

**FURTHER EVIDENCE of
SEAWATER INTRUSION in
COASTAL LOPEZ ISLAND (WA) AQUIFERS**



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KWIÀHT

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Summary

Aquifers in low-lying coastal areas, including islands, are frequently in contact with seawater. Significant withdrawals from wells can draw seawater into these aquifers, gradually increasing aquifer salinity to the point that water is no longer potable. The San Juan Islands were largely below sea level in early post-glacial times (8,000-10,000 years ago), moreover, flooding aquifers with seawater that may remain trapped under lenses of more recent freshwater additions. While these aquifers may no longer be in contact with the sea, withdrawals that exceed the rate of recharge (from precipitation and infiltration) can mix the relict saline water with remaining fresh water. Relict seawater and seawater intrusion limit the availability of potable water throughout the San Juan Archipelago, but especially for low-relief islands such as Lopez where most aquifers lay below current sea levels.

The U.S. Geological Survey tested 184 Lopez wells for chlorides in 1997. Half of the wells tested had chlorides in excess of 100 mg/L (parts per million); one in ten wells exceeded 250 parts per million. While these values are very small in comparison with the chloride concentrations in seawater around the islands (32,000 parts per million), they are evidence of underground mixing of seawater and freshwater, and the U.S. Environmental Protection Agency recommends that drinking water be kept below 250 parts per million chlorides. Increased rates of withdrawal from compromised aquifers—or decreased rates of aquifer recharge due to climate change—may continue to increase salinity in affected wells until they are no longer potable.

More than a decade has passed since the USGS study. County health authorities have had an opportunity to take steps to manage existing wells and permits for new wells in a manner to prevent further aquifer degradation. To determine whether Lopez water is still at risk, we solicited submissions of well water from all of the pupils at Lopez School, followed by an open public call for water samples in autumn 2009. All samples received (N=169) were tested for chlorides as well as pH, total dissolved solids (TDS), alkalinity, and hardness. After rejecting samples with inadequate documentation, and samples from rain catchment systems, and grouping samples from Class A and B (multi-user) wells, we had data from 146 Lopez wells.

Overall, the wells we tested were somewhat less salty than those tested in 1997 by USGS. One-third (31 percent) were at least 100 parts per million chlorides, and 3 percent exceeded 250 parts per million. Since we could not re-test all of the same wells tested by USGS 13 years ago, it is unclear whether the differences between the 1997 and 2009 data are due to sampling biases, or to a change in underlying conditions. It is possible that the apparent reduction in overall saltiness is due to closure of salty wells and drilling of new wells since 1997. It is also possible that USGS biased its sample by selecting its wells for study of seawater intrusion. Both studies indicate a widespread threat to water supplies, however, that is most severe but not limited to the “south end” of the island.

Further Evidence of Seawater Intrusion in Coastal Lopez Island (WA) Aquifers

Laura Strom and Russel Barsh

In 1997, the U.S. Geological Survey measured chloride concentrations in samples from 185 Lopez Island wells, and concluded that nearly half of the wells sampled showed evidence of seawater intrusion (USGS 2000). The agency recommended sampling Lopez wells more frequently and systematically for chlorides. It also recommended a number of water conservation measures such as reducing outdoor water use and reusing or recycling water, as well as reducing the depth and pumping rates of Lopez wells.

Seawater intrusion is widespread in exploited coastal aquifers. Unless the aquifer is perched entirely above sea level, some part of it may be in contact with saltwater below sea level at a modest distance offshore. If freshwater is withdrawn from the aquifer faster than it is replenished by precipitation and infiltration, seawater gradually replaces it. The problem can be hidden for years because fresh water floats on top of the denser seawater, and wells can continue to produce superficially uncontaminated water as long as the fresh water lens is not completely exhausted.¹ The early warning sign of seawater intrusion is a gradual increase in saltiness (chlorides) that can continue unnoticed for decades until well water finally becomes unpalatable at about 250-500 parts per million chlorides. Seawater around the islands averages about 32,000 parts per million chlorides, for comparison.

