R01E, Sec. 4

Well GC-008, 29N/01E-04G
Domestic well, altitude 50 feet

Brown top soil	0	2	
Brown sandy loam soil	2	12	Qvt
Brown lightly cemented sand w/small gravel	12	19	
Brown loose sand, dry	19	46.5	
Brown sand, water bearing	46.5	47	Qva, sand
Gray sandstone	47	200.5	Bedrock, Tsb

Casing 6-inch to 45.5 feet. Liner 5-inch PVC from 43.5 to 50.6 feet and 4.5-inch PVC from 50.6 to 201.5 feet. Yield 0.25 gallons per minute with complete drawdown after 4 hours. Static water level 47.5 feet on 06/24/1986.

T29N, R01E, Sec. 5

Well GC-018, 29N/01E-05J
Domestic well, altitude 12 feet

Brown sandy clay	0	11	Qvt
Gray clay and broken shale	11	21	
Gray sandstone	21	200	Bedrock, Tsb

Casing 6-inch to 21.6 feet. Liner 4-inch PVC, from 0 to 200 feet. Liner perforated from 60 to 200 feet. Yield 0.5 gallons per minute with complete drawdown after 2 hours. Static water level 30 feet on 01/30/1978.

T29N, R01E, Sec. 8

Well AAB012, 29N/01E-08A
Domestic well, altitude 25 feet

Brown top soil	0	2	
Brown subsoil and boulders	2	12	
Brown cemented subsoil	12	18	Qva, sand, sandy clay, & clay
Brown clay and sand, firm	18	30	
Brown sand and gravel, firm	30	32	
Brown sand and gravel, medium	32	34	
Brown sand, coarse	34	38	Qva, sand & gravel
Brown sand, fine	38	44	
Brown sand, tacky	44	45	
Brown sandy clay, tacky	45	50	Qva, sandy clay

Casing 6-inch to 40 feet and 5-inch from 38.5 to 39 and 44 to 49 feet. Screened 5.5-inch, slot size 20 from 39 to 44 feet. Yield 14 gallons per minute with 1.5 feet of drawdown after 2 hours (bailer test). Static water level 31.5 feet on 03/07/1986.

T29N, R01E, Sec. 8

Well AAB069, 29N/01E-08R
Domestic well, altitude 60 feet

Materials	Thickness in Feet (From)	Thickness in Feet (To)	Lithologic Interpretations Used on Geologic Cross Sections
Sandy soil	0	1	Qvt
Clay with gravel	1	8	
Sandy clay	8	16	
Cemented sand and gravel	16	25	
Clay with rocks	25	28	
Clay	28	32	
Clay with sand	32	38	
Clay	38	42	
Cemented sand	42	53	sand & sandy clay
Cemented gravel	53	56	Qva, gravel & sand
Clay, sand, gravel, water bearing at 56 ft.	56	57	
Clay to soft sandstone	57	108	Bedrock, Tsb

Static water level 27 feet on 12/09/1970.

Well GC-072, 29N/01E-08R
Domestic well, altitude 35 feet

Materials	Thickness in Feet (From)	Thickness in Feet (To)	Lithologic Interpretations Used on Geologic Cross Sections
Soil	0	1	Qvt
Brown clay with rocks	1	10	
Brown clay with sand and gravel	10	38	
Brown clay with coarse sand	38	48	Qva, sand
Blue clay, medium soft	48	51	Bedrock, Tsb
Blue clay, soft	51	154	
Black shale, medium hard	154	157	

Casing 6-inch to 157 feet. Yield 10 gallons per minute with 100 feet of drawdown after 24 hours (bailer test). Static water level 57 feet on 12/12/1975.

T29N, R01E, Sec. 9

Well AAB005, 29N/01E-09G
Domestic well, altitude 118 feet

Materials	Thickness in Feet (From)	Thickness in Feet (To)	Lithologic Interpretations Used on Geologic Cross Sections
Gray clay	1	40	Qvt
Sandy clay	40	93	Qva, sand & sandy clay
Brown sandy clay	93	104	
Hard packed gravel	104	123	Qva, gravel & sand
Black peat soil	123	133	Qva, clay (?)
Brown sandy loam	133	138	
Brown gravel, water bearing	138	141	Qva, gravel & sand
Hardpan	141	---	Bedrock, Tsb

Casing 6-inch to 141 feet. Yield 15 gpm with little drawdown after 2 hours (bailer test). Static water level 112 feet on 12/17/1975.

Materials	**Thickness in Feet (From)**	**(To)**	**Lithologic Interpretations Used on Geologic Cross Sections**

T29N, R01E, Sec. 9

Well AAB006, 29N/01E-09B
Domestic well, altitude 94 feet

Top soil	0	1	
Gravel hardpan	1	4	Qvr
Brown sandy clay	4	18	Qvt
Brown sand, dry	18	95	
Brown sand, fine, wet	95	98	Qva, sand & sandy clay
Brown sand, coarse, wet	98	114	Qva, gravel & sand

Casing 6-inch to 109 feet. Screened 5-inch, slot size 14, from 109 to 114 feet. Yield 30 gallons per minute with 1 foot of drawdown after 2 hours (bailer test). Static water level 94 feet on 10/17/1989.

Well AAB007, 29N/01E-09A
Domestic well, altitude 70 feet

Sandy top soil	0	2
Sand, gravel, rocks and clay	2	6
Hard clay with sand and gravel	6	30
Hard clay with rocks	30	35
Hard clay with sand and gravel	35	72
Sandy clay with charcoal, water bearing	72	88
Gray clay with sand and gravel	88	105

Casing 6-inch to 100 feet. Screened 6-inch, slot size 15 from 100 to 105 feet. Yield 8 gallons per minute with 19 feet of drawdown after 2 hours (bailer test). Static water level 76 feet on 02/10/1981.

Well AAB010, 29N/01E-09D
Domestic well, altitude 113 feet

Brown top soil	0	2	
Brown sand and gravel	2	6	
Brown clay and gravel	6	23	Qvt
Gray hard clay	23	52	
Brown sandy clay	52	83	
Brown medium sand, loose	83	120	Qva, sand, sandy clay, & clay
Brown coarse sand, water bearing	120	134	
Brown muddy sand	134	---	Qva, sand & gravel

Casing 6-inch to 130 feet. Screened 5.5-inch, slot size 15, from 129 to 134 feet. Yield 15 gallons per minute with little drawdown after 1 hour (bailer test). Static water level 120 feet on 01/15/1983.

