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IS SEAWATER INTRUSION AFFECTING GROUND WATER ON LOPEZ ISLAND, WASHINGTON?

HAS SEAWATER INTRUDED INTO LOPEZ ISLAND'S GROUND WATER?

Lopez Island lies among the San Juan Islands, an archipelago in the coastal waters of Washington State, just offshore of Seattle and of Vancouver, British Columbia. Its scenic views and relatively little precipitation have made it one of Washington's premier places to live and play. So its population has been burgeoning, and its interior and shorelines have been under development.

The Island's main freshwater source is ground water. Local surface water cannot be developed to meet increasing needs for freshwater because the Island lacks lakes and continuously flowing streams. But Islanders are concerned that pumping more ground water will affect its availability and quality. Because many wells are near the shores and the recharge rates to the aquifers are low, there is a great potential for seawater intrusion.

In 1997, the U.S. Geological Survey (USGS), in cooperation with the San Juan County Conservation District, studied the possibilities of seawater intrusion on the Island and found that 46 percent of 185 freshwater samples had chloride concentrations indicating seawater intrusion.

THE SOURCE OF LOPEZ ISLAND'S GROUND WATER

Precipitation, mostly rain, is the main source of recharge to the Lopez Island's ground-water system. The Island, shielded by the rain shadow of the Olympic Mountains, receives 20 to 30 inches of precipitation a year, considerably less than other areas of western Washington more directly in the paths of storms from the Pacific Ocean (Oregon Climate Service, Oregon State University, 1999).

Some precipitation is lost to runoff and evapotranspiration. But some precipitation filters downward to recharge the ground-water system of aquifers made up geologically of unconsolidated glacial drift lying over a complex of sedimentary and volcanic bedrock that is metamorphosed in many areas. The glacial drift deposits of sand, gravel, silt, clay, and till cover an estimated 80 percent of the Island and vary in thickness from 0 to as great as 250 feet.

How much of the comparatively little recharge the Island gets each year depends on many factors—the distribution and intensity of the precipitation; the air temperature, and incident solar radiation; the amount and types of vegetation; the slope of the land; the moisture-holding capacity of the soils; and the vertical permeability of the sediments above the aquifers.

But the small amount of yearly precipitation keeps the Island's ground-water system in a fragile balance between the recharge rates and the ground-water pumping. Increased pumping rates may upset this balance and result in seawater intrusion into nearshore aquifers.

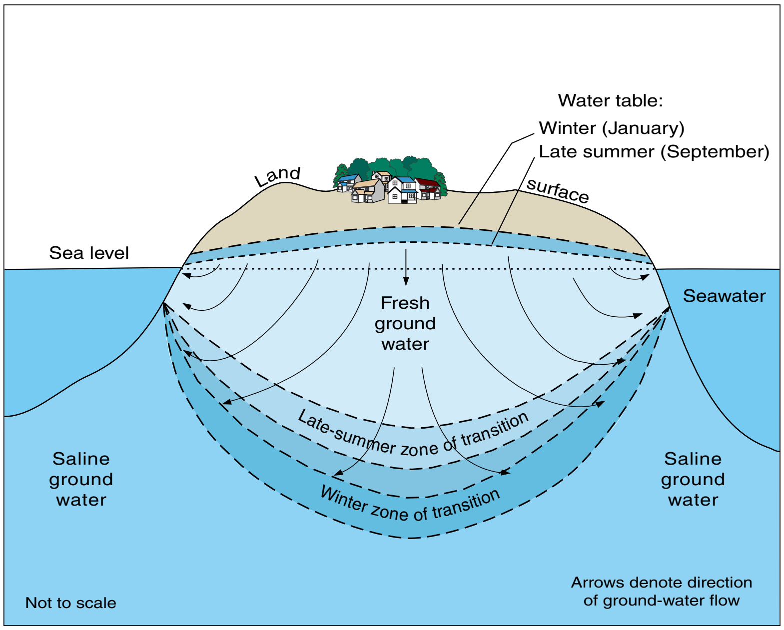


Figure 1. *Generalized flow pattern of an homogeneous island aquifer. Movement of the zone of transition and water table shown for winter and late summer.*

WHAT IS SEAWATER INTRUSION?

In an unconfined aquifer that contacts the sea at the shoreline or seaward, the freshwater, which is less dense than seawater, floats as a lens-shaped layer on top of seawater (fig. 1), and the weight of the overlying freshwater depresses the seawater below sea level. Generally, freshwater recharge in these aquifers moves downgradient and eventually discharges to low-lying coastal areas and into the sea. But pumping out fresh ground water reduces the weight of the overlying freshwater, which in turn can decrease or even reverse the seaward flow so that seawater moves landward into the freshwater aquifer. This migration of seawater into the freshwater aquifer is known as *seawater intrusion*.

