STATE OF WASHINGTON

John D. Spellman, Governor

DEPARTMENT OF ECOLOGY

Donald W. Moos, Director

Water-Supply Bulletin 56

SEAWATER INTRUSION INTO COASTAL AQUIFERS IN WASHINGTON, 1978

By

N.P. Dion and S.S. Sumioka

Prepared in cooperation with

UNITED STATES GEOLOGICAL SURVEY

WATER RESOURCES DIVISION

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DEPARTMENT OF ECOLOGY

Olympia, Washington 98504

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[Plates are in pocket]

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METRIC CONVERSION (SI) FACTORS

Multiply	By	To Obtain
inch (in.)	25.4	millimeter (mm)
	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre	4047.0	square meter (m^2)
degree Fahrenheit (°F)	0.5556, after subtracting 32	degree Celsius (°C)

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called "Mean Sea Level." NGVD of 1929 is referred to as sea level in this report.

SEAWATER INTRUSION INTO COASTAL AQUIFERS IN WASHINGTON, 1978

By N. P. Dion and S. S. Sumioka

ABSTRACT

The extent and severity of seawater intrusion was determined using chloride data from 1,289 wells in 14 counties of coastal Washington in 1978. In addition, comparisons were made of chloride concentrations in 680 wells sampled both in 1966-68 and in 1978 to determine long-term trends of intrusion.

Seawater-intrusion conditions in 1978 were similar to those detected in the late 1960's; for the most part, intrusion continued to be a problem of only local concern in Washington. Many of the counties surveyed in 1978, such as Clallam, Jefferson, Pierce, Thurston, and Whatcom Counties, had several areas of severe but localized intrusion. Chloride concentrations in other counties, such as Island and San Juan Counties, were moderately high throughout the coastal areas and suggest a more widespread problem. Many of the individual wells that yielded high-chloride water in the late 1960's had been abandoned or destroyed by 1978.

Comparisons of chloride data from 1966-68 and 1978 suggest that, in general, concentrations decreased slightly. This apparent decrease, however, could reflect seasonal differences caused by pumping patterns or climatic variation.

INTRODUCTION

Background

The State of Washington has many miles of coastline bordering the Pacific Ocean, Strait of Juan de Fuca, and Puget Sound (fig. 1). Much of the residential and industrial development in mainland and island areas of western Washington has been along these coastlines, and the trend is expected to continue. Ground water is the chief source of freshwater supply in many of the developed areas, and heavy demands are being placed on coastal aquifers that may be in hydraulic connection with seawater bodies. These conditions lead to the intrusion of seawater into the aquifers.

A reconnaissance of seawater intrusion in 1966-68 (Walters, 1971) indicated that ground-water use had led to moderate intrusion in several coastal areas. In addition, the reconnaissance indicated that intrusion was incipient in other coastal areas and that these conditions could worsen with increased ground-water withdrawals.

Development has continued in coastal Washington since the time of the earlier study. Correspondingly, demands on ground water have probably increased in continuously developing areas, and begun in newly developing areas. Thus, it is possible that seawater intrusion has increased in the previously developed areas, has materialized where it was previously incipient, or has become incipient in newly developed areas.

It is generally considered desirable to prevent or detect seawater intrusion. Excessive salts in drinking-water supplies produce unpalatable tastes and possible physiological effects; they may be corrosive and they increase the cost of water treatment. Moreover, once seawater intrudes a coastal aquifer it is difficult and expensive, sometimes impossible, to control or reverse the condition. Because ground water moves slowly, remedial measures usually require several years to take effect.

Objectives of Study

The objectives of this study are to (1) determine the present location, extent, and severity of seawater intrusion in coastal Washington; (2) identify those areas where future intrusion may occur; and (3) determine if the extent or severity of intrusion, as described by Walters (1971), has changed substantially.

The study was made in 1978 by the U.S. Geological Survey in cooperation with the Washington Department of Ecology as part of a continuing program for the collection and interpretation of data relating to the water resources of Washington.