T29N, R01E, Sec. 9

Well AAB011, 29N/01E-09C
Domestic well, altitude 102 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Light brown sandy clay	0	6	Qvt
Brown sandy clay	6	16	
Gray gravel and brown sand	16	16.5	Qva, sand & sandy clay
Brown sandstone	16.5	20	
Brown sandy clay, hardpacked	20	87	
Sandy gravel, gray fine sand, pea gravel	87	101	Qva, sand & gravel
Gravel, medium to large, water bearing	101	116	Qva, gravel

Casing 6-inch to 110 feet. Screened 5-inch, slot size 12, from 110 to 115 feet. Yield 6 gallons per minute with 5 feet of drawdown after 1.5 hours (bailer test). Static water level 104 feet on 05/12/1989.

Well AAB070, 29N/01E-09P
Domestic well, altitude 90 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Brown clay and rocks, hard	0	8	
Gray clay with sand and gravel, hard	8	22	
Gray clay with sand, hard	22	46	
Gray clay with sand and gravel, hard	46	54	
Gray clay with sand, hard	54	68	
Gray clay with sand and gravel, hard	68	78	

Casing 6-inch to 73 feet. Screened 6-inch, slot size 25 from 73 to 78 feet. Yield 9 gallons per minute with 10 feet of drawdown after 2 hours (bailer test). Static water level 63 feet on 10/24/1977.

Well AAB073, 29N/01E-09P
Domestic well, altitude 125 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Top soil	0	5	Qvt
Sandy hardpan	5	30	
Cemented sand	30	37	
Gray mud, water bearing	37	40	
Brown sandy clay	40	60	
Brown sand	60	108	Qva, sand & sandy clay
Gray sand	108	124	
Water bearing gravel	124	130	Qva, gravel & sand
Blue clay	130	150	Bedrock, Tsb
Gray shale	150	200	
Gray clay	200	240	

Casing 6-inch to 235 feet, perforated from 37 to 40 and 124 to 130 feet. Yield 12 gallons per minute with 6 feet of drawdown after 3 hours (bailer test). Static water level 102 feet on 06/13/1978.

T29N, R01E, Sec. 9

Well AAB074, 29N/01E-09P
Domestic well, altitude 90 feet

Materials	Thickness in Feet		Lithologic Interpretations Used on Geologic Cross Sections
	(From)	(To)	
Rocky soil	0	8	Qvt
Cemented gravel	8	25	
Clay with sand, hard	25	65	
Gray clay with sand and some gravel	65	72	Qva, sand

Screened slot size 25 from 64 to 69 feet. Static water level 57 feet in 10/1972.

Well GC-075, 29N/01E-09J
Domestic well, altitude 65 feet

Brown topsoil, sandy loam	0	4	Qvt
Gray clay hardpan	4	12	
Brown clay, sandy	12	36	
Brown sand, clay	36	53	Qva, sand
Gray clay, chunky	53	56	Qva, clay
Gray sandstone, trace water	56	58	Bedrock, Tsb
Dark gray clay, sandy, soft	58	108	
Light-gray clay, soft	108	125	
Medium-gray clay, soft	125	150	
Gray sandstone, fractured, water bearing	150	151	
Gray clay, hard	151	---	

Casing 6-inch to 151 feet. Static water level 61 feet on 11/09/1988.

Well GC-076, 29N/01E-09A
Domestic well, altitude 90 feet

Topsoil	0	2	Qvt
Gray brown sand	2	23	
Sand	23	103	Qva, sand, sandy clay, & clay
Clay brown cemented sand gravel	103	108	Qva, sand & gravel

Casing 6-inch to 98 feet, screened slot size 20 from 98 to 103 feet. Yield 12 gallons per minute with zero feet drawdown after one hour (bailer test). Static water level 95 feet on 01/06/1984.

Well GC-077, 29N/01E-09A
Domestic well, altitude 90 feet

No description	0	96	Qvt & Qva - contact unknown
Rock iron & course sand	96	105	Qva, sand & gravel
Course water bearing sand	105	107	
Water bearing brown sandy clay	107	111	Qva, sandy clay
Gray hard clay	111	---	Bedrock, Tsb

Casing 6-inch to 102 feet, screened slot size 20 from 102 to 111 feet. Yield 5 plus gallons per minute with zero feet drawdown after one-half hour (bailer test). Static water level 100 feet on 10/24/1986.

T30N, R01E, Sec. 18

Well AAB051, 30N/01E-18R
Domestic well, altitude 85 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Surface soil	0	1	
Brown sand medium	1	4	Qvt
Brown to gray cemented sand	4	12	
Brown sandy clay	12	19	
Brown and gray sand	19	26	
Brown fine sandy clay	26	33	
Brown sand medium	33	38	Qva, sand & clay
Brown silty clay	38	45	
Brown silty sand	45	51	
Brown silty clay	51	69	
Firm brown clay	69	76	
Brown sand	76	78	
Brown coarse sand	78	90	
Brown fine sand, water bearing	90	94	Qva, sand
Brown coarse sand, water bearing	94	105	

Casing 6-inch to 91 feet, 5-inch from 89 to 91 and 96 to 101 feet. Screened 5.5-inch, slot size 14, from 91 to 96 feet. Yield 10 gallons per minute with 5 feet of drawdown (bailer test). Static water level 83 feet in 04/1982.

T30N, R01E, Sec. 20

Well AAB043, 30N/01E-20P
Domestic well, altitude 104 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Fill material	0	3	
Brown gravelly clay	3	21	Qvt
Brown till, boulder at 45 feet	21	63	
Brown cemented gravel	63	82	Qva, gravel
Brown sandy clay	82	89	Qva, sandy clay
Brown sand, dry	89	108	
Brown medium sand, water bearing	108	113	Qva, sand
Brown coarse sand, water bearing	113	121	

Casing 6-inch to 109 feet. Screened from 109.5 to 114.8. Yield 10 gallons per minute with little drawdown after 3 hours (bailer test).