The interface between the salty ground water below and fresh ground water above is a transition zone (fig. 2) of gradually mixing fresh and salt waters. Under natural, undeveloped conditions, the location of this zone will move slightly as the tide rises or falls and as recharge fluctuates seasonally. However, when a well pumps fresh ground water from near the transition zone, the equilibrium can be disturbed and the ground-water flow pattern changed (fig. 2b). As water is pumped out of the water-bearing zone, the transition zone moves upward toward the well. Prolonged or large-scale pumping can raise the transition zone to the well, which may then draw in salty water (fig. 2c).

Withdrawing freshwater from a well affects not only the location of the transition zone around that well but also the location of the Island's regional transition zone. Thus, pumping wells, whether shallow or deep, no matter what their locations, will affect the whole Island's fresh-water system (fig. 1).

The location of the transition zone depends on several natural and human-made conditions: the relative densities of seawater and freshwater; the tides; the pumpage from wells; the rate of ground-water recharge; and the hydraulic characteristics of the aquifer. Because these conditions vary locally, the depth to the transition zone below sea level differs from one place to another on the Island.

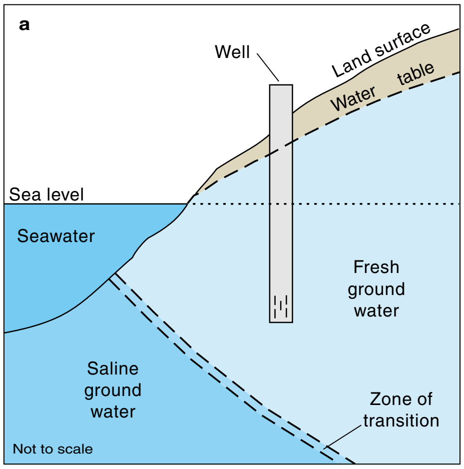
WHAT INDICATES SEAWATER INTRUSION?

One indicator of seawater intrusion is an increased chloride concentration in a freshwater aquifer, because chloride, a major constituent of seawater, is chemically stable and moves at about the same rate as intruding seawater. For the purposes of this study, chloride concentrations of 100 milligrams per liter (mg/L) or more were assumed to indicate seawater intrusion.

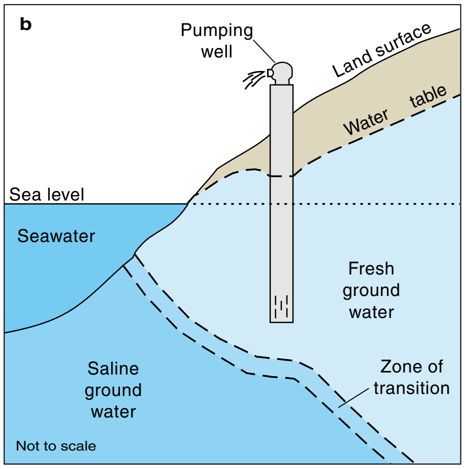
This study's indication of seawater was also used in a previous USGS study conducted in San Juan County in 1981. That 1981 study used graphical analysis and the cumulative frequency distribution of chloride concentrations to establish a threshold value of 100 mg/L for seawater intrusion (Whiteman and others, 1983).

Seawater contains approximately 35,000 mg/L of dissolved solids, which include about 19,000 mg/L of chloride. Fresh ground water in most coastal areas of Washington generally contains less than 10 mg/L of chloride. Even so, concentrations in excess of 10 mg/L are not conclusive evidence of seawater intrusion because they could be due to airborne sea spray in precipitation, to substantial well pumping rates, to local sources of chlorides, including septic systems or animal manure, or to *relict seawater* in the aquifer.

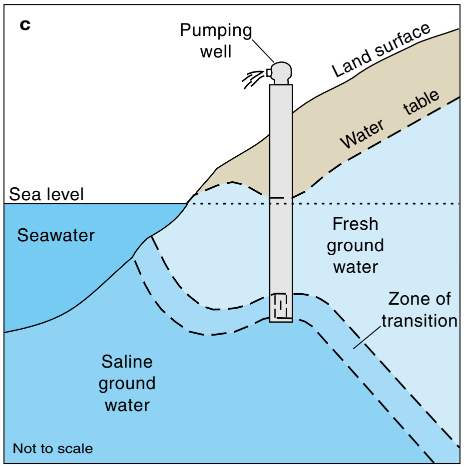
At times during the last million and a half years, the sea level along the Washington coastline was higher than now, and the transition zone between fresh and salty ground water was correspondingly farther inland and at higher elevations. Today, occurrences of salt water in Washington coastal aquifers may be due to *relict seawater*— seawater incompletely flushed from rock materials after the latest decline of sea level. The term *relict seawater* can also refer to *connate water*, or water trapped in an aquifer since its formation (Dion and Sumioka, 1984).



