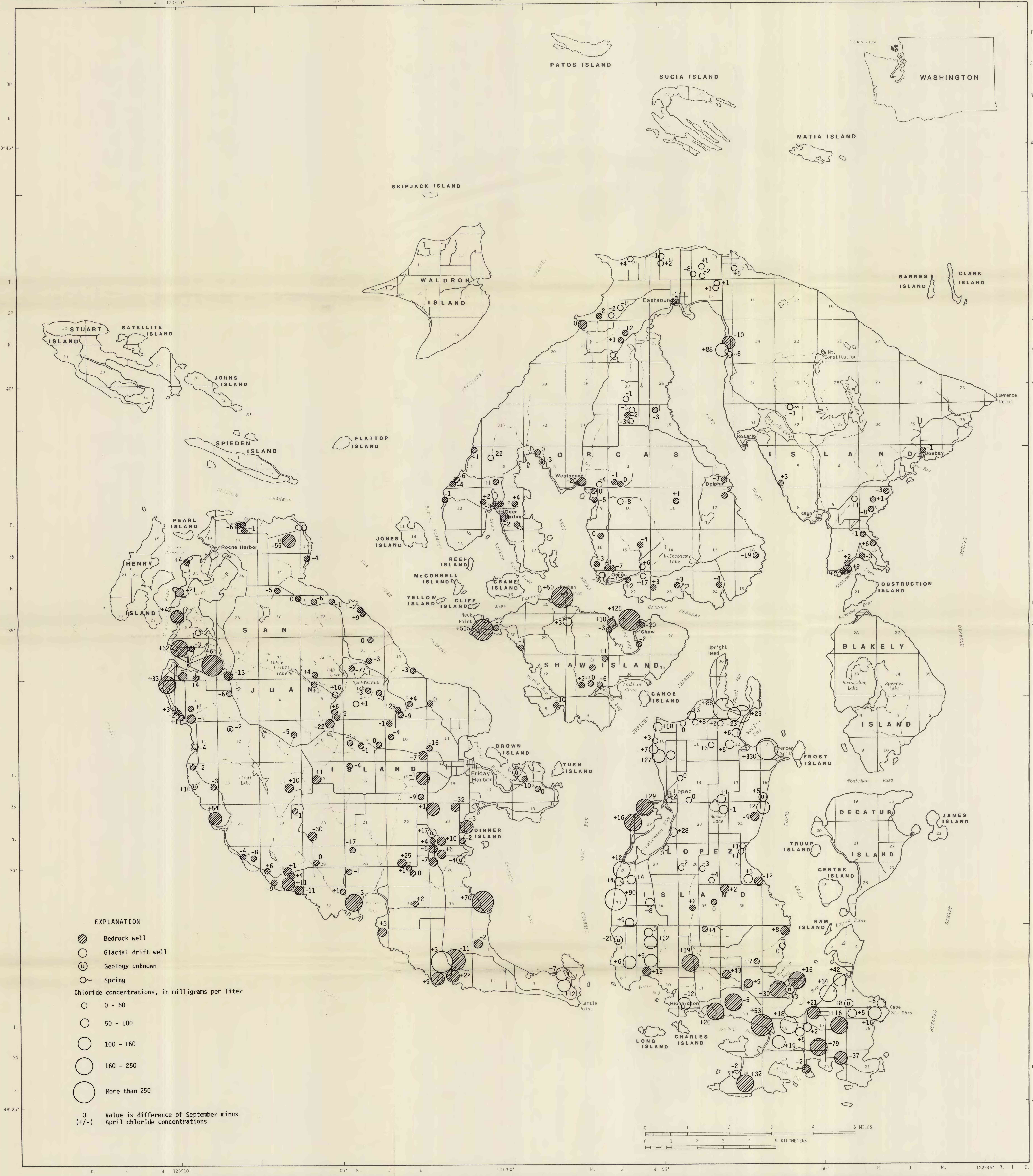
DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

Prepared in Cooperation with the
San Juan County Board of Commissioners



Base from U.S. Geological Survey
Orcas Island, Richardson 1:62,500, 1957,
Sucia Island, 1973, Stuart Island, 1953,
Waldron Island, 1954, Roche Harbor, 1954,
Friday Harbor, 1954, False Bay, 1:24,000,
1954.