Well AAB044, 30N/01E-20Q
Domestic well, altitude 94 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Brown sandy clay	0	5	
Gray sandy clay	5	60	Qvt on top, Qva beneath
Brown sandy clay	60	85	Contact unknown - sandy clay
Gray sandy clay	85	100	
Sand, water bearing	100	117	Qva & sand

Casing 6-inch to 114 feet. Screened 6-inch, slot size 14, from 114 to 117 feet. Yield 12 gallons per minute with 2 feet of drawdown after 1 hour (bailer test). Static water level 97 feet on 08/14/1985.

T30N, R01E, Sec. 20

Well AAB045, 30N/01E-20Q
Domestic well, altitude 104 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Surface soil	0	1	Qvt
Brown cemented clay and gravel	1	10	
Brown sandy clay and gravel	10	25	
Brown firm sand and gravel with cobbles	25	38	Qva, sand & gravel
Brown fine sand	38	92	Qva, sand
Brown firm clay	92	95	Qva, clay
Brown medium sand	95	97	
Brown clay	97	98	
Brown medium sand, water bearing	98	110	Qva, sand
Gray sand, water bearing	110	125	

Casing 6-inch to 109 feet, 5-inch from 108 to 109 and 114 to 120 feet. Screened 5.5-inch, slot size 16, from 109 to 114 feet. Yield 10 gallons per minute with 1 foot of drawdown after 2 hours. Static water level 103 feet on 05/04/1983.

Well AAB047, 30N/01E-20M
Domestic well, altitude 35 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Top soil	0	5	Qvt
Hardpan	5	17	
Sandy clay	17	36	Qva, sandy clay
Sand, water bearing	36	44.5	Qva, sand

Casing 6-inch to 40 feet. Screened 6-inch, slot size 12, from 40 to 44.5 feet. Yield 8 gallons per minute with little drawdown (bailer test). Static water level 36 feet on 09/13/1977.

Well AAB049, 30N/01E-20D
Public water supply well, altitude 35 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Brown sandy clay	0	20	Qva, sandy clay
Brown fine sand	20	23	Qva, sand
Brown sand, medium, water bearing	23	50	

Casing 6-inch to 45 feet. Screened 5.5-inch, slot size 10, from 45 to 49.5 feet. Yield 12 gallons per minute with 2 feet of drawdown after 2 hours (bailer test). Static water level 39 feet on 05/20/1969.

Well AAB050, 30N/01E-20D
Domestic well, altitude 43 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Brown sandy clay	0	31	Qva, sandy clay
Brown tight firm sand	31	49	Qva, sand
Brown fine sand, water bearing	49	60	

Casing 6-inch to 53 feet, 5-inch from 51 to 53 feet. Screened 5-inch, slot size 15, from 53 to 58 feet. Yield 10 gallons per minute with 6 feet of drawdown after 2 hours (bailer test). Static water level 47 feet on 07/05/1979.

T30N, R01E, Sec. 20

Well GC-048, 30N/01E-20D
Domestic well, altitude 25 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Brown surface soil	0	2	
Brown sandy gravely clay	2	23	Qva, sandy clay
Brown sand, fine, water bearing	23	33	Qva, sand

Casing 6-inch to 29 feet, 5-inch from 27.5 to 28 feet. Screened 5.5-inch, slot size 10 , from 28 to 33 feet. Yield 6 gallons per minute with 1 foot of drawdown after 1 hour (bailer test). Static water level 23 feet on 01/12/1981.

T30N, R01E, Sec. 21

Well AAB046, 30N/01E-21E
Domestic well, altitude 120 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Surface soil	0	2	
Brown cemented sandy clay and gravel	2	19	Qvt
Brown loose sand	19	24	
Brown to gray cemented sandy clay and gravel	24	51	Qva, sand & gravel
Brown fine sand and silty clay	51	72	Qva, sand
Brown and gray clay with peat layers	72	87	Qva, clay
Brown fine sand	87	104	Qva, sand
Brown silty clay	104	120	Qva, sandy clay
Brown medium sand	120	125	
Brown medium sand, water bearing	125	140	Qva, sand

Casing 6-inch to 133 feet. Screened 5.5-inch, slot size 12, from 133 to 138 feet. Yield 15 gallons per minute with 1 foot of drawdown (bailer test). Static water level 125 feet on 07/13/1981.

T30N, R01E, Sec. 28

Well AAB030, 30N/01E-28L
Domestic well, altitude 35 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Top soil	0	5	
Sandy hardpan	5	15	
Sand	15	35	
Sand, water bearing at 37 feet	35	46	

Casing 6-inch to 42 feet. Screened 6-inch, slot size 12 from 42 to 46 feet. Yield 8 gallons per minute with little drawdown (bailer test). Static water level 37.5 feet on 09/09/1977.

T30N, R01E, Sec. 28

Well AAB031, 30N/01E-28F
Domestic well, altitude 60 feet

Materials	Thickness in Feet (From)	Thickness in Feet (To)	Lithologic Interpretations Used on Geologic Cross Sections
Brown sandy clay and gravel	0	10	
Gray sandy clay	10	45	
Gray hardpan with gravel	45	50	
Gray sandy clay	50	58	
Sand and gravel, clean	58	65	
Sand and gravel, water bearing	65	80	

Casing 6-inch to 64 feet, 5-inch from 61.6 to 62.3 and 67.6 to 72.6. Screened 5-inch, slot size 15, from 62.3 to 67.6. Yield 7.5 gallons per minute with 1 foot of drawdown after 4 hours (bailer test). Static water level 60 feet on 11/26/1986.

Well AAB032, 30N/01E-28L
Domestic well, altitude 64 feet

Materials	Thickness in Feet (From)	Thickness in Feet (To)	Lithologic Interpretations Used on Geologic Cross Sections
Top soil	0	1	
Clay, with gravel	1	4	
Sand, cemented	4	22	
Gravel, cemented	22	51	
Sand, cemented	51	55	
Clay, with fine sand	55	65	
Sand with clay	65	71	

Casing 6-inch to 66 feet. Screened 6-inch, slot size 20, from 66 to 71 feet. Static water level 60 feet on 05/19/1973.

Well AAB034, 30N/01E-28E
Domestic well, altitude 105 feet

Materials	Thickness in Feet (From)	Thickness in Feet (To)	Lithologic Interpretations Used on Geologic Cross Sections
Brown surface soil	0	2	
Brown cemented sand and gravely clay	2	75	Qvt
Brown sand and gravel	75	90	
Brown sandy clay and gravel	90	99	
Brown sand, water bearing	99	106	Qva, sand & gravel
Gray clay, cemented gravel	106	111	

Casing 6-inch to 101 feet, 5-inch from 105 to 111 feet. Screened 5.5-inch, slot size 12, from 99.5 to 105 feet. Yield 5 gallons per minute with 1 foot of drawdown after 2 hours (bailer test). Static water level 99 feet on 02/24/1981.