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



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



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

Figure 2. *Hypothetical hydrologic conditions before and after seawater intrusion.*

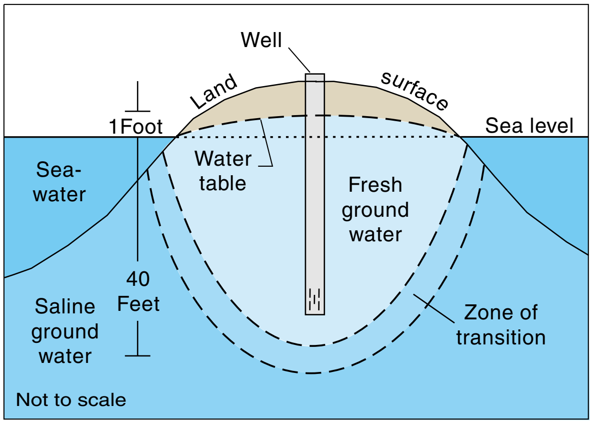
WHAT CAN HELP REDUCE SEAWATER INTRUSION?

Seawater intrusion on Lopez Island can be minimized by water conservation, efficient well construction, and by judicious well-operation practices like these:

- *Using such water-conserving devices as low-volume plumbing fixtures and toilets.*
- *Keeping outdoor watering to a minimum.*
- *Reusing or recycling water when possible.*
- *Augmenting fresh ground-water recharge by, for example, using surface ponds to slow surface runoff and raise infiltration rates.*
- *Constructing wells that do not penetrate deeper below sea level than necessary.*
- *Sizing pumps for lower pumping rates and minimizing lengths of pumping cycles.*
- *In multiple-well systems, pumping wells alternately.*

1-to-40 and the GHYBEN-HERZBERG PRINCIPLE

In general, if the water table in an aquifer is lowered 1 foot, the freshwater-seawater transition zone will rise about 40 feet, and the total vertical thickness of the freshwater lens will be reduced by about 41 feet (Freeze and Cherry, 1979).



A century ago, hydrologists working along Europe's coast observed that fresh ground water, appearing to float as a lens-shaped body on seawater, extended below sea level approximately 40 times the height of the freshwater table above sea level. Named the Ghyben-Herzberg Principle after the two scientists who described it, this 1-to-40 relation occurs because freshwater is slightly less dense than seawater (1.000 grams per cubic centimeter (g/cm^3) versus 1.025 g/cm^3). Thus, for example, if the water table at a given site is 3 feet above sea level, the freshwater-seawater transition zone is 120 feet below sea level, and the vertical thickness of the freshwater body there is 123 feet.

SAMPLING, ANALYSIS, AND QUALITY ASSURANCE

In spring 1997, after USGS scientists had reviewed data from more than 400 possible sites, giving priority to those previously visited (Whiteman and others, 1983 and Dion and Sumioka, 1984), field personnel visited 258 wells and a spring (see table 1) representing the Island.

Water samples from 184 wells and one spring (fig. 3 and table 1) were collected for analysis of specific conductance and chloride concentration. Specific conductance measurements were determined at the USGS Tacoma Field Service Unit (Tacoma FSU), Tacoma, Wash. The chloride content was determined colorimetrically using ferric thiocyanate (Friedman and Erdmann, 1982) at the Tacoma FSU.

Replicate and blank samples were collected and analyzed for chloride at the Tacoma FSU and at the USGS Quality of Water Service Unit in Ocala, Fla., in accordance with the Quality Assurance Plan for Water-Quality Activities of the Pacific Northwest District (Bortleson, U.S. Geological Survey, written commun., 1991). For every six samples, one sample of deionized water blanks was collected and analyzed at the Tacoma FSU. The results for all samples were acceptable. All replicates analyzed at both Tacoma and Ocala agreed within 5 percent of the replicate mean. Reference samples were within 5 percent of the known concentration of chloride. Chloride was not detected in any of the blank samples. The resulting field and quality-assurance data were reviewed and stored in the National Water Information System (Garcia and others, 1997).

WHAT THE STUDY FOUND

The 1997 study found chloride concentrations of 100 mg/L or more in 46 percent of the Island's 185 sites, indicating possible seawater intrusion. Chloride concentrations from the 185 ground-water samples ranged from 12 mg/L to 420 mg/L, with a median value of 92 mg/L.