As coastal human settlements grow and demand more potable water, more wells are drilled, new wells are drilled deeper, and water is withdrawn more quickly from wells—factors that increase the likelihood of seawater intrusion. The risk is also a function of local geology and natural aquifer recharge rates. Here in the San Juan Islands we have a geologically relatively young landscape shaped by glacial erosion and outwash sediments over less than ten thousand years. Thick accumulations of unconsolidated sands, gravels, and clays fill some ancient valleys and bays, or form low ridges such as Whiskey Hill on Lopez. Most of the islands' landscape is exposed bedrock with at best a thin covering of soil, however. A majority of island aquifers are simply fractured rock, and recharge rates for bedrock aquifers are low (Orr et al. 2002; Dion & Sumioka 1984). The likelihood of seawater intrusion is correspondingly high (Whiteman et al. 1983).

Indeed, as the San Juan Islands slowly rebounded elastically from glacial loading and reemerged from a sea swollen with glacial melt water, aquifers that perch well above the sea today were below sea level for hundreds to thousands of years. It is therefore not uncommon to find high salinity in island aquifers that are hundreds of feet above current sea levels. Overdrawing the freshwater cap in these aquifers will have the same effect as overdrawing aquifers that still extend below sea level: well water will grow saltier and eventually become unpalatable. Whether the source of chlorides is relict seawater or the influence of present-day seawater intrusion, water conservation measures are necessary to balance consumption with recharge lest the aquifer become non-potable.

¹ Although the freshwater and seawater lenses remain distinct, salts in the seawater slowly diffuse into the lighter layer of freshwater above, causing a very small and gradual increase in its salinity.

By the time wells become unpalatably salty requiring treatment (reverse osmosis) or abandonment, water users may already have suffered adverse health consequences if a condition such as hypertension requires them to manage salt (sodium chloride) intake. At 500-1000 parts per million chlorides, well water does not taste salty, but drinking a quart of it is equivalent to adding a quarter-teaspoon of table salt to food. Home water filters, which generally employ activated charcoal or special adsorptive resins to remove metals and potentially toxic organic compounds, do not significantly reduce salt.

The present study aimed to re-sample a broad cross-section of Lopez wells to see whether intrusion zones identified by USGS more than a decade ago have grown, or new intrusion zones have appeared. We did not expect to find significant additional saltiness in the wells tested by USGS in 1997, given the slow diffusion of salts in aquifers and the vagaries of seasonal and annual variation in rainfall and consequently, recharge, dilution, and withdrawals. Indeed, USGS researchers did not discern a clear pattern of increasing chlorides in 46 Lopez wells that had first been tested 16-18 years earlier. We concluded that it would be more meaningful, in light of the time interval and underlying variability of chloride concentrations, to draw an independent sample of Lopez wells to see whether our results were (at least) consistent with the 1997 USGS data set as a whole.

Methods

Handbills describing the study and its objectives were distributed to K-12 teachers at Lopez School at the beginning of the 2009-2010 academic year, followed by classroom visits to answer teacher and student questions, distribute sample vials and blank data slips and explain the sampling protocol. A subsequent broad public appeal was issued through the community newspaper, *The Islands Weekly*. Students were asked to return filled vials and completed data slips to specially marked boxes at school offices. A drop box was set up at the public library for other participants.

Pre-coded pre-cleaned (VOA Level II) 125-mL glass vials with Teflon cap liners were distributed to Grade 6-12 students and the general public with matching blank data slips attached with a rubber band. At the request of the elementary school principal, glass containers were replaced with soft plastic for Grade 1-5 students: pre-coded sealed sterile 150-cc medical specimen cups. Of 200 containers distributed, 171 were returned and 159 were returned with sufficient contextual data (well location and whether single household or multi-household) for inclusion in this study. After adjusting for multiple samples from group wells, the total number of wells represented in our study was 146.

Anonymity was maintained throughout the collection and testing process. Sample containers were separated from data slips and not reconciled until the second stage of QA described below. Participants were given the option of including contact information on data slips for receiving individual test results, and a majority of them availed themselves of this opportunity.

Water samples were tested in four randomized batches on separate dates. Positive and negative controls and reagent blanks were included in each batch, as described below in greater detail under quality assurance.

An Oakton PCS Testr 35 (Vernon Hills, IL) calibrated at the beginning of each batch was used to measure pH and Total Dissolved Solids (TDS). Colorimetric titrations were employed to measure alkalinity and hardness, and total chlorides were determined colorimetrically by the silver nitrate method with a single-beam spectrophotometer, using LaMotte (Chestertown, MD) reagent kits.