Materials | **Thickness in Feet (From) (To)** | **Lithologic Interpretations Used on Geologic Cross Sections**

T30N, R01E, Sec. 28

Well AAB085, 30N/01E-28D
Domestic well, altitude 120 feet

Brown top soil	0	3	
Brown cemented subsoil, hard	3	27	
Brown cemented sand and gravel	27	78	
Brown lightly cemented sand with some gravel	78	93	
Brown lightly cemented sand and clay	93	106	
Brown sand and clay	106	111	
Brown fine sand, loose, dry	111	121	
Brown fine sand, water bearing	121	136	
Brown coarse sand, water bearing	136	140	

Casing 6-inch to 130 feet, 5-inch from 135 to 140 feet. Screened 5.5-inch, slot size 12, from 130 to 135 feet. Yield 7 gallons per minute with little drawdown after 3 hours (bailer test). Static water level 121 feet on 05/24/1990.

T30N, R01E, Sec. 29

Well AAB036, 29N/01E-29J
Domestic well, altitude 89 feet

Brown surface soil	0	2	
Brown cemented sand and gravel	2	79	
Brown cemented sand and gravel with Qvt gray clay	79	83	Qvt
Loose sand and gravel, seepage	83	84	
Gray cemented sand and gravel	84	116	
Gray fine sand	116	119	Qva, sand & gravel
Gray cemented gravel	119	120	

Casing 6-inch to 115 feet. Screened 5.5-inch, slot size 12, from 114.5 to 119.5 feet. Yield 6 gallons per minute with 17 feet of drawdown after 2 hours (bailer test). Static water level 91 feet on 07/12/1982.

Well AAB037, 30N/01E-29A
Domestic well, altitude 106 feet

Brown surface soil	0	2	
Brown cemented sand and gravel	2	55	Qvt
Brown medium sand	55	70	
Brown cemented sand and gravel	70	83	Qva, sand & gravel
Brown sandy clay with layers of cemented gravel	83	105	Qva, sandy clay
Brown sand and gravel	105	111	
Gray cemented sand and gravel	111	119	Qva, sand & gravel
Gray fine to medium sand and gravel	119	125	

Casing 6-inch to 119 feet, 5-inch from 117 to 119 feet. Screened 5.5-inch, slot size 30, from 119 to 124 feet. Yield 7 gallons per minute with 6 feet of drawdown after 2 hours (bailer test). Static water level 109 feet on 10/21/1981.

Well AAB038, 30N/01E-29R
Domestic well, altitude 20 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Brown surface soil	0	1	
Cemented gravel and clay	1	25	Qvt
Cemented gravel and clay	25	37	
Brown tight gravel, water bearing	37	40	
Grayish brown cemented sand, Gravel and clay	40	56	Qva, sand & gravel
Brown clay	56	60	Qva, clay

Casing 6-inch to 60 feet, perforated from 39.5 to 42.5 feet. Yield 100 gallons per minute with 21 feet of drawdown (bailer test). Static water level 17 feet on 11/29/1977.

Well AAB039, 30N/01E-29R
Public supply well, altitude 22 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Brown top soil	0	5	
Brown gravel, clay, and boulders, cemented	5	16	
Brown gravel and clay	16	25	
Brown gravel and coarse sand, tight, water bearing	25	30	
Brown gravel, loose, water bearing	30	32	
Gravel, tight, water bearing	32	33	
Gray sand, water bearing	33	47	
Gray sand and medium gravel, water bearing	47	60	

Casing 6-inch to 26 feet, 5.5-inch from 24 to 26.3 feet and 31.6 to 41.6 feet. Screened 5.5-inch, slot size 60 from 26.3 to 31.6 feet. Yield 20 gallons per minute with 1 foot of drawdown after 4 hours (bailer test). Static water level 22.5 feet on 12/27/1977.

Well AAB041, 30N/01E-29K
Domestic well, altitude 38 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Brown top soil	0	2	
Brown clay, sandy	2	10	
Brown gravel, cemented	10	32	
Brown sand, coarse, dry	32	40	
Sand and gravel, loose	40	43	
Brown gravel, water bearing	43	61	

Casing 6-inch to 46.5 feet, 5-inch from 45 to 45.5 feet and 50.5 to 61 feet. Screen 5.5-inch, slot size 22 from 45.5 to 50.5 feet. Yield 20 gallons per minute with 1 foot of drawdown after 3 hours (bailer test). Static water level 43 feet on 10/17/1978.

T30N, R01E, Sec. 29

Well AAB042, 30N/01E-29C
Domestic well, altitude 50 feet

Materials	From	To	Lithologic Interpretations
Brown sandy clay and boulders	0	15	Qvt
Brown sandy clay	15	54	Qva, sandy clay
Gray sand, water bearing	54	64	Qva, sand

Casing 6-inch to 59 feet. Screened 6-inch, slot size 15, from 59 to 64 feet. Yield 12 gallons per minute with 3 feet of drawdown after 1 hour (bailer test). Static water level 50.5 feet on 08/02/1985.

Well AAB068, 30N/01E-29K
Domestic well, altitude 40 feet

Materials	From	To	Lithologic Interpretations
Brown top soil	0	1	
Brown sandy subsoil	1	3	
Brown gravel and boulders, cemented	3	12	
Brown sandy clay	12	15	
Brown sand, gravel, and clay, dry	15	23	
Brown sand, dry	23	30	
Brown gravel, tight	30	38	
Brown gravel, tight, water bearing	38	44	
Brown gravel, loose, water bearing	44	46	

Casing 6-inch to 39 feet, 5-inch from 36.3 to 36.8 feet and 42 to 47 feet. Screened 5-inch, slot size 18 from 36.8 to 42 feet. Yield 6 gallons per minute with 1 foot of drawdown after 4 hours (bailer test). Static water level 37.4 feet on 09/25/1986.