When the 1997 and the 1981 chloride data were compared, there was no evident change in the areal distribution of chloride values from 1981 to 1997. Both chloride data sets had similar patterns of lowest concentrations near the center of the Island and highest concentrations mainly near the Island's southwestern, western, and northern shores. Moreover, there was no distinct pattern of changes of chloride concentrations in individual wells.

Of wells completed in bedrock units, 56 percent (28 wells) evinced seawater intrusion, while 39 percent of wells completed in glacial drift units (42 sites) showed such signs (fig. 1). One reason the bedrock wells may have shown more seawater intrusion was because they are generally deeper and thus closer to the transition zone.

Table 1. Summary of concentrations of chlorides, physical data, and hydrologic data for wells and a spring sampled in 1997 on Lopez Island [Hydrogeologic unit: B, basalt; G, glacial; M, gravel and basalt; mg/L as CL, milligrams per liter of Chloride; —, no data; . Chloride data rounded to two significant digits, all other data rounded to nearest foot; Altitude of land surface is based on sea level (NGVD of 1927)]

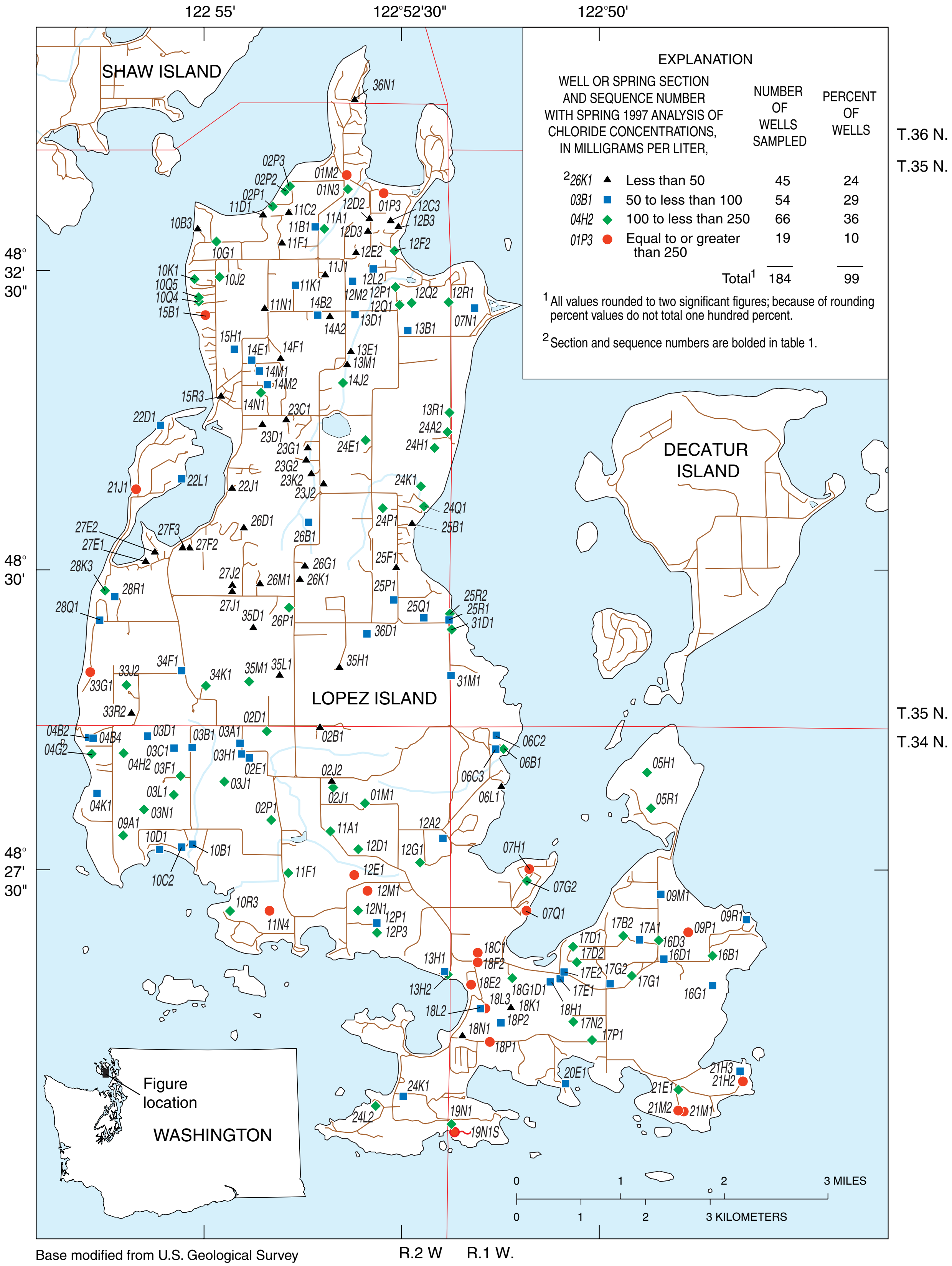
Station name (township/range-section and sequence number)	Altitude of land surface (feet)	Well depth (feet below land surface)	Depth to first opening of well (feet)	Spring 1997 water-level altitude (feet)	Chloride dissolved (mg/L as CL)			Hydrogeologic unit
					Spring 1997	Spring 1981	Spring 1978	
34N/1W-05H1	40	340	132	41	190	—	—	B
34N/1W-05R1	90	400	59	—	120	—	—	G
34N/1W-06B1	100	270	35	—	120	85	—	B
34N/1W-06C2	200	200	—	188	62	—	—	—
34N/1W-06C3	140	315	25	—	82	—	—	B
34N/1W-06L1	40	214	41	10	30	34	28	B
34N/1W-07G2	170	184	184	—	190	—	—	G
34N/1W-07H1	135	174	147	—	260	170	—	B
34N/1W-07Q1	40	270	—	—	290	150	150	—
