Technical Summary of Todos Santos Aquifer Seawater Intrusion Evaluation Results:

Marissa Fichera - April 18th, 2019

<u>Sampling techniques:</u>

Water samples were taken in collaboration with CONAGUA in March and June of 2017. Data measured from samples included temperature, pH, specific conductance, and dissolved oxygen content. Water table elevation depths were not measured in 2017. The 21 samples taken in June were the ones used in the study. Samples were analyzed for stable isotopes $\delta^{18}O$ and $\delta^{2}H$, major ions, and trace elements. Bill Sanford has more information on water quality not related to seawater intrusion.

Current water table elevations were unavailable, however, 12 water table elevation values were published in CONAGUA's 2007 report on the region (*Estudio Para Determinar La Factibilidad de Extraccion de Agua Subterranea Salobre Para Su Desalacion En Los Acuiferos de: Migrino Plutarco Elias Calles, El Pescadero, Todos Santos y Canada Honda, B.C.S.* 2007). These hydraulic head values, along with a vast amount of additional data published in the same study, were used to calibrate the initial groundwater flow model. Aquifer extent as delineated by CONAGUA is shown in Figure 1, sample locations for years 2007 and 2017 are shown in Figures 2 and 3. Data utilized in study is displayed in Table 1.

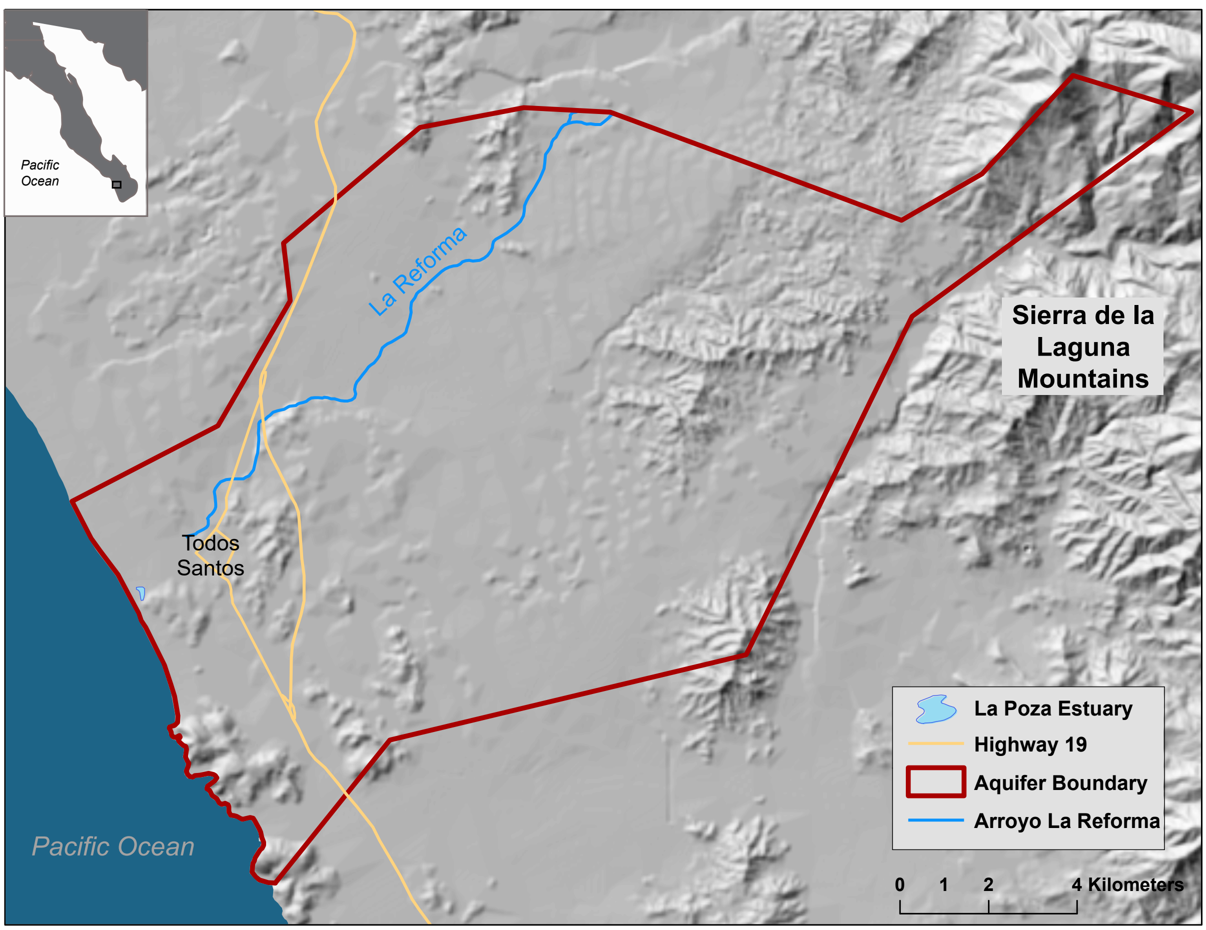


Figure 1: Area of aquifer study within Baja California Sur, Mexico. Aquifer extent is delinated by CONAGUA. Arroyo La Reforma is the main surface water catchment in the area. La Poza is a small estuary located southeast of town.

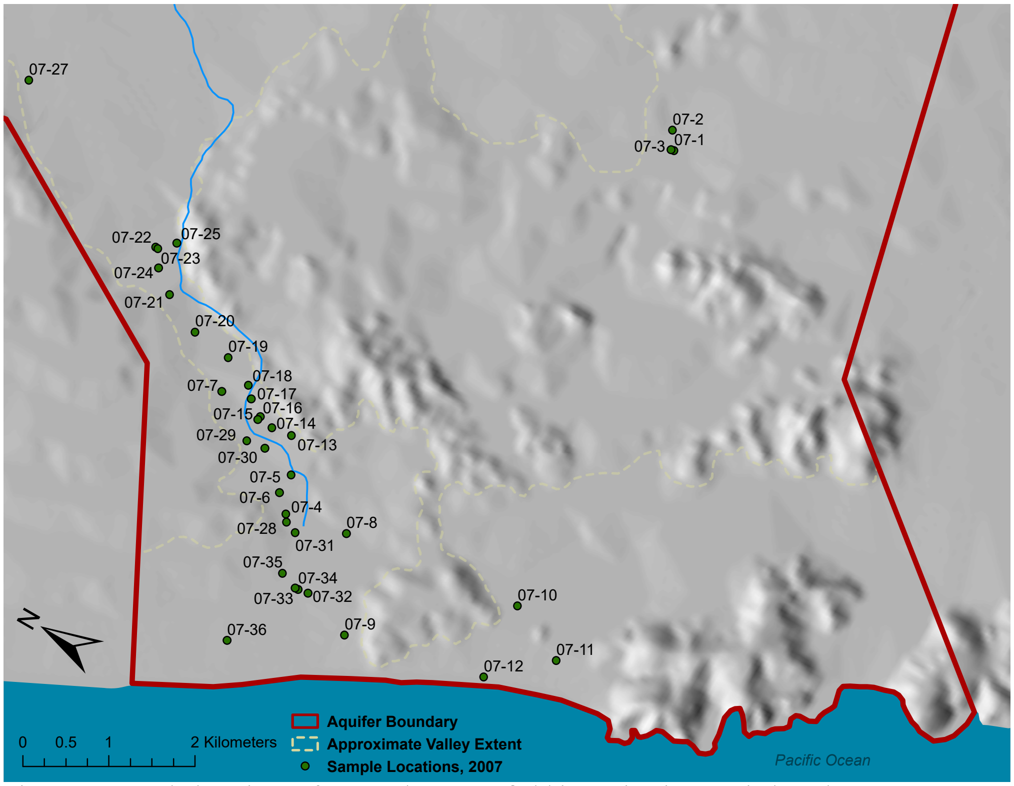


Figure 2: Sample locations of November 2007 field investigation carried out by CONAGUA. Interpreted extent of the Todos Santos valley is shown.