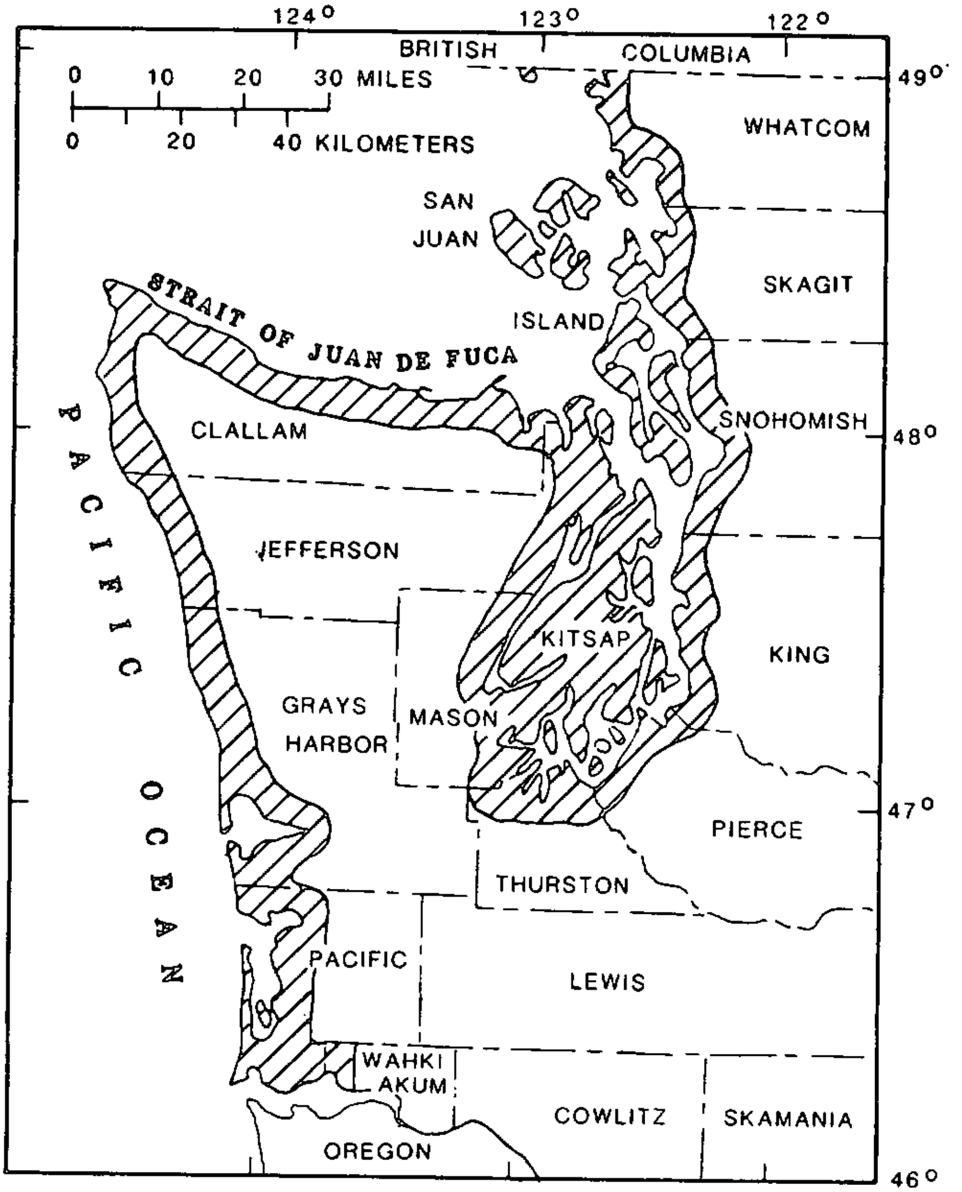


FIGURE 1.--Map of western Washington showing coastal regions studied.

Methods of Investigation

The chloride concentration of ground water was used as the principal criterion for the recognition of seawater intrusion (Revelle, 1941). The term "seawater" as used in this report includes any saline water originating from an ocean, strait, or sound. The specific conductance of ground-water samples was also measured in order to establish a correlation between specific conductance and chloride concentration for a relatively quick and inexpensive method to approximate chloride concentrations in the field. The correlation coefficient (table 1) for each county is expressed numerically and is discussed on page 10.

All water samples were analyzed in the Tacoma laboratory of the U.S. Geological Survey. Chloride concentration was determined using the mercuric nitrate method (American Public Health Association, 1976); specific conductance was measured using a calibrated field conductivity meter.