34N/1W-09M1	130	168	163	27	76	—	—	G
34N/1W-09P1	105	440	232	—	270	—	—	B
34N/1W-09R1	60	164	30	34	87	87	72	B
34N/1W-16B1	75	143	138	72	150	130	110	B
34N/1W-16D1	150	112	112	—	72	—	—	G
34N/1W-16D3	165	300	—	—	110	—	—	—
34N/1W-16G1	90	338	44	66	90	—	—	B
34N/1W-17A1	180	198	192	—	96	—	—	G
34N/1W-17B2	180	299	262	19	130	—	—	M
34N/1W-17D1	200	250	32	—	170	100	—	B
34N/1W-17D2	220	152	18	205	150	—	—	G
34N/1W-17E1	70	115	106	13	56	59	52	G
34N/1W-17E2	70	87	82	17	90	—	—	G
34N/1W-17G1	150	290	40	—	200	—	—	B
34N/1W-17G2	170	124	19	—	70	—	—	B
34N/1W-17N2	150	142	—	—	200	—	—	—
34N/1W-17P1	110	170	99	45	170	100	—	B
34N/1W-18C1	140	259	102	—	260	—	—	B
34N/1W-18E2	120	260	75	—	280	350	410	B
34N/1W-18F2	100	35	—	97	260	—	—	—
34N/1W-18G1D1	80	132	132	6	160	150	—	G
34N/1W-18H1	100	115	115	—	82	46	—	G
34N/1W-18K1	110	15	—	108	48	—	—	—
34N/1W-18L2	15	46	41	—	80	—	—	G
34N/1W-18L3	20	104	99	—	260	—	—	G
34N/1W-18N1	20	62	62	—	23	—	—	G
34N/1W-18P1	40	58	50	27	280	—	—	G
34N/1W-18P2	60	52	47	43	94	—	—	G
34N/1W-19N1	70	69	68	48	180	—	—	G
34N/1W-19N1S	40	spring	—	—	270	—	—	—
34N/1W-20E1	30	164	11	18	52	73	42	G
34N/1W-21E1	80	30	—	77	110	—	—	—
34N/1W-21H2	70	345	20	38	400	—	—	B
34N/1W-21H3	55	—	—	—	64	—	—	—
34N/1W-21M1	80	200	—	44	260	—	—	—
34N/1W-21M2	100	500	—	21	250	—	—	—
34N/2W-01M1	260	260	—	—	100	—	—	—
34N/2W-02B1	270	266	20	251	42	30	—	B
34N/2W-02D1	155	307	65	130	140	—	—	B
34N/2W-02E1	170	250	160	—	94	—	—	B
34N/2W-02J1	225	300	19	—	170	—	—	B
34N/2W-02J2	205	30	—	203	12	—	—	—
34N/2W-02P1	140	414	23	—	230	180	150	B
34N/2W-03A1	150	226	226	—	70	—	—	G
34N/2W-03B1	180	194	194	1	88	—	—	G
34N/2W-03C1	200	229	199	—	86	67	—	G
34N/2W-03D1	180	216	216	—	78	—	—	G
34N/2W-03F1	130	154	144	—	150	120	—	G
34N/2W-03H1	170	204	204	7	86	—	—	G
34N/2W-03J1	170	181	176	—	100	—	—	G
34N/2W-03L1	145	265	135	—	140	92	—	G
34N/2W-03N1	105	166	166	35	110	—	—	B