Quality assurance (QA): Accuracy and consistency of results were assessed at two levels. Positive controls (standard solutions of analytes) and negative controls (ultra-pure water) were included with each batch of samples tested. Very high test results triggered a re-test of the sample on the same day to confirm or reject the original value. After all the samples had been tested and the results were linked with the location of the source wells, anomalies—such as high salinity at an inland location, or higher salinity in some samples drawn from the same group well—also triggered re-testing. This error-trapping strategy aims to minimize false positives. In other words, if errors remain in our results, they are most likely to be in the direction of *understating* the salinity of a well.

Accuracy of results: Errors of measurement can be estimated from the analysis of negative and positive controls. Negative controls or blanks (Milli-Q water), and positive controls (standard solutions of Calcium Carbonate and Calcium Chloride), were included in the sample queue on each day of laboratory work. Results are summarized in Table 1 (N=number of controls tested, SD=standard deviation, TDS=Total Dissolved Solids). All results are for negative controls except where otherwise indicated.

Table 1: Results of positive and negative controls (in ppm except for pH)

Analyte	N	Expected value	Mean result	SD
PH	6	6.90	6.83	0.11
TDS	7	0	1.97	1.09
Alkalinity (CO ₃)	7	0	4.29	1.80
Hardness (negative)	7	0	0	0
Hardness (positive)	7	200	207	11.0
Chlorides (negative)	7	0	1.2	0.47
Chlorides (positive)	6	10	10.2	1.6

As seen in Table 1, our measurements of chloride concentrations were relatively accurate, with a reagent blank (negative control) of just a little over 1 ppm, and corrected standard deviation in the positive control of only 1.6 ppm or approximately 16 percent of the true value. This means that a test result of 150 ppm Chlorides should be construed as $149 \pm 16\%$ or 149 ± 24 .

Measurements of Hardness were also relatively accurate, with no reagent effects, and a corrected standard deviation in the positive control of 5.5 percent. A test result of 300 ppm Hardness should accordingly be construed as 300 ± 16 ppm.

At the levels of TDS and Alkalinity measured in our samples, reagent effects for these analytes (just over 2 and 4 ppm respectively) were negligible. The instrument used to measure TDS and pH was calibrated daily with two standard solutions for each of the parameters.

Results and Discussion

Results of testing are summarized in Appendix A, organized by the alphanumeric codes assigned to sample vials when they were distributed. Only well water samples are shown. A number of rainwater catchment samples were also submitted and tested but are not included here. Table 2 summarizes our 2009 chloride data, and compares them with the 1997 USGS data set.

Table 2: Summary of 1997 and 2009 results for chlorides

	1997 USGS	2009 Kwiáht	Difference
Sample size	184	146	
Mean chlorides all wells	112	95	-15%
% of wells \geq 100 ppm	46	31	-33%
% of wells \geq 250 ppm	10	3	-70%
Range (in ppm)	12-420	13-442	

Mean chlorides (all wells tested) were somewhat lower in 2009 than 1997. Most of the difference can be attributed to a decrease in the number of wells with chlorides that exceed EPA drinking water standards (*i.e.* 250 ppm). In other words there were far fewer very salty wells in the more recent study. The total range of test results for chlorides was almost identical for the two studies, however, suggesting that they are broadly consistent.