Data collection was limited to areas within about 1 mile of the coast and to wells drilled to depths at or below sea level. The term "sea level" as used in this report is synonomous with mean sea level or National Geodetic Vertical Datum of 1929 (NGVD). Most of the 1,289 wells were sampled during the period May-August 1978. Analyses for 34 wells in Island County, however, were supplied by the Washington Department of Ecology and represent samples collected during the period 1976-78.

For purposes of comparison, 680 wells which were sampled by Walters (1971) during the 1966-68 period were resampled. Sampled wells that showed significant departures from the previous (1966-68) reconnaissance data were sampled once again in October 1978.

In discussions of chemical data, the median is used throughout this report in preference to the arithmetic mean or "average." The median is the middle value (or halfway point) when all values have been ranked in order of size; that is, half the values are larger than the median and half are smaller. The chief advantage of the median over the mean is that the median is less affected by a few extreme values. Medians were compared only from paired samples, namely samples from wells sampled both in the late 1960's and again in 1978. The comparisons of the medians are thought to be useful for indications of change. They are not offered as having high statistical significance.

The chloride concentrations and specific conductances of waters analyzed in 1978 were evaluated in relation to geologic and hydrologic conditions. In some instances, temporal changes in salinity between 1966-68 and 1978 were related to seasonal pumpage and recharge patterns. No attempt was made to relate chloride concentration to tidal fluctuations or changes in ground-water levels, nor to define the position of the freshwater-seawater interface. The potential for seawater intrusion was interpreted largely on the basis of theoretical considerations because wells and ground-water data are scarce or lacking in many areas.

TABLE 1.--Summary of chemical data from analyses of ground water collected in 1978

County	Number of samples	Median specific conductance[1]	Median chloride concentrations[2]	Correlation coefficient
Clallam	35	351	7.3	0.85
Grays Harbor	69	222	16	.56
Island[3]	208	435	26	.98
Jefferson	74	350	14	.97
King	27	248	4.9	.95
Kitsap	165	181	3.3	.67
Mason	155	121	1.8	.91
Pacific	85	195	18	.92
Pierce	153	140	3.2	.97
San Juan	94	570	40	.88
Skagit	30	515	25	.92
Snohomish	23	198	7.2	.45
Thurston	133	164	3.4	.98
Whatcom	37	380	20	.96
Total	1,289			

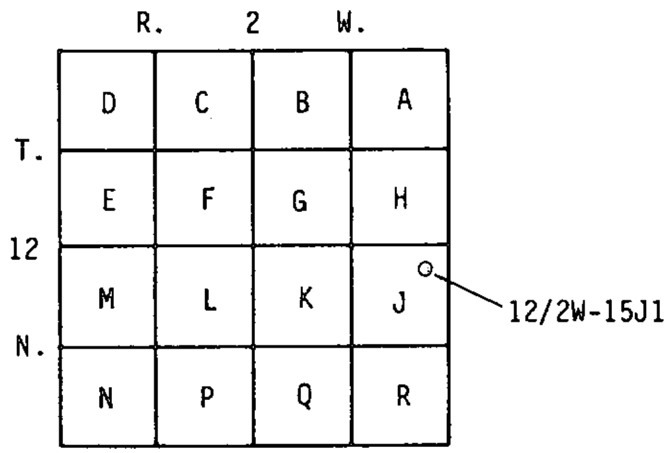
[1]In micromhos per centimeter at 25°C.

[2]In milligrams per liter.

[3]Some samples collected by DOE in 1975-77.

Well-Numbering System

The well numbers listed in this report indicate the locations of the wells according to the rectangular grid system of land subdivision. The number shows the location by township, range, section, and position within the section. A typical illustration of this method of location is shown below.



Section 15

Well number 12/2W-15Ji is used as an example. The set of numbers preceding the hyphen indicate the township north (T.12 N.) and the range east or west (R.2 W.) of the Willamette base line and meridian, respectively. Because the entire State is north of the Willamette base line, the letter "N" to denote north is omitted. Most of the State is east of the Willamette meridian, and the letter "E" is omitted for locations east of the meridian, but the letter "W" is included for locations west of the meridian. The first number(s) after the hyphen indicates the section (sec. 15), and the letter "J" gives the 40-acre subdivision of the section as shown above. The last number (1) is the sequence number of the well as recorded within a particular 40-acre tract. Thus, 12/2W-15J1 is the first well recorded in the northeast quarter of the southeast quarter of Section 15, Township 12 North, Range 2 West.