Well AAB084, 30N/01E-29R
Domestic well, altitude 30 feet

Materials	From	To	Lithologic Interpretations
Brown sandy clay	0	14	
Gray sandy clay hardpan	14	25	
Gray sandy clay	25	50	
Sandy clay, water bearing	50	62	
Brown shale	62	--	

Casing 6-inch to 55 feet. Screened 6-inch, slot size 16 from 55 to 60 feet. Yield 4 gallons per minute with 27 feet of drawdown after 3 hours (bailer test). Static water level 28 feet on 11/04/1985.

Materials	**Thickness in Feet (From)**	**(To)**	**Lithologic Interpretations Used on Geologic Cross Sections**

T30N, R01E, Sec. 32

Well AAB052, 30N/01E-32Q
Domestic well, altitude 20 feet

Brown rocky top soil	0	4	
Brown sand and gravel	4	6	
Brown sandstone	6	12	
Gray sandstone	12	39	
Dark gray shale	39	46	
Gray sandstone	46	55	

Casing 6-inch to 20 feet. Yield 1 gallon per minute with total drawdown after 1 hour. Static water level 5 feet on 05/23/1974.

Well AAB053, 30N/01E-32Q
Domestic well, altitude 25 feet

Black top soil	0	2	
Brown clay with sand and gravel	2	6	
Brown clay with fine sand	6	13	
Gray sandstone	13	35	
Gray shale	35	36	
Gray sandstone	36	46	
Gray shale	46	47	
Gray shale, water bearing	47	48	
Gray shale, hard	48	61	
Gray sandstone	61	92	
Gray shale, soft	92	93	
Gray sandstone, hard	93	105	
Gray shale	105	106	
Gray sandstone, hard	106	111	
Gray shale, water bearing	111	112	
Gray sandstone, hard	112	115	
Gray shale	115	117	
Gray sandstone	117	130	
Gray shale, hard	130	139	
Gray sandstone, soft	139	146	
Gray shale, hard	146	147	
Gray sandstone	147	152	
Gray shale, hard	152	153	
Gray sandstone	153	167	
Gray shale, hard	167	168	
Gray sandstone	168	175	
Gray shale	175	183	
Gray sandstone, hard	183	190	
Gray shale, soft	190	194	
Gray sandstone	194	208	
Gray sand, water bearing	208	209	
Gray sandstone, hard	209	---	

Casing 6-inch to 19 feet. Liner 4.5-inch from 11 to 209 feet. Liner perforated from 141 to 181 and 201 to 209 feet. Yield 10 gallons per minute with 20 feet of drawdown after 2 hours (bailer test). Static water level 28 feet on 08/03/1989.

T30N, R01E, Sec. 32

Well AAB054, 30N/01E-32K
Domestic well, altitude 30 feet

Materials	Thickness in Feet (From)	Thickness in Feet (To)	Lithologic Interpretations Used on Geologic Cross Sections
Top soil	0	3	
Brown sticky clay	3	14	
Gray clay, sandy	14	18	
Gray sandstone	18	235	

Casing 6-inch to 22 feet. Yield 1 gallon per minute (bailer test). Static water level 20 feet on 10/20/1974.

Well AAB056, 30N/01E-32K
Domestic well, altitude 35 feet

Materials	Thickness in Feet (From)	Thickness in Feet (To)	Lithologic Interpretations Used on Geologic Cross Sections
Top soil	0	2	
Brown clay	2	6	
Brown hardpan	6	10	
Blue clay	10	11	
Blue sandstone	11	64	
Blue clay	64	65	
Blue sandstone	65	120	
Blue clay	120	121	
Blue sandstone	121	155	
Blue sandstone, fractured	155	157	
Blue sandstone	157	160	

Casing 6-inch to 28 feet. Yield 5 gallons per minute with 148 feet of drawdown after 2 hours (bailer test). Static water level 7 feet on 06/25/1984.

Well AAB061, 30N/01E-32G
Domestic well, altitude 48 feet

Materials	Thickness in Feet (From)	Thickness in Feet (To)	Lithologic Interpretations Used on Geologic Cross Sections
Top soil with clay	0	15	
Sandstone, water bearing fracture at 180 feet	15	240	

Casing 6-inch to 20 feet. Yield 5 gallons per minute (bailer test). Static water level 20 feet on 10/26/1976.

Well AAB065, 30N/01E-32H
Domestic well, altitude 49 feet

Materials	Thickness in Feet (From)	Thickness in Feet (To)	Lithologic Interpretations Used on Geologic Cross Sections
Top soil	0	7	Qvt
Shale	7	65	
Shale, water bearing	65	130	
Gray clay	130	150	Bedrock, Tm & Tq (?)
Sandstone, water bearing	150	180	

Casing 6-inch to 21 feet. Yield 3 gallons per minute (bailer test). Static water level 24 feet on 07/18/1977.

T30N, R01E, Sec. 32

Well GC-058, 30N/01E-32G
Domestic well, altitude 40 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Topsoil	0	2	
Gray sandy clay	2	8	Qvt
Yellow sandy clay	8	11	
Gray sandstone, soft	11	135	
Gray sandstone, hard	135	136	
Gray sandstone, soft	136	147	
Gray sandstone, hard	147	151	Bedrock, Tm
Gray sandstone, soft	151	154	
Gray sandstone, hard	154	160	
Gray sandstone, soft	160	185	

Casing 6-inch to 14 feet. Yield 1 gallon per minute (bailer test). Static water level 18 feet in 03/1972.

Well GC-063, 30N/01E-32H
Domestic well, altitude 45 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Brown sandy clay	0	12	
Dark gray sandy clay	12	18	Qvt
Dark gray sandstone	18	85	
Light gray sandstone	85	103	Bedrock, Tm
Sandstone, water bearing	103	225	

Casing 6-inch to 18 feet. Yield 165 gallons in 24 hours. Static water level 17 feet on 07/07/1986.

T30N, R01E, Sec. 33

Well AAB024, 30N/01E-33M
Domestic well, altitude 50 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Brown top soil	0	2	
Brown till	2	12	
Gray till	12	39	
Gray sand, coarse	39	48	
Gray sand and gravel	48	49	
Brown clay	49	50	
Gray sand and gravel, water bearing at 51 ft.	50	57	
Brown till	57	--	

Casing 6-inch to 51 feet, 5-inch from 52 to 56 feet. Screened 5.5-inch, slot size 50 from 48 to 52 feet. Yield 3 gallons per minute with 0.3 feet of drawdown after 2 hours (bailer test). Static water level 51 feet on 03/25/1984.