OCCURRENCE, QUALITY, AND USE OF GROUND WATER IN ORCAS, SAN JUAN, LOPEZ, AND SHAW ISLANDS, SAN JUAN COUNTY, WASHINGTON

Chloride Concentrations and Seawater Intrusion in Aquifers

By K. J. Whiteman, Dee Molenaar, G. C. Bortleson, and J. M. Jacoby

1983

INTRODUCTION

San Juan County has several hundred miles of marine shore along which much of the residential development has occurred. Shoreline development has increased markedly since 1960 and the trend is expected to continue. Ground water is the chief source of freshwater supply in most of the county. However, many wells are in a fragile balance between rates of ground-water pumping that provide current freshwater supplies for water-distribution systems and increased pumping rates that might result in the intrusion of seawater into nearshore aquifers. Excessive salts in drinking water produce unpalatable tastes, are corrosive to plumbing, and may increase the cost of water treatment. Furthermore, removal of the influence of seawater, already intruded into a coastal aquifer, may in some cases be a slow process difficult to achieve.

The purpose of this part of the study was to determine the present location and extent of seawater intrusion of the four main islands in San Juan County.

HYDROLOGIC CONDITIONS OF SEAWATER INTRUSION

In an unconfined nearshore aquifer, freshwater, which is less dense than seawater, occurs as a lense-shaped layer that floats on top of salty water (fig. 1). The weight of the overlying freshwater is the major mechanism by which seawater is depressed below sea level in the ground-water system. The freshwater glacial-drift and bedrock aquifers come in contact with the sea at or seaward of the coastline. Water recharged to these aquifers from the land surface will generally move downgradient towards the sea and eventually, if not intercepted by pumping wells, will be discharged into the sea. Withdrawal of ground water in coastal areas will reduce the weight of the overlying freshwater body and decrease or even reverse the seaward flow of fresh ground water, causing seawater to move landward into the freshwater aquifer (fig. 2).

The interface between seawater and freshwater is not always sharp; rather, a zone of diffusion (figs. 1 and 2) usually results from the gradual mixing of the fresh and saline waters. The salinity of the water gradually increases as one proceeds downward or seaward through the zone of diffusion. The position of the interface, be it sharp or diffuse, depends on several conditions: the relative densities of the seawater and the freshwater; tides; the seasonal altitude of the water table above or below sea level; pumpage from wells; the rate of recharge to the ground-water reservoir; and the hydraulic characteristics of the aquifer. Because of both natural and man-induced differences in these conditions, the depth below sea level at which the interface is encountered differs from one locality to another on the islands.

The situation portrayed in figure 1 assumes a continuous and homogeneous aquifer that extends laterally across the island and vertically to depths below the freshwater-seawater interface. As indicated in sheet 2, bedrock predominates in most of the islands and ground water in the bedrock generally occurs in fractures. Seawater intrusion into a bedrock well can occur only if the fracture system from which the well obtains water extends into the seawater and the well is deeper than sea level. It is possible that conditions similar to those shown in figure 1 exist for the areas of Lopez Island underlain by deposits of glacial drift.

METHODS OF DATA COLLECTION AND ANALYSIS

Chloride concentrations were measured monthly from April to September in water samples from 56 observation wells and in April and September 1981 in samples from 279 wells (including the 56 observation wells) and one spring. The distribution of the 279 sampling sites is shown on the map. The months of April and September were chosen for sampling because they represent, respectively, the period of high water levels following spring and winter recharge and the period of low water levels following the low precipitation and high ground-water pumpage of summer.

Chloride concentrations were determined using a chloride specific-ion electrode. After calibration, the chloride electrode is simply immersed in the water sample and the concentration determined. Throughout the study, however, quality-control checks with U.S. Geological Survey laboratory determinations revealed that the electrodes yielded data of generally poor accuracy, but high precision at higher concentration. Therefore, because of the high precision obtained, an excellent relation between the chloride electrode and accepted laboratory determinations was established to correct chloride values measured with the electrode. Details explaining precautions needed when using chloride electrodes are provided for in the coming report by Bortleson and Roberts (written commun., 1982).

CRITERIA FOR DETECTING SEAWATER INTRUSION

High chloride concentrations or chloride concentrations increasing over time may well be the first indication of seawater encroachment. Chloride, a major chemical constituent in seawater, is fairly stable chemically, and will move through a saturated zone at virtually the same rate as intruding water. Seawater has a concentration of about 19,000 milligrams per liter (mg/L) of chloride. The average concentration of chloride in surface water on San Juan Islands is 9.5 mg/L (Tomlinson, 1975), and is probably representative of the concentration of water recharging the underlying aquifers. Weathering and leaching of rocks, minerals, and soils as the recharge water moves through the soils and rocks, however, will release chloride below the ground surface. For example, based on September observations, the median concentration of chloride from 277 ground-water sites was 39 mg/L. Ground water with chloride concentrations considerably higher than these levels may be in a zone in which ground water is a mixture of freshwater and intruded seawater.