Acknowledgments

The authors wish to express their appreciation to the many property owners who supplied information about their wells and who permitted the withdrawal of water samples. Appreciation is also expressed to the Washington Department of Ecology for supplying physical and chemical data for wells in Island County.

HYDROLOGIC CONDITIONS OF SEAWATER INTRUSION

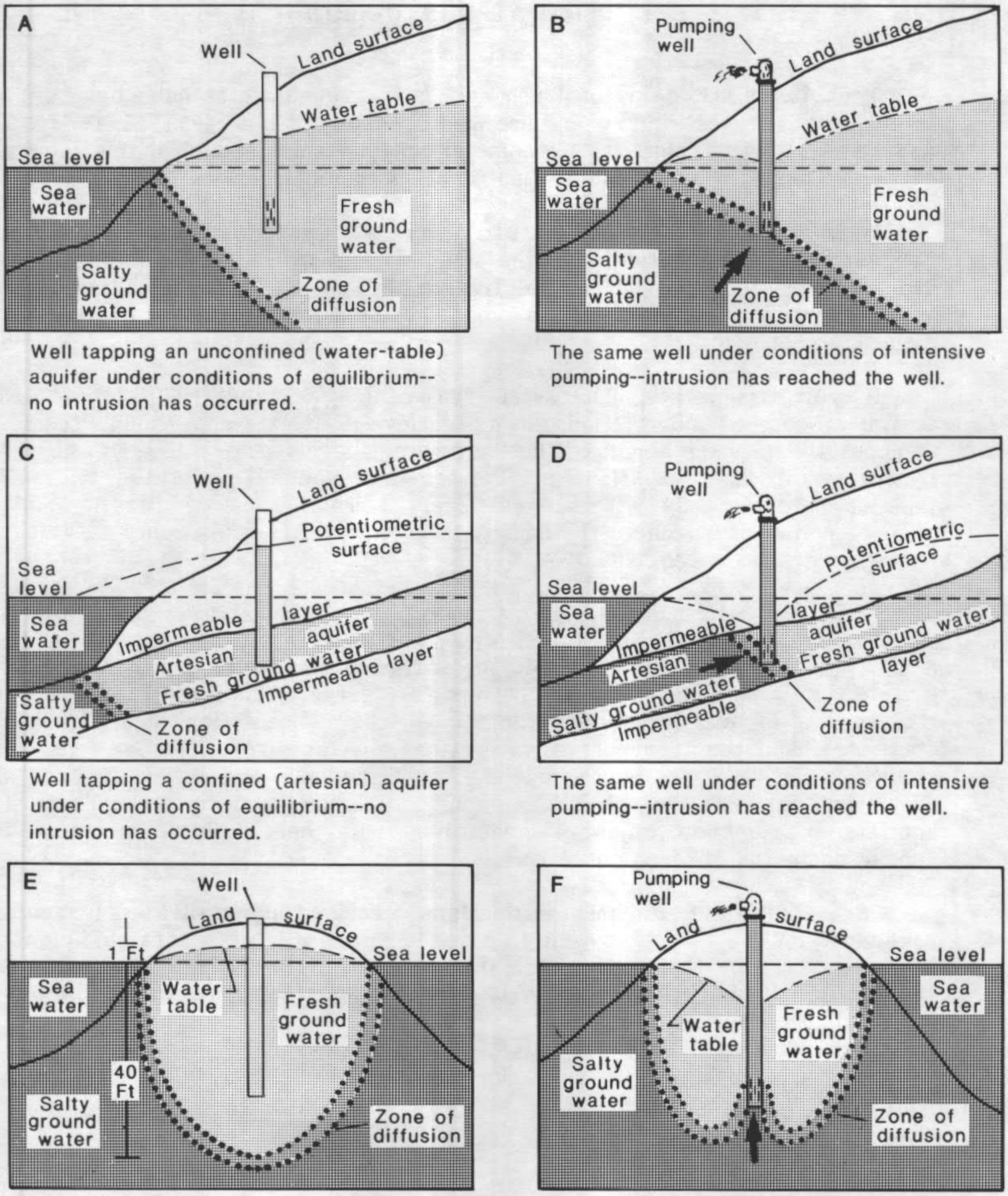
The interrelationships of fresh and salty ground water have been studied intensively in several regions and are well documented (Parker, 1955; Todd, 1959; and Chow, 1964). These relationships are briefly summarized in this report to serve as a basis for discussion of specific areas or counties.