T30N, R01E, Sec. 33

Well AAB025, 30N/01E-33F
Domestic well, altitude 75 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Brown top soil	0	3	
Brown gravel and boulders, cemented	3	19	Qvt
Brown sand	19	59	
Brown sand, water bearing	59	70	Qva, sand

Casing 6-inch to 57 feet, 5-inch from 61 to 69 feet. Screened 5.5- inch, slot size 20 from 56 to 61 feet. Yield 5 gallons per minute with little drawdown after 2 hours (bailer test). Static water level 59 feet on 11/08/1982.

Well AAB026, 30N/01E-33C
Domestic well, altitude 40 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Top soil	0	1	
Sand	1	7	
Sandy gravel hardpan	7	18	
Brown sand, some gravel, water at 45 feet	18	53	

Casing 6-inch to 42 feet. Screened 5-inch, slot size 30 from 42 to 47 feet. Yield 8 gallons per minute with 5 feet of drawdown after 2 hours (bailer test). Static water level 39 feet on 05/23/1977.

Well AAB028, 30N/01E-33D
Domestic well, altitude 45 feet

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Top soil	0	1	
Brown clay, sand, and gravel	1	22	
Gray clay and sand, hard	22	36	
Brown clay, sand, and gravel, hard	36	38	
Gray clay and sand, hard	38	42	
Gray clay, sand, and gravel, soft	42	48	

Casing 6-inch to 43 feet. Screened 6-inch, slot size 20 from 43 to 48 feet. Yield 20 gallons per minute with 4 feet of drawdown after 3 hours (bailer test). Static water level 38 feet on 05/18/1976.

Well AAB083, 30N/01E-33E
Domestic well, altitude 35 feet.

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections
Brown sandy clay	0	15	Qvt
Brown sandstone	15	60	
Gravel, water bearing	60	61	Bedrock, Tm (?)
Gray sandstone	61	62	

Casing 6-inch to 60 feet. Yield 0.5 gallons per minute with total drawdown. Static water level 57 feet on 06/15/1988.

Materials	Thickness in Feet (From)	(To)	Lithologic Interpretations Used on Geologic Cross Sections

T30N, R01E, Sec. 33

Well GC-082, 30N/01E-33L
Domestic Well, altitude 50 feet

Brown top soil	0	1
Brown cemented gravel and sand	1	40
Brown sand, dry	40	47.5
Brown gravel, lightly cemented	47.5	50
Brown sand with clay binder	50	51
Large gravel, tight, water bearing	51	54
Brown sand and small gravel, water bearing	54	60

Casing 6-inch to 51.7 feet. Screened slot size 25 from 48.5 to 53.5 feet. Yield 6 gallons per minute with little drawdown after 2 hours. Static water level 51.6 feet on 07/14/1986.

Well GC-088, 30N/01E-33P
Domestic well, altitude 80 feet

Brown top soil	0	1
Brown sandy clay	1	19
Brown sand	19	48
Gray gravel, sand, and clay	48	69
Gray gravel	69	81
Gray shale and sandstone	81	470

Encountered saltwater, well grouted and abandoned.

Appendix E

Useful Information for Sizing a Rainfall Catchment System

In recent years, rainfall-catchment systems have become increasingly popular on Marrowstone Island as primary or secondary water sources. Several residents are currently collecting rainfall to satisfy both their potable and non-potable water needs and to reduce reliance on well water.

Literature about designing, sizing, and installing catchment systems is readily available through the library system. Please refer to the works by Williams (1991), Frasier and Myers (1983), and AAVIM (1982) for a detailed discussion of catchment system design and installation.

Williams (1991), poses a list of questions one should consider prior to designing and installing a catchment system.

1) How much surface area (roofs, etc.) is available to capture rainfall?
2) What is the average annual rainfall in your area?
3) What type of catchment and storage system will work best given your finances, space constraints, etc.?
4) What will the water be used for (domestic, irrigation, etc.), when (year round, summer only, etc.), and how much will be used?
5) What water treatment, if any, will be required to safely satisfy the above needs?
6) Can you buy or build a container(s) capable of safely storing the amount of water you need or desire?

The following information is provided to help property owners on Marrowstone Island answer these and other questions that may arise during the design and installation of a catchment system.

Useful Formulas:

The quantity of rainfall available for capture, per square foot of catchment surface area, per inch of precipitation, can be calculated using the following formula:

$$C = P \times A \times E \times 0.623$$

Where:

C = Quantity of rainfall available for capture, in gallons.

P = Quantity of rainfall, in inches.

A = "Footprint" surface area of the catchment system, in square feet.

E = Runoff efficiency of the catchment surface

The runoff efficiency of catchment surfaces varies according to the material used to construct them. Catchments constructed of impervious-membrane material such as asphalt-fabric, sheet metal, or artificial rubber are essentially 100 percent efficient at capturing rainfall (Table E-1). Accordingly, most of the rainfall that lands on catchments constructed of these materials will be available for storage and later use. More permeable catchment surfaces such as concrete, paraffin wax, or gravel covered polyethylene are less efficient at capturing runoff and have efficiencies of 60 to 90 percent.

TABLE E-1
Runoff Efficiencies for Selected Catchment Materials (after Frasier and Myers, 1983)

	Runoff Efficiency (Percent)	Efficiency Factor
Concrete surfaces	60-85	0.6 to 0.85
Paraffin wax surface	70-95	0.7 to 0.95
Gravel covered polyethylene	85-90	0.85 to 0.90
Asphalt-fabric	95-100	0.95 to 1.0
Sheet Metal	95-100	0.95 to 1.0
Artificial Rubber Membranes	98-100	0.95 to 1.0

Tables E-2 and E-3 assume 100 percent capture efficiency. For most systems, capture volumes will be less than indicated, due to evaporative loss, storage within depressions on the catchment surface, or passage of rainfall through or into the catchment material. Capture volumes for less efficient materials can be determined from Tables E-2 and E-3 by multiplying the indicated capture volume by the efficiency factor for the appropriate catchment material (Table E-1).