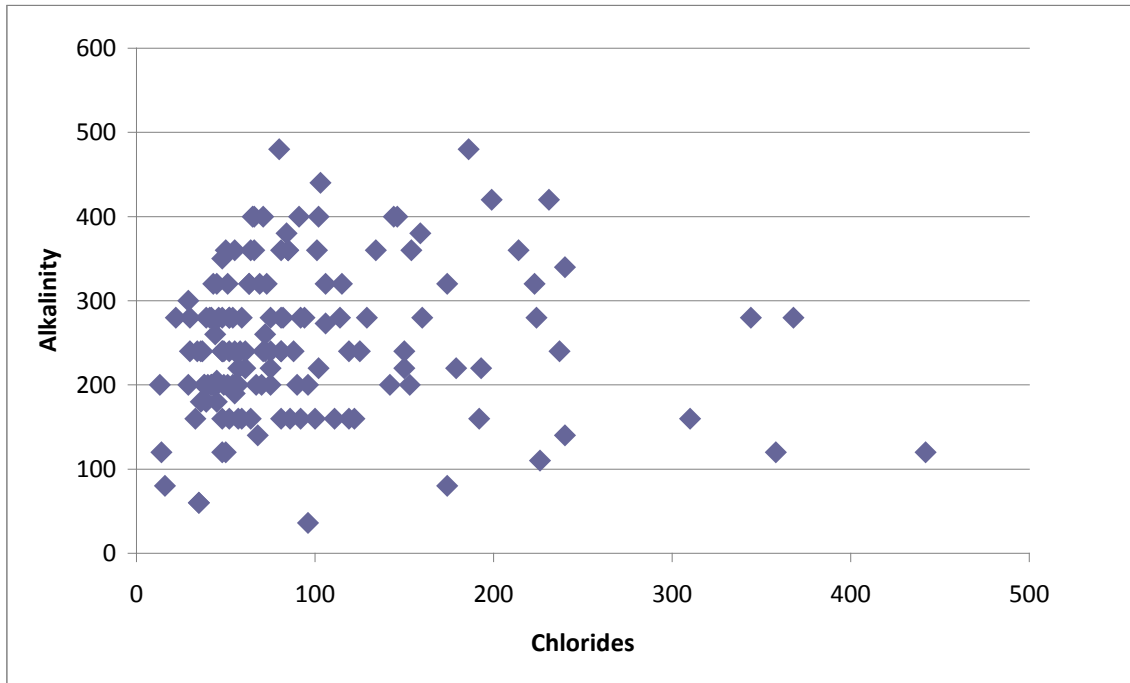
Differences between the 1997 and 2009 data could be due to closure of salty wells and drilling of new wells since 1997. It is also possible that USGS biased its sample in the direction of saltier wells by selecting which wells to include in its study, whereas the present study relied on voluntary submissions, and may be more broadly representative of actual conditions on Lopez. In either case, whether the actual proportion of salty wells is 46 or 31 percent, salinity is a still significant potential threat to Lopez water supplies.

The geographic distribution of test results for chlorides is shown in Appendix B. Red circles represent 250 ppm chlorides or greater. Yellow represents 100-249 ppm, and green represents less than 100 ppm. In both the 1997 and 2009 studies, highest chlorides were observed on the “south end” of Lopez, although the number of very salty wells that exceed EPA drinking water standards was smaller in 2009.

Wells in excess of 100 ppm were observed throughout the island in both 1997 and 2009. There are clusters of elevated salinity in the Shark Reef area, the central valley, the Shoal Bay and Swift's Bay watersheds, even in the vicinity of Lopez Hill. Only Whiskey Hill, a large moraine complex on the east side of Fisherman Bay, was largely unaffected. This suggests that relict seawater and/or current seawater intrusion is a factor for wells in all Lopez aquifers except, perhaps, the Whiskey Hill moraine.

The present study also explored possible relationships between saltiness, hardness (dissolved calcium and magnesium), alkalinity (dissolved carbonates), and TDS or Total Dissolved Solids. Seawater is very rich in inorganic salts including calcium, magnesium, and carbonates. Bedrock derived from old marine sediments can be enriched in calcium, magnesium, and carbonates; limestone is mainly calcium and magnesium carbonates. Do these water quality factors co-vary or reflect (at least in part) different sources/processes? Figures 1, 2, 3 and 4 show their inter-relationships.

Figure 1: Alkalinity as a function of Chlorides (values in ppm)



There is no significant co-variance of alkalinity or hardness with chlorides: hence the causes of salinity, hardness and alkalinity in wells are not entirely the same. In any case, nearly all of the Lopez well water we tested is very hard and alkaline, which itself can affect potability. Hardness and alkalinity tend to co-vary to some extent, with an r^2 value of 0.22 indicating that this relationship explains about 22% of the variation in each of these parameters—still not a very strong correlation.