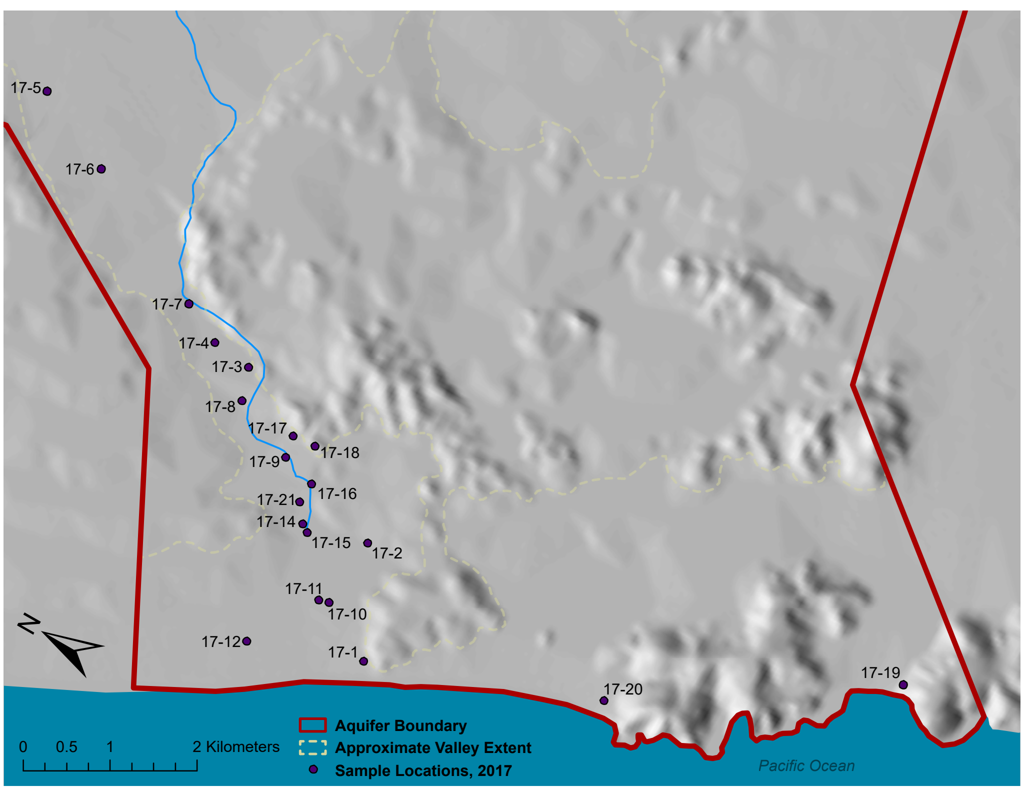


Figure 3: Sample locations of June 2017 field investigation.