TABLE E-2
Gallons of Water Potentially Available for Capture
(Based on Catchment System Surface Area and Precipitation Volume)

Precipitation (inches)	Surface Area of Catchment (Ft^2)									
	250	500	750	1000	1250	1500	1750	2000	2250	2500
	Gallons of Rainfall Available for Capture									
0.1	16	31	47	62	78	94	109	125	140	156
0.2	31	62	94	125	156	187	218	249	281	312
0.3	47	94	140	187	234	281	327	374	421	468
0.4	62	125	187	249	312	374	436	499	561	623
0.5	78	156	234	312	390	468	545	623	701	779
0.6	94	187	281	374	468	561	655	748	842	935
0.7	109	218	327	436	545	655	764	873	982	1091
0.8	125	249	374	499	623	748	873	997	1122	1247
0.9	140	281	421	561	701	842	982	1122	1262	1403
1.0	156	312	468	623	779	935	1091	1247	1403	1558
1.1	171	343	514	686	857	1029	1200	1371	1543	1714
1.2	187	374	561	748	935	1122	1309	1496	1683	1870
1.3	203	405	608	810	1013	1216	1418	1621	1823	2026
1.4	218	436	655	873	1091	1309	1527	1745	1964	2182
1.5	234	468	701	935	1169	1403	1636	1870	2104	2338
1.6	249	499	748	997	1247	1496	1745	1995	2244	2493
1.7	265	530	795	1060	1325	1590	1854	2119	2384	2649
1.8	281	561	842	1122	1403	1683	1964	2244	2525	2805
1.9	296	592	888	1184	1480	1777	2073	2369	2665	2961
2.0	312	623	935	1247	1558	1870	2182	2493	2805	3117
2.1	327	655	982	1309	1636	1964	2291	2618	2945	3273
2.2	343	686	1029	1371	1714	2057	2400	2743	3086	3428
2.3	358	717	1075	1434	1792	2151	2509	2867	3226	3584
2.4	374	748	1122	1496	1870	2244	2618	2992	3366	3740
2.5	390	779	1169	1558	1948	2338	2727	3117	3506	3896
2.6	405	810	1216	1621	2026	2431	2836	3241	3647	4052
2.7	421	842	1262	1683	2104	2525	2945	3366	3787	4208
2.8	436	873	1309	1745	2182	2618	3054	3491	3927	4363
2.9	452	904	1356	1808	2260	2712	3163	3615	4067	4519
3.0	468	935	1403	1870	2338	2805	3273	3740	4208	4675
3.1	483	966	1449	1932	2415	2899	3382	3865	4348	4831
3.2	499	997	1496	1995	2493	2992	3491	3989	4488	4987
3.3	514	1029	1543	2057	2571	3086	3600	4114	4628	5143
3.4	530	1060	1590	2119	2649	3179	3709	4239	4769	5298
3.5	545	1091	1636	2182	2727	3273	3818	4363	4909	5454
3.6	561	1122	1683	2244	2805	3366	3927	4488	5049	5610
3.7	577	1153	1730	2306	2883	3460	4036	4613	5189	5766
3.8	592	1184	1777	2369	2961	3553	4145	4737	5330	5922
3.9	608	1216	1823	2431	3039	3647	4254	4862	5470	6078
4.0	623	1247	1870	2493	3117	3740	4363	4987	5610	6233
4.1	639	1278	1917	2556	3195	3834	4472	5111	5750	6389
4.2	655	1309	1964	2618	3273	3927	4582	5236	5891	6545
4.3	670	1340	2010	2680	3350	4021	4691	5361	6031	6701
4.4	686	1371	2057	2743	3428	4114	4800	5485	6171	6857
4.5	701	1403	2104	2805	3506	4208	4909	5610	6311	7013
4.6	717	1434	2151	2867	3584	4301	5018	5735	6452	7168
4.7	732	1465	2197	2930	3662	4395	5127	5859	6592	7324
4.8	748	1496	2244	2992	3740	4488	5236	5984	6732	7480
4.9	764	1527	2291	3054	3818	4582	5345	6109	6872	7636
5.0	779	1558	2338	3117	3896	4675	5454	6233	7013	7792
5.1	795	1590	2384	3179	3974	4769	5563	6358	7153	7948
5.2	810	1621	2431	3241	4052	4862	5672	6483	7293	8103
5.3	826	1652	2478	3304	4130	4956	5781	6607	7433	8259
5.4	842	1683	2525	3366	4208	5049	5891	6732	7574	8415
5.5	857	1714	2571	3428	4285	5143	6000	6857	7714	8571
5.6	873	1745	2618	3491	4363	5236	6109	6981	7854	8727
5.7	888	1777	2665	3553	4441	5330	6218	7106	7994	8883
5.8	904	1808	2712	3615	4519	5423	6327	7231	8135	9038
5.9	919	1839	2758	3678	4597	5517	6436	7355	8275	9194
6.0	935	1870	2805	3740	4675	5610	6545	7480	8415	9350

TABLE E-3
Gallons of Rainfall Available for Capture by Month and Year, for Port Townsend, Wa.