Figure 2: Hardness as a function of Chlorides (values in ppm)

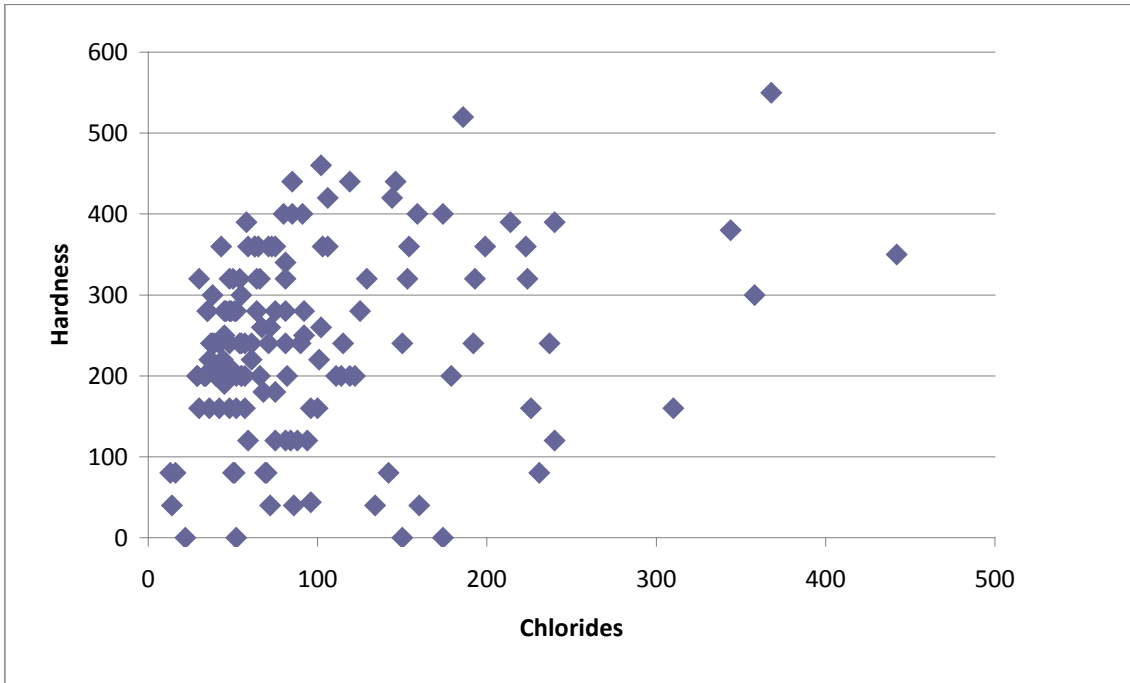


Figure 3: Co-variance of Alkalinity and Hardness (values in ppm)