2594011	579159	07/11/07	-	-	-	-	-	-	-	-	-	-	
2594027	578913	07/11/07	-	-	-	-	-	-	-	-	-	-	
2595193	579595	07/11/07	-	-	-	-	-	-	-	-	-	-	
2593116	578891	13/11/07	22.3	6.93	1037.0	46.7	37.6	118.84	13.99	180.8	380	20.31	
2592546	577859	13/11/07	22.9	7.05	718.0	66.9	18.9	60.87	4.17	113.4	220	55.71	
2590973	579158	13/11/07	-	-	-	-	-	-	-	-	-	-	
2590267	578836	13/11/07	-	-	-	-	-	-	-	-	-	-	
2590901	578247	13/11/07	-	-	-	-	-	-	-	-	-	-	
2594235	579557	13/11/07	25.6	6.22	659.0	29.5	18.7	60.87	5.06	69.1	200	15.4	
2594478	579524	13/11/07	25.3	6.58	601.0	-	-	-	-	-	-	-	
2594663	579543	13/11/07	25.6	6.45	600.0	-	-	-	-	-	-	-	
2594660	579538	13/11/07	25.3	6.84	608.0	-	-	-	-	-	-	-	
2594855	579693	13/11/07	26.0	6.46	590.0	-	-	-	-	-	-	-	
2594962	579812	13/11/07	25.8	7.12	569.0	38.9	19.9	46.38	3.57	79.8	280	29.82	
2595326	579974	13/11/07	27.3	6.27	1664.0	-	-	-	-	-	-	-	
2595807	580037	13/11/07	25.4	6.60	390.0	24.9	9.6	29.09	2.78	21.3	200	5.68	
2596279	580265	13/11/07	25.2	6.70	324.0	-	-	-	-	-	-	-	
2596697	580662	13/11/07	-	-	-	-	-	-	-	-	-	-	
2596686	580665	13/11/07	-	-	-	-	-	-	-	-	-	-	
2596547	580468	14/11/07	25.8	6.80	794.0	-	-	-	-	-	-	-	
2596507	580824	14/11/07	27.7*	6.72	1550.0	116.6	36.3	163.01	5.23	381.1	300	27.62	
2597948	575320	14/11/07	26.5	7.52	381.0	23.3	9.7	28.6	2.22	46.1	120	9.79	
2598939	581603	14/11/07	24.1	7.18	308.0	-	-	-	-	-	-	-	
2593784	578658	14/11/07	26.7	6.95	954.0	-	-	-	-	-	-	-	
2594655	579247	14/11/07	25.6	7.21	509.0	-	-	-	-	-	-	-	
2594432	579276	14/11/07	25.2	7.00	612.0	-	-	-	-	-	-	-	
2593635	578602	14/11/07	25.5	7.32	777.0	-	-	-	-	-	-	-	
2593157	578070	15/11/07	24.9	6.93	755.0	62.2	23.6	61.69	3.91	113.4	220	49.31	
2593279	578050	15/11/07	23.9	6.80	879.0	-	-	-	-	-	-	-	
2593278	578050	15/11/07	-	-	-	-	-	-	-	-	-	-	
2593528	578120	15/11/07	24.7	6.90	869.0	68.4	18.9	65.2	4.29	124.1	260	16.67	
2593697	577123	15/11/07	26.6	6.96	1033.0	46.7	23	128.47	9.93	159.5	300	25.11	
													$\delta^{18}O$ %
2592274	577734	13/6/7	27.0	7.74	74400.0	1523	3450	24825	632.9	32388.6	-	4187.9	8.5051
2592919	578950	13/6/7	24.2	8.10	1307.0	67.7	29.865	82.6	7.13	216.896	273	61.45	-10.02
2595130	580038	13/6/7	26.4	7.36	898.4	44.005	16.82	63.45	2.1855	136.975	159	33.789	-9.595
2595610	580093	13/6/7	26.2	7.19	457.4	100.85	33.975	62	6.37	31.441	135	25.094	-10.71
2598742	581660	13/6/7	25.1	7.52	390.9	87.05	27.145	55.25	5.59	27.354	131	15.358	-9.614
2597750	581187	13/6/7	26.5	7.27	456.4	99.4	31.1	71	5.995	41.823	136	19.386	-8.537
2596095	580333	13/6/7	25.9	7.43	429.1	100.05	32.07	66.4	6.135	36.438	132	18.621	-9.485
2594998	579661	13/6/7	26.6	7.14	604.2	42.355	13.59	28.45	1.6245	68.662	135	26.086	-8.353
2594237	579340	13/6/7	26.6	7.31	1159.0	77.5	25.315	64.55	2.6685	205.01	198	65.822	-7.616
2592958	578129	14/6/17	25.9	6.94	1357.0	80.85	28.755	61.05	2.5985	205.655	226	57.997	-7.562
2593075	578096	14/6/17	25.4	6.91	1199.0	74.675	24.5125	57.1	1.86425	171.212	214	54.874	-7.773
2593553	577266	14/6/17	26.4	7.01	2505.0	156.3	69.61	132.9	13.39	549.244	305	213.1	-8.166

Groundwater flow model:

SEAWAT was the program used to model the aquifer system, as it takes into account the varying densities of seawater and freshwater. Groundwater Vistas was used as the graphic user interface. The model domain was gridded 50m x 50m and consisted of 6 layers to capture vertical salinity distributions near the coastline. The top four layers were 5 m in thickness and the bottom two were 10 m in thickness, resulting in a total aquifer thickness of 40 meters near the coastline. The modeled thickness increased inland as ground elevation increased. Depth to bedrock was unknown. Well depths were also unknown, and estimated based on Figure 6 (figure modified from CONAGUA (2017), with wells closest to the coastline reaching furthest depths (~20-30 meters below sea level) and wells located furthest inland reaching highest depths in terms of elevation (> 5 meters below sea level). The model extent is shown in Figures 7 and 8, with a conceptual model extent and domain also pictured. I lessened the inland model extent due to lack of data in the inland region of the watershed/aquifer boundary. Stable isotope results indicate groundwater is recharged by cyclone precipitation and are consistent with study results published in 2015 by C. J. Eastoe and Todos Santos resident Susana Mahieux (Figure 4).