Pt Townsend Monthly Precipitation (Inches)	Surface Area of Catchment System (Ft^2)									
	250	500	750	1000	1250	1500	1750	2000	2250	2500
	Gallons of Rainfall Available for Capture, by Month									
January										
Min (0.25)	39	78	117	156	195	234	273	312	350	389
Max (4.71)	734	1467	2201	2934	3668	4401	5135	5869	6602	7336
Mean (2.18)	340	679	1019	1358	1698	2037	2377	2716	3056	3395
February										
Min (0.30)	47	93	140	187	234	280	327	374	421	467
Max (3.54)	551	1103	1654	2205	2757	3308	3859	4411	4962	5514
Mean (1.69)	263	526	790	1053	1316	1579	1843	2106	2369	2632
March										
Min (0.26)	40	81	121	162	202	243	283	324	364	405
Max (3.47)	540	1081	1621	2162	2702	3243	3783	4324	4864	5405
Mean (1.74)	271	542	813	1084	1355	1626	1897	2168	2439	2710
April										
Min (0.03)	5	9	14	19	23	28	33	37	42	47
Max (3.41)	531	1062	1593	2124	2656	3187	3718	4249	4780	5311
Mean (1.45)	226	452	678	903	1129	1355	1581	1807	2033	2258
May										
Min (0.33)	51	103	154	206	257	308	360	411	463	514
Max (2.83)	441	882	1322	1763	2204	2645	3085	3526	3967	4408
Mean (1.43)	223	445	668	891	1114	1336	1559	1782	2005	2227
June										
Min (0.10)	16	31	47	62	78	93	109	125	140	156
Max (3.15)	491	981	1472	1962	2453	2944	3434	3925	4416	4906
Mean (1.29)	201	402	603	804	1005	1206	1406	1607	1808	2009
July										
Min (0.01)	2	3	5	6	8	9	11	12	14	16
Max (2.93)	456	913	1369	1825	2282	2738	3194	3651	4107	4563
Mean (0.86)	134	268	402	536	670	804	938	1072	1206	1339
August										
Min (0.00)	0	0	0	0	0	0	0	0	0	0
Max (2.80)	436	872	1308	1744	2181	2617	3053	3489	3925	4361
Mean (0.95)	148	296	444	592	740	888	1036	1184	1332	1480
September										
Min (0.07)	11	22	33	44	55	65	76	87	98	109
Max (3.18)	495	991	1486	1981	2476	2972	3467	3962	4458	4953
Mean (1.10)	171	343	514	685	857	1028	1199	1371	1542	1713
October										
Min (0.01)	2	3	5	6	8	9	11	12	14	16
Max (4.23)	659	1318	1976	2635	3294	3953	4612	5271	5929	6588
Mean (1.45)	226	452	678	903	1129	1355	1581	1807	2033	2258
November										
Min (0.62)	97	193	290	386	483	579	676	773	869	966
Max (4.27)	665	1330	1995	2660	3325	3990	4655	5320	5985	6651
Mean (2.53)	394	788	1182	1576	1970	2364	2758	3152	3546	3940
December										
Min (0.40)	62	125	187	249	312	374	436	498	561	623
Max (5.28)	822	1645	2467	3289	4112	4934	5757	6579	7401	8224
Mean (2.54)	396	791	1187	1582	1978	2374	2769	3165	3560	3956
Annual Precip. Totals	**Potential Annual Capture**									
Min (2.38)	371	741	1112	1483	1853	2224	2595	2965	3336	3707
Max (43.80)	6822	13644	20466	27287	34109	40931	47753	54575	61397	68219
Mean(19.21)	2992	5984	8976	11968	14960	17952	20944	23936	26928	29920

** Reported rainfall statistics are for Port Townsend Wa., as measured between 1948 and 1992.*

TABLE E-4
Capacities of Selected Round and Square Cisterns, in Gallons

Cistern Diameter (feet)	ROUND CISTERN Depth in Feet					
	1	2	3	4	5	6
	Capacity in Gallons					
3	53	106	159	211	264	317
4	94	188	282	376	470	564
5	147	294	441	587	734	881
6	211	423	634	846	1057	1269
7	288	576	864	1151	1439	1727
8	376	752	1128	1504	1880	2256
9	476	952	1428	1903	2379	2855
10	587	1175	1762	2350	2937	3525
11	711	1422	2133	2843	3554	4265
12	846	1692	2538	3384	4230	5076
13	993	1986	2979	3971	4964	5957
14	1151	2303	3454	4606	5757	6909
15	1322	2644	3965	5287	6609	7931
16	1504	3008	4512	6016	7520	9024
17	1698	3396	5093	6791	8489	10187
18	1903	3807	5710	7614	9517	11421
19	2121	4242	6362	8483	10604	12725
20	2350	4700	7050	9400	11750	14099
25	3672	7343	11015	14687	18359	22030

Example: A round, 10 foot diameter cistern, 4 feet deep has a capacity of 2350 gallons.

Length of Sides (feet)	SQUARE CISTERN Depth in Feet					
	1	2	3	4	5	6
	Capacity in Gallons					
3	67	135	202	269	337	404
4	120	239	359	479	598	718
5	187	374	561	748	935	1122
6	269	539	808	1077	1346	1616
7	367	733	1100	1466	1833	2199
8	479	957	1436	1915	2394	2872
9	606	1212	1818	2424	3029	3635
10	748	1496	2244	2992	3740	4488
11	905	1810	2715	3620	4525	5430
12	1077	2154	3231	4308	5386	6463
13	1264	2528	3792	5056	6321	7585
14	1466	2932	4398	5864	7330	8796
15	1683	3366	5049	6732	8415	10098
16	1915	3830	5745	7660	9574	11489
17	2162	4323	6485	8647	10809	12970
18	2424	4847	7271	9694	12118	14541
19	2700	5401	8101	10801	13501	16202
20	2992	5984	8976	11968	14960	17952
25	4675	9350	14025	18700	23375	28050

Example: A square, 10 foot diameter cistern, 4 feet deep has a capacity of 2992 gallons.

TABLE E-5
Useful Conversion Factors

Volume

1 gallon (U.S.) = 3.78 liters
= 0.134 cubic feet
= 8.34 pounds of water

1 liter = 0.0353 cubic foot
= 0.264 gallons (U.S.)

1 cubic foot = 7.48 gallons (U.S.)
= 28.3 liters
= 0.0283 cubic meters
= 0.037 cubic yards
= 62.43 pounds of water

1 cubic meter = 1000 liters
= 35.3 cubic feet
= 264 gallons (U.S.)

Flow Rate

1 gallon per minute = 1440 gallons per day
= 0.063 liters per second
= 0.004419 acre-feet per day
= 0.002228 cubic feet per second

Length

1 inch = 25.4 millimeters
= 0.083 feet

1 foot = 0.305 meters
= 12 inches

1 meter = 0.001 kilometers
= 1000 millimeters
= 39.4 inches
= 3.28 feet
= 1.09 yards

Area

1 acre = 43,560 square feet

1 square meter = 10.78 square feet
= 0.000247 acre

1 square foot = 0.0928 square meter

TABLE E-6
Typical Water Use Figures

	Approximate Gallons per Day
Dwellings (per Resident)	
Single family, residence	120
Multiple family, apartments	60
Rooming house	50
Livestock (per animal) (Frasier and Myers, 1983)	
Horse	10 - 12
Hog	4
Sheep	1 - 2
100 chickens	4
Beef cattle, mature	8 - 12
Cow with calves	10 - 15
Calf	5 - 8
Dairy cattle, mature	10 - 15
Cow with calves	12 - 18
Miscellaneous	
Yard fixtures: 1/2 inch hose with nozzle	200
3/4 inch hose with nozzle	300

	Gallons per Minute
Household fixtures (water efficient)	
Kitchen faucet	1.5
Bathroom faucet	1.5
Toilet (per flush)	1.5 - 3.0
Shower	1.5