In order for seawater intrusion to occur, the aquifers in coastal areas must be in hydraulic connection with the sea, and the hydraulic head of the fresh ground water must be reduced relative to that of the seawater. Because the head reduction is usually due to pumping, intrusion is usually the result of man-caused stresses.

Hydrologists working in coastal areas of Europe about 1900 observed that seawater occurred underground, not at sea level, but at a depth below sea level of about 40 times the height of the freshwater above sea level (see fig. 2E). The freshwater appeared to "float" on the seawater and mixing of the two water types took place only within a relatively narrow "zone of diffusion." This phenomenon occurs because the density of freshwater (1.000) is only 40/41 times the density of seawater (1.025).

Under natural conditions the altitude of the water table, or potentiometric surface, in a coastal aquifer is higher than sea level and it decreases toward the coast (fig. 2A, C, and E); the movement of fresh ground water along this gradient is seaward. When the freshwater gradient is decreased or reversed, such as by the pumping of nearshore wells (fig. 2B, D), the seaward flow of freshwater is decreased, and the front of seawater (the zone of diffusion) begins to move landward. In situations where artesian (confined) aquifers extend seaward and are in contact with the sea only at considerable distance from the coast, the aquifers could undergo intrusion undetected; many years could elapse before the appearance of seawater in coastal wells.

The freshwater-seawater relationships described above also apply beneath islands (fig. 2E). An island well that withdraws water at a rate sufficient to lower the water table (fig. 2F) disturbs the natural freshwater-seawater equilibrium. If the hydraulic head is lowered sufficiently, seawater rises as a cone and moves toward the well.



A. Well tapping an unconfined (water-table) aquifer under conditions of equilibrium--no intrusion has occurred.

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

C. Well tapping a confined (artesian) aquifer under conditions of equilibrium--no intrusion has occurred.

D. The same well under conditions of intensive pumping--intrusion has reached the well.

E. Well tapping an unconfined island aquuifer under conditions of equilibrium--no intrusion has occured.

F. The same well under conditions of intensive pumping--intrusion has reached the well.

FIGURE 2.--Schematic sections showing hydrologic conditions before and after intrusion.

CRITERION FOR DETECTING SEAWATER INTRUSION

Seawater contains approximately 35,000 mg/L (milligrams per liter) of dissolved solids, which includes about 19,000 mg/L of chloride. Uncontaminated ground water in most coastal areas of Washington generally contains less than 10 mg/L of chloride. Chloride concentrations in excess of 10 mg/L do not necessarily indicate seawater intrusion; the higher concentrations could be due to contamination introduced at or below ground surface, or to relict seawater in the aquifer.

Sea level along the Washington coastline at certain times during the Pleistocene Epoch was higher than at present, and the interface between fresh and salty ground water at that time was correspondingly farther inland. Many occurrences of saline ground water in Washington coastal areas are probably due to incomplete flushing of seawater from rock materials following the latest decline of sea level. The term "relict seawater" as used in this report includes both the incompletely flushed salty water from ancient intrusions and true connate water that has been in the aquifer since its deposition.

The U.S. Environmental Protection Agency (1977) recommends that the chloride concentration of drinking-water supplies be less than 250 mg/L. This concentration approximates the threshold concentration above which a salty taste is distinguishable to the average person. For purposes of this investigation only chloride concentrations in excess of 100 mg/L were deemed to represent seawater intrusion. This report, therefore, describes in detail only those wells whose waters exceeded the arbitrary limit of 100 mg/L. The same criterion was applied uniformly to all counties of coastal Washington on the premise that chloride concentrations below 100 mg/L could more likely be the result of contamination from surface sources, the presence of relict seawater, sea spray, or causes other than true seawater intrusion.