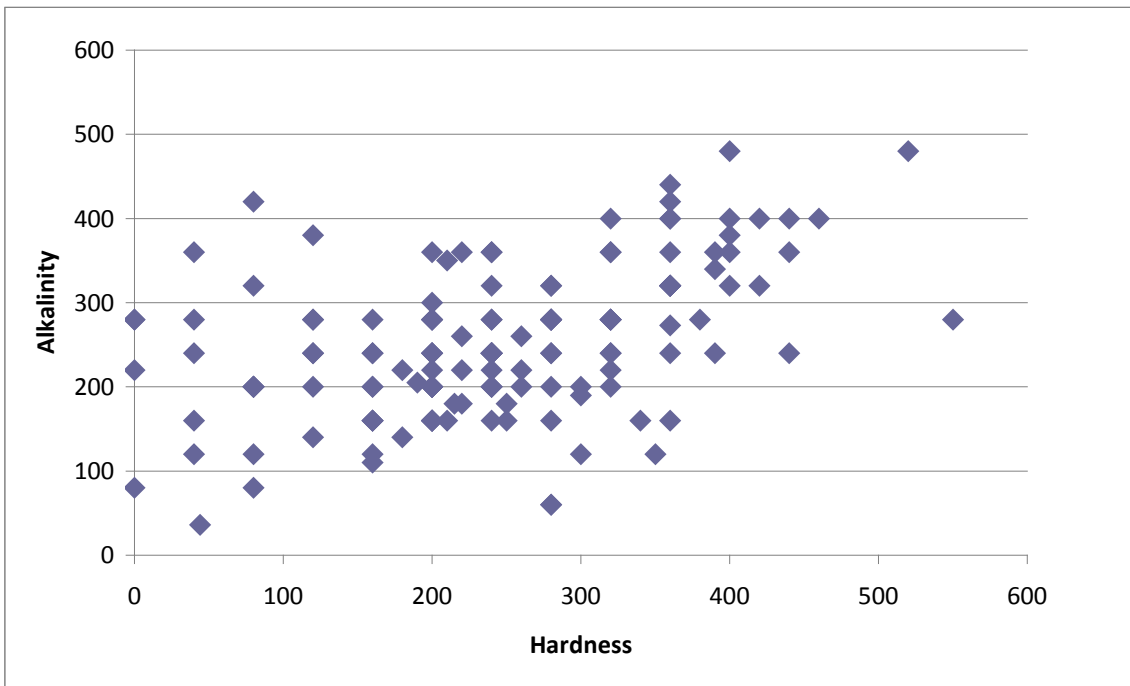
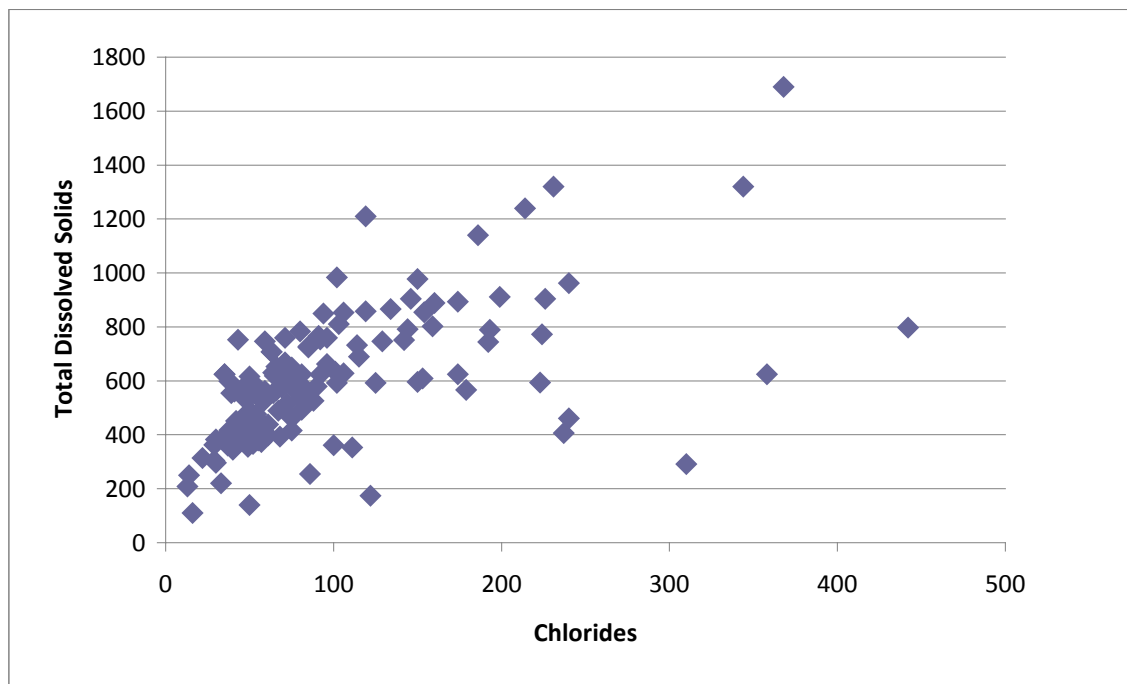


Figure 4: Total Dissolved Solids as a function of Chlorides



Total Dissolved Solids (TDS) co-vary with chlorides to a modest, but statistically significant extent ($r^2=0.37$). Chlorides explain roughly one-third of the variation in TDS in Lopez wells; other inorganic and organic ions, including nutrients such as nitrates and toxics (or contaminants) such as heavy metals must account for the rest. Very high TDS is a warning sign for salinity as well as contamination. The practical significance of this is the ease with which TDS can be measured using inexpensive electrical probes and self-logging instruments, at considerably less expense than laboratory testing for chlorides.

We considered the possibility that bedrock aquifers may be saltier—or less salty, on average—than unconsolidated sand and gravel aquifers. Lopez wells in bedrock were somewhat saltier on average (mean chlorides 117 ppm) than wells in unconsolidated sediments (mean chlorides 83 ppm), but the difference was not statistically significant ($t=0.284, p>0.05$).