Chloride concentrations in excess of apparent background (natural) levels do not necessarily indicate present-day seawater intrusion; the higher concentrations could be due to contamination introduced by artificial sources, to ancient seawater intrusions in the aquifer or to connate water—water that has been in the aquifer since its deposition. But in situations where high chloride concentrations occur near the coast in wells whose water levels are near or below sea level, seawater intrusion is the most probable cause.

For purposes of this investigation two criteria will be used as indicators of seawater intrusion. They are:

(1) Water samples in which sodium and chloride are the dominant dissolved chemical constituents in solution. This determination can be made only for wells in the observation well network for which cation and anion chemical analyses were made of the sampled waters; waters dominated by sodium and chloride always have high chloride concentrations, ranging from 160 to 2,700 mg/L (see sheet 6).

(2) Water samples containing chloride concentrations above estimated background levels.

If sodium and chloride are the dominant dissolved chemical constituents, seawater intrusion is strongly indicated, assuming it is known from other data sources that waste-water-discharge sources are absent. Supporting evidence for the use of water type as an indicator of seawater intrusion is provided by the fact that 9 of 10 ground-water samples dominated by sodium and chloride ions were from wells located near the shoreline.

Most of the wells sampled do not have cation and anion analyses, so the predominant ions cannot be determined. In such instances, it is necessary to establish limits for chloride concentrations that appear to separate background from contaminated (or intruded) levels. From a graph showing percentage cumulative frequency with chloride concentration (fig. 3), a lower threshold value of 100 mg/L chloride was established as the concentration above which contamination can reasonably be assumed.

As shown in figure 3, the changes in percentage cumulative frequency with chloride concentration is gradual from 10 to 100 mg/L chloride, but at about 100 mg/L the first break in slope appears. In the same figure, changes in chloride concentration with percentage cumulative frequency are plotted using samples from all wells that are above sea level only. The results show that 95 percent of the chloride concentrations in these wells were less than 90 mg/L; all but two values were less than 105 mg/L (not shown). Thus, concentrations greater than about 100 mg/L can reasonably be assumed to be above background levels.

Because a zone of diffusion exists where freshwater and seawater mix, the use of a single concentration value to separate background from seawater-intruded ground water, albeit convenient, is not entirely realistic. At about 90-percent cumulative frequency, corresponding to 160 mg/L chloride, a sharp upward increase begins in the solid line curve shown in figure 3. It is assumed that chloride concentrations above the 90-percent frequency represent ground water very likely contaminated by seawater, because of the divergence from normal occurrences.

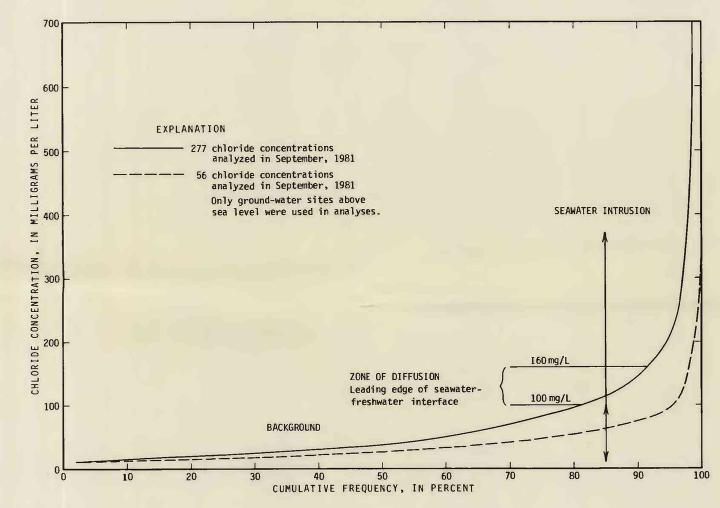


Figure 3. Relationship of chloride concentration to percentage cumulative frequency of occurrence, September, 1981.