Table 1. Summary of concentrations of chlorides, physical data, and hydrologic data for wells and a spring sampled in 1997 on Lopez Island—Continued

Station name (township/range-section and sequence number)	Altitude of land surface (feet)	Well depth (feet below land surface)	Depth to first opening of well (feet)	Spring 1997 water-level altitude (feet)	Chloride dissolved (mg/L as CL)			Hydrogeologic unit
					Spring 1997	Spring 1981	Spring 1978	
34N/2W-04B2	82	96	96	—	92	—	—	G
34N/2W-04B4	85	90	90	10	88	—	—	G
34N/2W-04G2	80	88	88	11	100	—	—	G
34N/2W-04H2	150	169	169	3	100	—	—	G
34N/2W-04K1	80	240	52	8	94	—	—	B
34N/2W-09A1	62	134	129	—	210	—	—	G
34N/2W-10B1	65	16	—	—	94	—	—	—
34N/2W-10C2	90	244	19	—	92	—	—	B
34N/2W-10D1	20	52	46	-4	54	—	—	G
34N/2W-10R3	50	330	28	—	230	—	—	M
34N/2W-11A1	125	106	106	87	150	—	—	B
34N/2W-11F1	70	272	46	55	110	—	—	B
34N/2W-11N4	20	150	39	—	320	—	—	M
34N/2W-12A2	150	40	—	148	58	—	—	—
34N/2W-12D1	130	134	25	103	130	47	—	B
34N/2W-12E1	100	179	18	—	400	—	—	B
34N/2W-12G1	150	196	20	132	100	73	—	B
34N/2W-12M1	110	252	18	—	280	—	—	B
34N/2W-12N1	70	328	20	—	120	—	—	B
34N/2W-12P1	135	265	42	—	86	180	—	B
34N/2W-12P3	135	405	33	—	130	—	—	B
34N/2W-13H1	80	12	—	77	50	—	—	—
34N/2W-13H2	80	180	35	70	170	—	—	B
34N/2W-24K1	60	203	20	—	85	—	77	M
34N/2W-24L2	60	238	45	—	160	—	—	B
35N/1W-07N1	130	128	118	18	78	—	—	G
35N/1W-31D1	75	305	30	60	140	—	—	B
35N/1W-31M1	170	245	20	—	74	—	—	B
35N/2W-01M2	60	80	60	15	360	—	—	G
35N/2W-01N3	40	64	58	8	110	—	—	G
35N/2W-01P3	40	50	—	11	300	—	—	—
35N/2W-02P1	40	60	55	—	100	50	—	G
35N/2W-02P2	70	99	94	-8	180	—	—	G
35N/2W-02P3	70	76	71	5	100	—	—	G
35N/2W-10B3	40	33	28	19	30	—	—	G
35N/2W-10G1	120	135	130	-2	120	—	—	G
35N/2W-10J2	170	180	180	7	100	—	—	G
35N/2W-10K1	140	135	125	19	100	—	—	G
35N/2W-10Q4	150	153	153	17	130	—	—	G
35N/2W-10Q5	160	150	151	—	150	—	—	G
35N/2W-11A1	60	104	98	12	110	—	—	G
35N/2W-11B1	60	130	—	-60	54	—	—	—
35N/2W-11C2	90	102	97	8	30	34	—	G
35N/2W-11D1	60	68	63	—	32	39	34	G
35N/2W-11F1	130	143	138	—	34	—	—	G
35N/2W-11J1	170	185	185	4	34	45	—	G
35N/2W-11K1	145	160	160	0	80	—	—	G
35N/2W-11N1	130	154	—	—	38	—	—	—
35N/2W-12B3	60	74	74	8	48	—	—	G
35N/2W-12C3	130	141	136	—	32	—	—	G
35N/2W-12D2	90	95	90	8	30	44	—	G
35N/2W-12D3	130	158	152	—	28	—	—	G
35N/2W-12E2	220	243	243	12	32	—	—	G
35N/2W-12F2	22	29	—	3	140	90	—	—
35N/2W-12L2	60	70	70	4	80	57	56	G
35N/2W-12M2	165	186	186	-2	80	—	—	G
35N/2W-12P1	18	40	34	1	110	—	—	G
35N/2W-12Q1	60	80	80	6	200	—	—	G
35N/2W-12Q2	60	66	66	18	100	—	—	G
35N/2W-12R1	165	181	180	-3	190	—	—	G
35N/2W-13B1	100	116	116	2	74	—	—	G
35N/2W-13D1	115	125	125	6	78	—	—	G

Table 1. Summary of concentrations of chlorides, physical data, and hydrologic data for wells and a spring sampled in 1997 on Lopez Island—Continued