Conclusions and Recommendations

The present study confirms the finding of the 1997 USGS study that a significant proportion of Lopez wells have elevated chlorides, presumably as a result of mixing with relict seawater, or more recent seawater intrusion. Nearly all parts of Lopez are affected, although the highest levels of chlorides were observed in both studies on the “south end” of the island, an area of very low relief, and exceptionally fractured bedrock very close to the San Juan Thrust Fault. Nearly all (97%) the wells tested meet current EPA drinking water standards for chlorides, but wells in the 100-249 part-per-million (chlorides) range should be consider at risk from the combined future effects of increased water withdrawal from existing and additional wells, and climate change. Current climate models predict a

pattern of stormier winters (more extreme precipitation events) and drier summers. More stormy winters will mean that a larger proportion of rainfall will run off to the sea, rather than infiltrating soils and recharging aquifers. Increased winter runoff and drier summers will result in reduced annual aquifer recharge and consequently increased risk of elevated salinity in groundwater. Drier summers may also result in increased per capita water use: another risk factor.

It would be prudent to begin taking serious water conservation measures, such as capping groundwater withdrawals at 2010 levels, increasing restrictions on new wells and promoting the use of rainwater for households and gardens. Conserving existing potable groundwater resources requires shifting the water requirements of growth to other water sources, in ways that will not further compromise aquifers or aquatic habitats. Rainwater resources are promising because runoff can be captured, used, recycled and then returned, without reducing recharge—if systems are properly designed. Other alternatives include importing water and desalinization, both of which require substantial infrastructure and energy, apart from possible environmental impacts.

As a first step, it would be useful for local authorities to monitor well levels and well water withdrawals systematically, as a basis for modeling the capacity of Lopez aquifers more accurately. Frequent (at least annual) measurement of chlorides in a subset of wells would moreover make it possible to model the response of aquifers to changing rates of water withdrawal, from which can be estimated the maximum rate of water withdrawal in each aquifer that will maintain salinity at current levels.

References

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Appendix A

Well water test results organized by sample codes

Code	pH	TDS	Chlorides	Alkalinity	Hardness
A1	7.89	296	30	240	160
A11	8.18	810	103	440	360
A12	8.07	305	29	200	200
A13	7.95	476	54	200	240
A15	8.03	767	91	400	400
A16	8.01	783	80	480	400
A2	7.79	452	42	280	240
A3	7.97	345	40	200	200
A4	7.67	904	146	400	440
A5	7.46	140	50	120	80
A61	8.83	563	59	280	120
A62	7.31	1140	186	480	520
A71	8.18	596	73	320	360
A72	8.31	893	174	320	400
A81	7.73	792	144	400	420
A82	7.66	554	39	280	240
A9	8.04	363	29	300	200
B11	7.39	625	35	60	280
B14 ^(A)	7.70	24	8	40	0
B16	7.35	373	48	160	210
B17	7.67	1210	119	240	440
B18	7.84	417	38	200	240
B19	7.68	416	48	240	240
B2	8.10	385	34	240	200
B20	8.12	978	150	220	0
B6	8.12	760	96	36	44
B8	8.30	623	92	160	250
C1	7.74	618	65	400	360
C10	7.71	759	71	240	240
C11	7.83	797	442	120	350
C12	7.86	392	45	180	250
C13	7.58	789	193	220	320
C14	8.06	369	42	200	160
C16	7.68	773	224	280	320
C2	7.26	379	55	190	300
C3	7.28	110	16	80	80
C5	8.36	625	358	120	300
C9	7.80	596	150	240	240
E11	8.31	858	119	160	200