PRESENT AND POTENTIAL SEAWATER INTRUSION

For convenience, the seawater intrusion conditions of each county are discussed separately. The physical and chemical data for wells sampled in 1978 are presented by county on plates 1-14 as follows:

Plate	County
1	Clallam
2	Grays Harbor
3	Island
4	Jefferson
5	King
6	Kitsap
7	Mason
8	Pacific
9	Pierce
10	San Juan
11	Skagit
12	Snohomish
13	Thurston
14	Whatcom

The 1960's data are included if available. A summary of the chemical data collected in 1978 is presented in table 1; a comparison of data collected in the 1960's and in 1978 is presented in table 2. The geologic conditions of all counties except San Juan County have been described by Walters (1971); the geologic conditions of San Juan County were described by Russell (1975).

Correlation coefficients relating specific conductance and chloride for 11 of 14 counties of coastal Washington ranged from 0.85 to 0.98 (table 1). The coefficients indicate that high specific-conductance values of ground water in the coastal parts of those counties are indicative of high chloride concentrations. Specific-conductance measurements are therefore a quick and effective means of approximating chloride concentrations in the field. Correlation coefficients in Grays Harbor, Kitsap, and Snohomish Counties, however, were only 0.56, 0.67, and 0.45, respectively, suggesting that in those counties the use of specific conductance for approximating chloride concentrations is unreliable.

TABLE 2.--Comparison of chemical data from analyses of ground water collected in the 1960's and in 1978

County	Number of samples	Median specific conductance[1] 1960's	Median specific conductance[1] 1978	Median chloride concentration[2] 1960's	Median chloride concentration[2] 1978
Clallam	23	340	331	7.0	6.8
Grays Harbor	55	210	222	14	15
Island[3]	93	506	465	34	27
Jefferson	39	365	356	12	14
King	20	276	252	6.0	4.8
Kitsap	116	182	181	5.1	3.4
Mason[4]	(128)	133	124	--	1.8
Do.	60	128	128	2.2	2.1
Pacific	65	187	190	19	19
Pierce	100	153	145	3.0	3.2
Skagit	18	518	510	22	24
Snohomish	17	223	198	8.5	7.2
Thurston[4]	(126)	174	161	--	3.1
Do.	48	273	259	14	6.6
Whatcom	21	441	420	23	21
Total[5]	675				

[1]In micromhos per centimeter at 25°C.

[2]In milligrams per liter.

[3]Some samples collected by DOE in 1975-77.

[4]1960's chloride data incomplete.

[5]Not including samples from 1960's with incomplete chloride data.

SUMMARY AND CONCLUSIONS

Seawater-intrusion conditions in 1978 were similar to those in 1968; for the most part, intrusion continued to be a local problem. Many of the counties surveyed in 1978, such as Clallam, Jefferson, Pierce, Thurston, and Whatcom Counties, had several areas of localized but severe intrusion. Chloride concentrations in other counties, such as Island and San Juan Counties, were moderately high throughout the coastal areas and represented a more widespread problem. Most of the local areas described as intruded in the 1966-68 period (Walters, 1971) remained so in 1978. However, many of the individual wells that produced high-chloride water in the late 1960's had been abandoned or destroyed prior to 1978. Because many wells in intruded areas have been abandoned, it is likely that many areas of severe intrusion were not detected in both the 1966-68 and 1978 investigations.

Comparisons of chloride concentrations in waters from wells sampled both in 1966-68 and 1978 suggest that, in general, chloride concentrations decreased slightly in the 10-year period. However, seasonal fluctuations of salinity occur because of varying short and long-term climatic conditions and pumping patterns, both of which lead to changing recharge-discharge relationships. Comparisons of only two measurements made 10 years apart are inadequate to detect permanent long-term changes in intrusion conditions.

Areas where ground-water development is progressing rapidly and where intrusion has already been detected are likely to experience increased intrusion in the future. Such areas include Island and San Juan Counties and parts of Kitsap, Pacific, Pierce, and Thurston Counties.

Correlations of specific conductance with chloride concentration indicated that, in 11 of 14 counties, the specific conductance of ground water would be a quick and effective means of approximating chloride concentrations in the field.

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