Station name (township/range-section and sequence number)	Altitude of land surface (feet)	Well depth (feet below land surface)	Depth to first opening of well (feet)	Spring 1997 water-level altitude (feet)	Chloride dissolved (mg/L as CL)			Hydrogeologic unit
					Spring 1997	Spring 1981	Spring 1978	
35N/2W-13E1	100	114	115	3	40	—	—	G
35N/2W-13M1	100	114	114	3	48	—	—	G
35N/2W-13R1	85	151	146	4	160	—	—	G
35N/2W-14A2	130	150	150	4	48	—	—	G
35N/2W-14B2	135	164	164	-0	62	—	—	G
35N/2W-14E1	100	113	108	-0	50	39	27	G
35N/2W-14F1	135	142	136	10	32	—	—	G
35N/2W-14J2	100	160	100	-2	100	—	—	G
35N/2W-14M1	110	113	105	10	52	—	—	G
35N/2W-14M2	180	155	136	45	50	—	—	G
35N/2W-14N1	170	137	132	48	120	—	—	G
35N/2W-15B1	130	158	153	—	290	—	200	G
35N/2W-15H1	70	102	102	-2	90	—	—	G
35N/2W-15R3	20	65	61	0	18	—	—	G
35N/2W-21J1	20	302	23	—	250	—	—	B
35N/2W-22D1	15	150	10	—	86	150	—	B
35N/2W-22J1	45	50	46	—	16	63	73	B
35N/2W-22L1	18	345	20	-9	94	—	—	B
35N/2W-23C1	80	100	99	0	32	—	—	G
35N/2W-23D1	80	99	89	—	46	—	—	G
35N/2W-23G1	160	173	173	3	14	—	—	B
35N/2W-23G2	182	216	216	-12	30	—	—	B
35N/2W-23J2	220	229	211	12	30	—	—	G
35N/2W-23K2	205	211	211	5	30	—	—	G
35N/2W-24A2	98	265	106	33	150	—	—	G
35N/2W-24E1	100	120	112	—	110	—	—	G
35N/2W-24H1	120	100	—	110	130	92	—	—
35N/2W-24K1	80	90	85	35	100	—	—	G
35N/2W-24P1	250	302	302	67	100	—	—	G
35N/2W-24Q1	44	91	86	26	100	—	—	G
35N/2W-25B1	40	141	95	—	32	39	74	G
35N/2W-25F1	139	237	83	—	40	—	—	B
35N/2W-25P1	190	300	40	50	60	—	—	B
35N/2W-25Q1	125	60	60	84	82	64	—	G
35N/2W-25R1	60	215	26	49	94	87	—	B
35N/2W-25R2	60	382	318	—	220	—	—	B
35N/2W-26B1	218	220	220	9	64	—	—	G
35N/2W-26D1	290	322	296	10	40	—	—	G
35N/2W-26G1	265	280	275	10	20	—	—	G
35N/2W-26K1	230	261	261	1	40	38	—	G
35N/2W-26M1	220	249	241	—	30	25	—	G
35N/2W-26P1	190	426	426	-7	160	—	—	G
35N/2W-27E1	33	38	38	5	30	—	—	G
35N/2W-27E2	22	22	18	13	12	—	—	G
35N/2W-27F2	70	78	78	12	40	—	—	G
35N/2W-27F3	40	—	—	9	30	—	—	—
35N/2W-27J1	230	241	241	102	28	—	—	G
35N/2W-27J2	250	270	165	-5	20	—	—	G
35N/2W-28K3	110	122	117	8	150	—	—	G
35N/2W-28Q1	190	212	207	-3	60	72	—	G
35N/2W-28R1	150	155	155	11	60	55	—	G
35N/2W-33G1	130	140	140	15	420	360	390	G
35N/2W-33J2	190	220	—	-6	150	—	—	—
35N/2W-33R2	190	190	189	16	24	—	—	G
35N/2W-34F1	180	194	188	-1	68	75	—	G
35N/2W-34K1	190	203	203	4	100	—	—	G
35N/2W-35D1	205	191	191	22	28	—	—	G
35N/2W-35H1	280	255	30	270	28	38	—	B
35N/2W-35L1	210	310	131	—	28	23	—	B
35N/2W-35M1	185	219	219	3	100	—	—	G
35N/2W-36D1	290	485	300	—	50	51	—	M
36N/2W-36N1	80	149	20	—	24	—	—	B



EXPLANATION

WELL OR SPRING SECTION AND SEQUENCE NUMBER WITH SPRING 1997 ANALYSIS OF CHLORIDE CONCENTRATIONS, IN MILLIGRAMS PER LITER,		NUMBER OF WELLS SAMPLED	PERCENT OF WELLS
[2]26K1 ▲	Less than 50	45	24
03B1 ■	50 to less than 100	54	29
04H2 ◆	100 to less than 250	66	36
01P3 ●	Equal to or greater than 250	19	10
	Total[1]	184	99

[1] All values rounded to two significant figures; because of rounding percent values do not total one hundred percent.