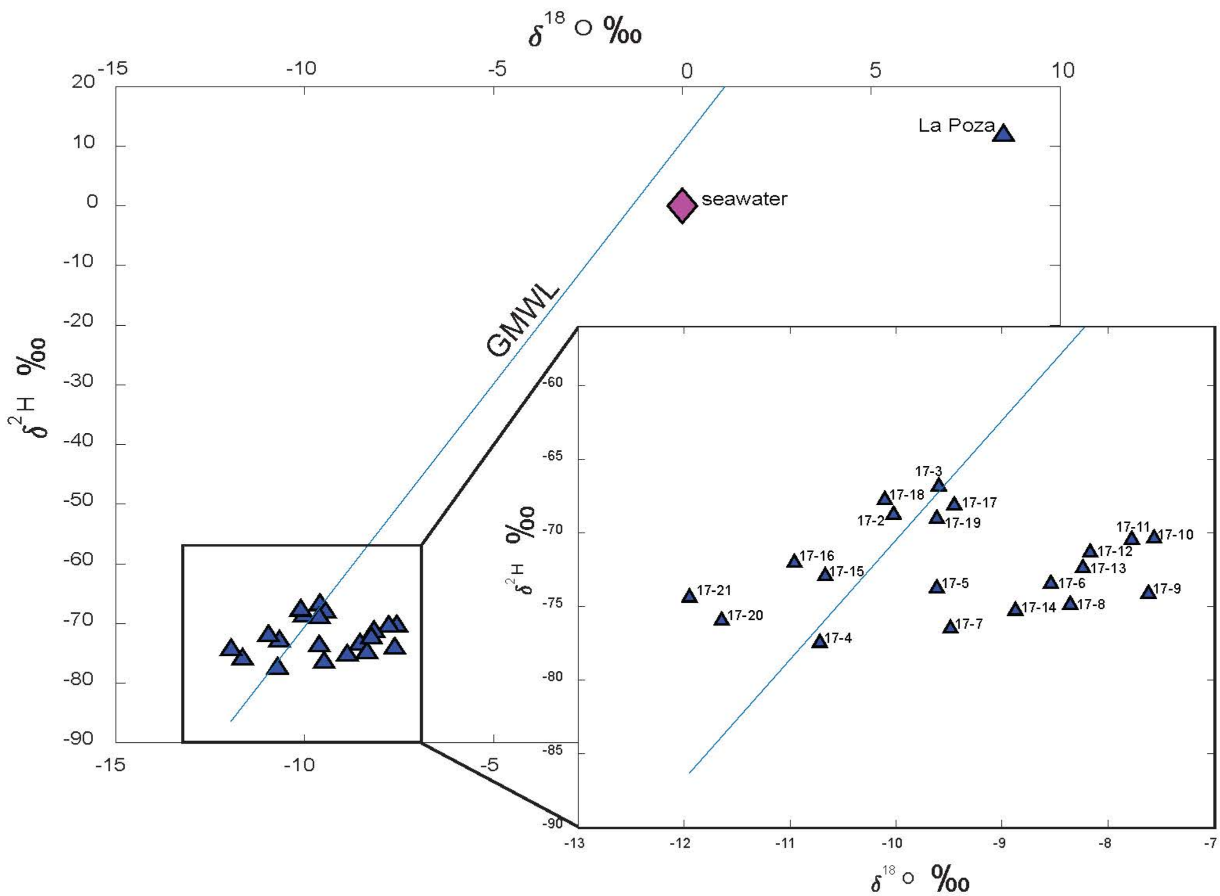


Figure 4: Stable isotope analysis results from June 2017 field investigation. Isotopic signatures are generally depleted, indicating that groundwater recharge is sourced from hurricane precipitation (Eastoe et al., 2015). Samples plotting to the right of the Global Meteoric Water Line (GMWL) indicate groundwater which has been subject to evaporation. The location of the sample taken from La Poza relative to seawater indicates that its composition is that of evaporated seawater, suggesting a lack of freshwater influx.