The use of chloride concentration in excess of 160 mg/L as an indication of seawater intrusion is supported, but not confirmed, by the results of comparisons of ion ratios of standard seawater and ground water—the ratios of chloride to calcium, chloride to sulfate, and calcium to sodium (table 1). Sodium, calcium, and sulfate are chemically reactive constituents; therefore, the mixing of seawater and freshwater will result in waters whose ion ratio is determined by dilution, chemical, physical, and other processes. Despite the above interpretive precautions, ground water with chloride concentrations above 160 mg/L was observed to be nearer the chemical ratios of standard seawater than a comparison of ground water with chloride concentrations below 160 mg/L. Notably, a concentration of 160 mg/L chloride is also the lowest observed concentration of chloride for ground water (well 35/3-36E1) dominated by sodium chloride. From the above evidence, it appears reasonable, by the use of chloride concentrations, to define ground water as relatively unaffected by seawater intrusion or contaminated by chloride as follows:

(1) Water with chloride concentrations greater than 100 mg/L is presumed to be above background levels.

(2) Water with chloride concentrations between 100 and 160 mg/L is likely representative of the leading edge of the seawater-freshwater interface within the zone of diffusion.

(3) Water with chloride concentrations greater than 160 mg/L is indicative of seawater intrusion or water pumped from the zone of diffusion.

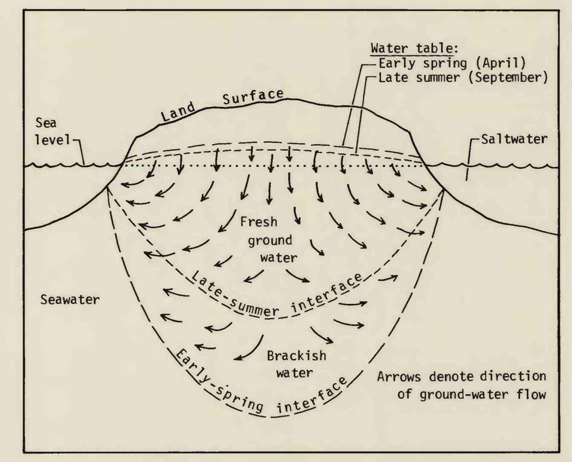
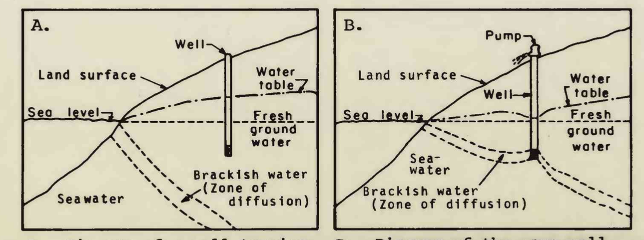


Figure 1. Generalized occurrence and seasonal position of the seawater-freshwater interface.



A. Diagram of a well tapping an unconfined near-shore aquifer under conditions of equilibrium--no intrusion has occured.

B. Diagram of the same well under conditions of intensive pumping--intrusion has reached the well.

Figure 2. Idealized effects of pumping on the zone of diffusion.

TABLE 1.--Comparison of chemical ratios of standard seawater and ground water with various chloride concentrations

Water	Number of samples	Ratio (by weight): Calcium/Sodium Mean	Calcium/Sodium Median	Chloride/Sulfate Mean	Chloride/Sulfate Median	Chloride/Calcium Mean	Chloride/Calcium Median
Seawater	--	0.038	--	7.0	--	47	--
Ground water with chloride concentrations greater than 160 mg/L	13	.4	.4	76	7	6.8	4.6
Ground water with chloride concentrations of 10-160 mg/L	44	1.6	1.1	3.6	1.4	2.5	.9

VARIATIONS IN CHLORIDE CONCENTRATIONS

The accompanying map shows the areal variations in chloride concentrations as observed at 279 ground-water sites in 1981 and the seasonal changes observed between April and September of that year. The information shown on the map is summarized as follows:

1. Coastal wells yielding water with chloride concentrations greater than 160 mg/L were primarily near the southern, western, and northern shores of Lopez Island, northern shore of Shaw Island, and the southern and northwestern shores of San Juan Island. About 60 percent of the wells with water exceeding 160 mg/L chloride concentration were located on Lopez Island; almost all wells on Orcas Island had water with concentrations of chloride less than 100 mg/L.
2. All of the ground-water samples with chloride concentrations greater than 250 mg/L were from wells located near the coast, and only three samples with concentrations greater than 160 mg/L were from wells more than 1/2 mile from the coastline. In contrast, most wells in the central parts of San Juan and Lopez Islands yielded water with chloride concentration less than 100 mg/L.
3. Median chloride concentrations observed in September 1981 in glacial-drift wells and bedrock wells were within 12 mg/L. A data summary according to rock type is given in table 2 for the April and September measurements.
4. The median change in chloride concentration between the samplings of April and September was zero for samples with less than 160 mg/L and 32 mg/L for samples with more than 160 mg/L (table 3). Thus, at wells already intruded by seawater, the seasonal changes in chloride concentration are the more dramatic.