Code	pH	TDS	Chlorides	Alkalinity	Hardness
E12	7.54	668	71	400	360
E13 (B)	8.27	625	110	240	320
E141	8.32	585	65	280	240
E142	8.53	567	82	280	200
E15	7.83	624	81	160	340
E17	8.16	584	81	360	240
E2	7.73	380	44	200	240
E22	8.23	641	108	240	280
E23	8.28	462	75	200	120
E24	7.97	662	96	200	160
E26	8.38	427	38	240	240
E3	8.06	536	34	240	280
E30	8.36	751	142	200	80
E31	8.46	434	49	280	200
E33	8.29	649	75	240	360
E37	7.86	533	48	240	320
E38	8.34	573	46	280	280
E39	8.12	581	54	280	320
E4	7.70	744	192	160	240
E41	8.14	526	88	240	120
E42	7.75	546	84	380	120
E43	7.36	255	86	160	40
E44	7.97	366	52	160	200
E47	5.91	221	33	160	200
E5	8.31	493	81	240	120
E6	8.01	391	43	200	200
E62	7.68	802	159	380	400
E67	8.32	732	114	280	200
E71	7.87	724	85	360	400
E73	7.75	371	36	240	160
E74 (A)	8.77	384	47	200	320
E75 (B)	8.21	601	112	240	40
E761	7.58	1690	368	280	550
E762	7.71	405	52	280	160
E771	8.72	423	42	200	200
E772	8.23	690	115	320	240
E78	7.88	653	66	360	200
E8	7.66	412	51	200	160
E81	7.57	461	51	320	280
E83	6.59	250	14	120	40
E84	7.96	299	34	200	200
E85	8.04	560	41	280	200
K1	8.92	516	72	240	40
K10	6.53	174	122	160	200

Code	pH	TDS	Chlorides	Alkalinity	Hardness
K11	8.15	533	81	280	280
K13	7.82	1240	214	360	390
K14	8.28	866	134	360	40
K2	7.74	424	45	320	280
K5	7.56	592	125	240	280
K6	7.91	727	85	360	440
K8	8.00	428	51	200	80
K9	7.46	707	63	320	360
M1	7.64	410	49	240	200
M10	8.26	628	79	240	280
M11	8.15	962	240	340	390
M12	8.31	416	75	220	180
M13	7.89	746	129	280	320
M14	8.11	529	48	350	210
M16	7.54	548	63	280	320
M20	8.48	438	61	220	220
M25	8.22	542	81	240	320
M3	7.91	477	48	280	280
M32	7.09	555	64	360	320
M33	7.88	314	22	280	0
M34	7.68	565	66	400	320
M35	8.39	634	101	360	220
M40	7.81	355	49	200	280
M41	8.19	853	106	320	420
M5	8.32	579	90	200	240
M52	7.25	209	13	200	80
M55	7.46	707	63	320	360
M56	7.57	544	57	200	200
M6	7.90	889	160	280	40
M64	7.51	752	43	320	360
M66	7.79	666	102	240	320
M69	7.90	850	94	280	120
M7	8.43	911	199	420	360
M8	7.83	383	30	280	320
N12	8.01	476	52	280	0
N13	7.69	361	100	160	160
N2	7.89	398	61	240	240
N4	7.98	609	153	200	320
N5	8.06	754	92	280	280
N8	8.65	1320	231	420	80
N9	8.16	637	113	280	320
O11	7.82	566	52	240	280
O12	7.93	625	35	60	280
O16	8.47	389	55	200	200

Code	pH	TDS	Chlorides	Alkalinity	Hardness
O17	8.19	519	103	200	200
O2	8.21	379	36	180	220
O3	7.81	453	33	210	200
O5	7.28	567	179	220	200
O6	7.96	413	62	200	200
O7 ^(A)	7.77	12	1	80	0
O8	8.73	461	240	140	120
O9	8.71	645	70	200	80
P1A	7.89	353	111	160	200
P1B	8.41	292	310	160	160
P10	8.90	576	69	320	80
P12A	7.93	1320	344	280	380
P12B	8.01	984	102	400	460
P13	9.03	625	174	80	0
P14	7.76	747	59	160	360
P15	7.76	444	57	220	240
P16A	7.82	630	64	160	280
P16B	7.99	594	223	320	360
P17	7.45	378	84	160	160
P18	7.53	407	237	240	240
P2	8.03	616	50	360	320
P4	7.78	405	55	240	200
P5	7.96	525	77	200	280
P6	7.86	411	51	120	200
P7	8.07	599	38	200	300
P8	7.69	576	75	280	280
P9	7.87	425	34	160	190
R10	7.88	132	12	120	0
R2	7.76	422	45	200	200
R4	7.19	413	48	120	160
R5	8.31	455	55	360	240
R6	7.95	728	137	240	240
R7	8.13	360	37	240	240
R8	8.00	1080	316	200	280
X1	7.82	489	67	200	260
X2	8.22	606	97	300	480
X3	7.65	373	57	160	160
X4	7.69	854	154	360	360

Notes: (A) Rain catchment

(B) After in-home treatment

Appendix B