[2] Section and sequence numbers are bolded in table 1.

Base modified from U.S. Geological Survey digital data, 1:2,000,000, 1972

Figure 3. *Areal distribution of chloride concentrations from wells or spring on Lopez Island measured in the spring of 1997.*

Table 2. Chloride concentrations in ground-water samples collected April 1981 and in late April to early June 1997, Lopez Island, Washington
[Chloride data rounded to two significant digits]

Group of samples	Year	Number of samples	Chloride concentration, in milligrams per liter					P-value
			Minimum	25th percentile	Median	75th percentile	Maximum	
Paired, all	1981	44	23	45	67	100	360	[1]0.01
	1997	44	16	42	86	140	420	
Paired, within 1,500 feet of shoreline	1981	28	34	54	86	140	360	[1]0.06
	1997	28	16	59	90	160	420	

[1] A Wilcoxon signed-rank test (one-sided) was used to test the hypothesis that the chloride concen-trations in 1997 were not greater than chloride concentrations in 1981. The test was conducted using onlywells that were sampled in 1981 and again in 1997. P-values less than 0.05 indicate a significant increase in chloride concentrations from 1981 to 1997.

When seawater intrudes, three trends are usually apparent. First, chloride concentrations at a given site may increase over time. Second, for wells open at the same depth, there may be a strong relation between chloride concentrations and a well's distance from the shoreline, with chlorides being greater the closer a well is to shore. Third, chloride concentrations at a given site may increase with depth.

The first trend was found on Lopez Island. Chloride samples collected from the same wells in 1981 and in 1997 showed a statistically significant increase in concentration over time (table 2). But no trends were found between chloride concentrations and distance from shore or between chloride concentrations and the depth of a well's open interval. These trends may not have been apparent because of wells too shallow to be strongly influenced by the freshwater-saltwater transition zone or because of the effects of sea spray, varying lithologies, different ground-water levels, possible pumping before sampling, or uneven areal distribution of sampled sites.

The 1981 and 1997 chloride data were subjected to two statistical tests: Wilcoxon signed-rank tests on (1) all paired samples and (2) paired samples from near-shoreline wells within 1,500 feet of the shoreline (Helsel and Hirsch, 1992). Using paired samples removes the influence of many environmental factors, so the test more accurately indicates real differences in chloride concentrations over time. The paired samples from near-shoreline wells were tested because one may expect the wells closer to the shoreline to be more sensitive to seawater intrusion. The wells tested for chlorides in 1981 and 1997 showed a statistically significant increase in concentration. But no significant increase in concentration was found for the near-shoreline wells (table 2).

Chloride concentrations in excess of 100 mg/L suggested seawater intrusion, and the statistical tests indicated that concentrations had increased over time. But the data did not show trends of consistently higher concentrations near the shoreline or consistent increases of concentration with depth. Thus, further investigations are needed to rule out sources of chloride other than seawater intrusion.

HOW CHLORIDE AFFECTS THE QUALITY OF THE WATER?

According to the U.S. Environmental Protection Agency (EPA), water with high chloride content may, among other things, cause high blood pressure; taste salty; corrode pipes, fixtures, and appliances; and blacken and pit stainless steel. The EPA has set a Secondary Maximum Contaminant Level (SMCL) of 250 mg/L for chlorides. An SMCL is the concentration limit for a nuisance contaminant that could affect the aesthetic quality of water by causing taste, odor, or staining problems (U.S. Environmental Protection Agency, 1996).

FUTURE STUDIES

Future studies like these examples could help assist understanding of seawater intrusion on Lopez Island:

- Twice-a-year sampling of a network of monitoring wells for specific conductance and chloride concentrations to observe minimum values in early spring and maximum values in late summer or early fall.

- Detailed evaluation of the hydrogeologic conditions that control the movement of the freshwater-seawater transition zone. A three-dimensional digital model of the ground-water system would enable this evaluation and this would require definition of hydrogeologic boundaries, hydraulic properties, water levels, and a water budget.

- Determination and mapping of the location of seawater versus the location of the freshwater aquifers using geophysical methods or electromagnetic induction.

-Target drilling and installation of multi-depth monitoring wells in suspect nearshore areas; constructing flow path sections.

-Installment of precipitation collectors to measure the amount of chloride in precipitation.

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