TABLE 2.--Statistical summary of chloride concentrations observed in April and September 1981 according to rock type

Concentration statistic	Glacial drift: April (82 samples)	Glacial drift: September (81 samples)	Bedrock: April	Bedrock: September
			(183 samples)	
Minimum	10	11	9	10
Maximum	876	1,200	2,700	2,800
Mean	83	89	74	81
Median	43	46	36	35

TABLE 3.--Comparison of seasonal increases in chloride for concentration above and below 160 mg/L. Difference is September concentrations minus April concentrations

Concentration statistic	Increases in chloride (mg/L): April to September (247 samples) Less than 160 mg/L	April to September (17 samples) Greater than 160 mg/L
Number	247	17
Minimum	* -77	-11
Maximum	88	515
Mean	.66	96
Median	0	32

*Negative value indicates April concentration was greater than September concentration.

SIGNIFICANT FINDINGS

Ground water with high chloride concentrations (greater then 160 mg/L) was located near the shorelines of Lopez, San Juan, and Shaw Islands. Most of the wells displaying characteristics of seawater intrusion were in the southern parts of Lopez and San Juan Islands. In these areas additional ground-water supplies probably cannot be developed without the risk of aggravating the intrusion problems already observed. Pumping wells near the coast causes water levels to drop and the freshwater/seawater interface to migrate inland. For example, at the north end of Lopez Island there appears to be a relationship between heavy pumping and seawater intrusion (sheet 11). For those wells that have already been intruded, the concentrations of chloride were generally found to be highest in fall, indicating that the freshwater/seawater interface moves inland during the summer, following the period of heaviest pumping. In contrast, winter recharge raises the water table and shifts the interface seaward, and therefore lower chloride concentrations are generally observed in the spring. Because seasonal changes in chloride concentrations can be dramatic at wells already intruded, long-term monitoring of intruded areas should be carefully designed to account for these seasonal variations and to avoid spurious conclusions.

Background concentrations of chloride in ground water in the San Juan Islands are considerably higher than the average concentration observed in surface water, indicating that geologic factors are also important in contributing chloride to the ground water. Estimated background chloride concentrations range from 10 to 100 mg/L, whereas ground water containing more than 160 mg/L of chloride is strongly suspected of being contaminated by seawater. By this definition, 9 percent, or 26 of 279, of the wells are possibly contaminated by seawater intrusion. Three percent of the wells yield water with chloride concentrations that exceed the secondary standards for chloride (greater than 250 mg/L).

FUTURE STUDIES

Future studies should include three major efforts:

(1) Detailed evaluations of geohydrologic conditions that control the movement of the freshwater-seawater interface. This could require the construction of freshwater-seawater digital models representing conditions at selected cross sections through the unconsolidated sediments of Lopez and San Juan Islands.

(2) Continued monitoring of selected wells for chloride concentrations and water levels, using the information gained in this study for the judicious selection of an observation-well network. Sampling at selected nonpumping wells at coastal and inland sites would be a useful addition to the observation network to assess the natural seasonal migration of the freshwater-seawater interface. Year-round sampling and analysis would provide more information on seasonal recharge characteristics. Monitoring of water levels would alert the managers to water-level declines that could provide an early warning of the onset of seawater intrusion.

(3) Monitoring of the effects of intrusion control measures that could be implemented in unconsolidated sediments, such as:

(a) Reduction of pumping and (or) redistribution of pumping sites.
(b) Augmentation of fresh ground-water recharge. For example, surface runoff could be slowed by use of surface ponds, resulting in higher infiltration rates.
(c) Maintenance of a freshwater mound above sea level along the coast to prevent encroachment of saltwater inland. This method requires a line of recharge wells along the coast and a supplemental water supply to create the freshwater barrier, unless some pumpage from the aquifer farther inland is used for recharge.