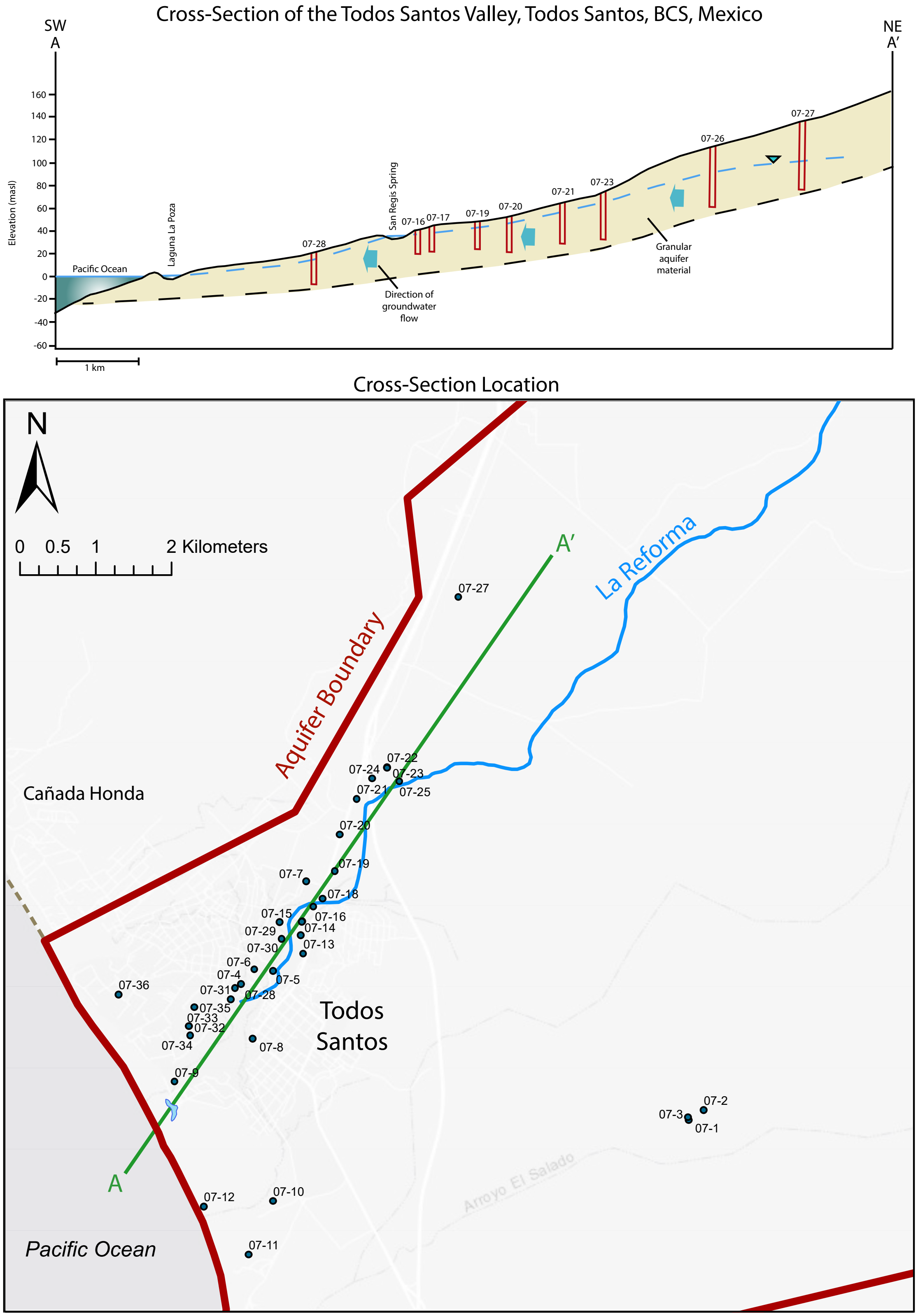


Figure 6: Cross-section of the Todos Santos Aquifer within the Todos Santos Valley, modified from CONAGUA (2007). Well depths were estimated based on the above cross-section, as well depth data was unavailable. Generally, wells reaching greatest depths are located near the coastline, and get progressively shallower with distance inland.

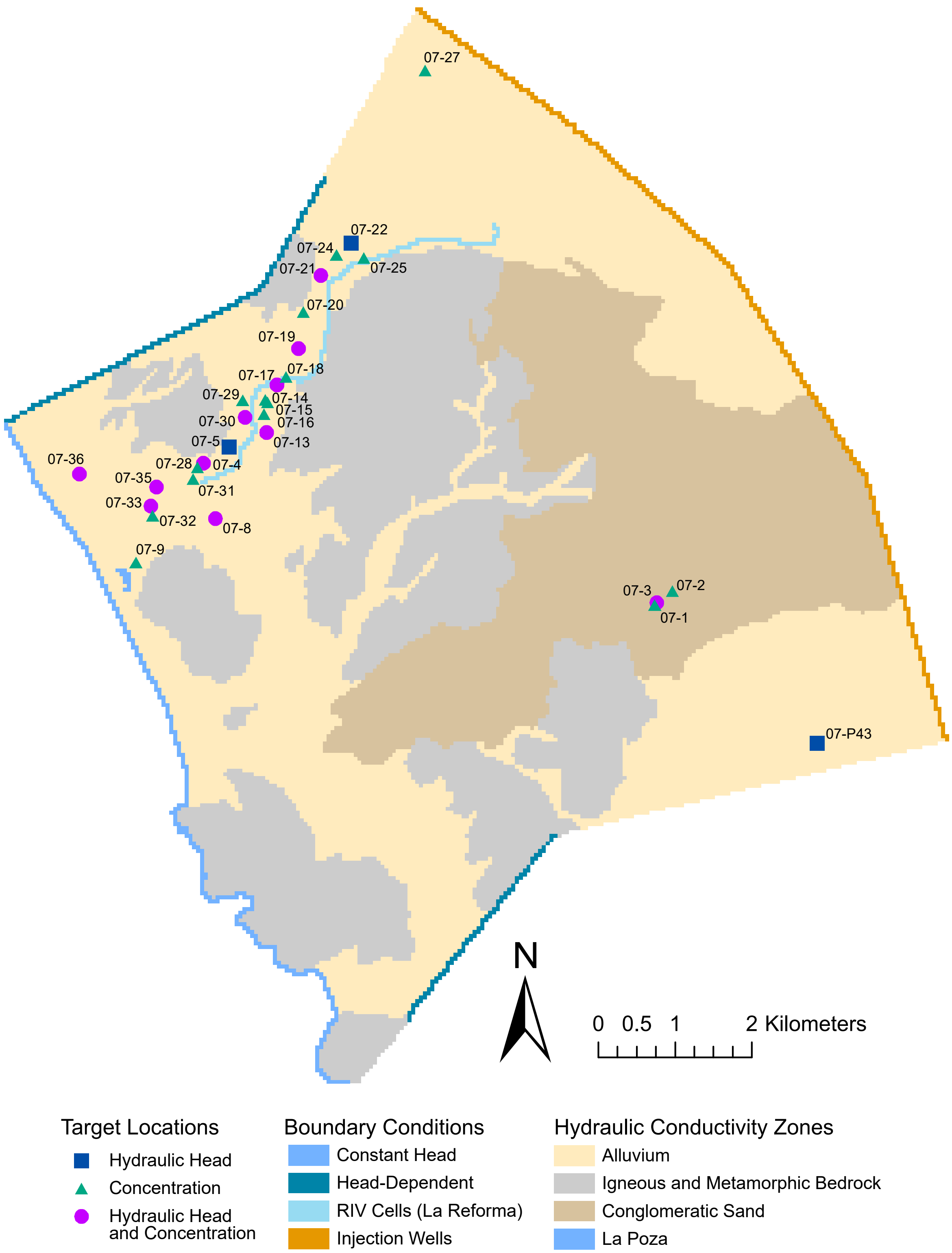


Figure 10: Steady-state model target locations and display of target types (hydraulic head and salinity) utilized in calibration. Data was compiled from CONAGUA (2007).

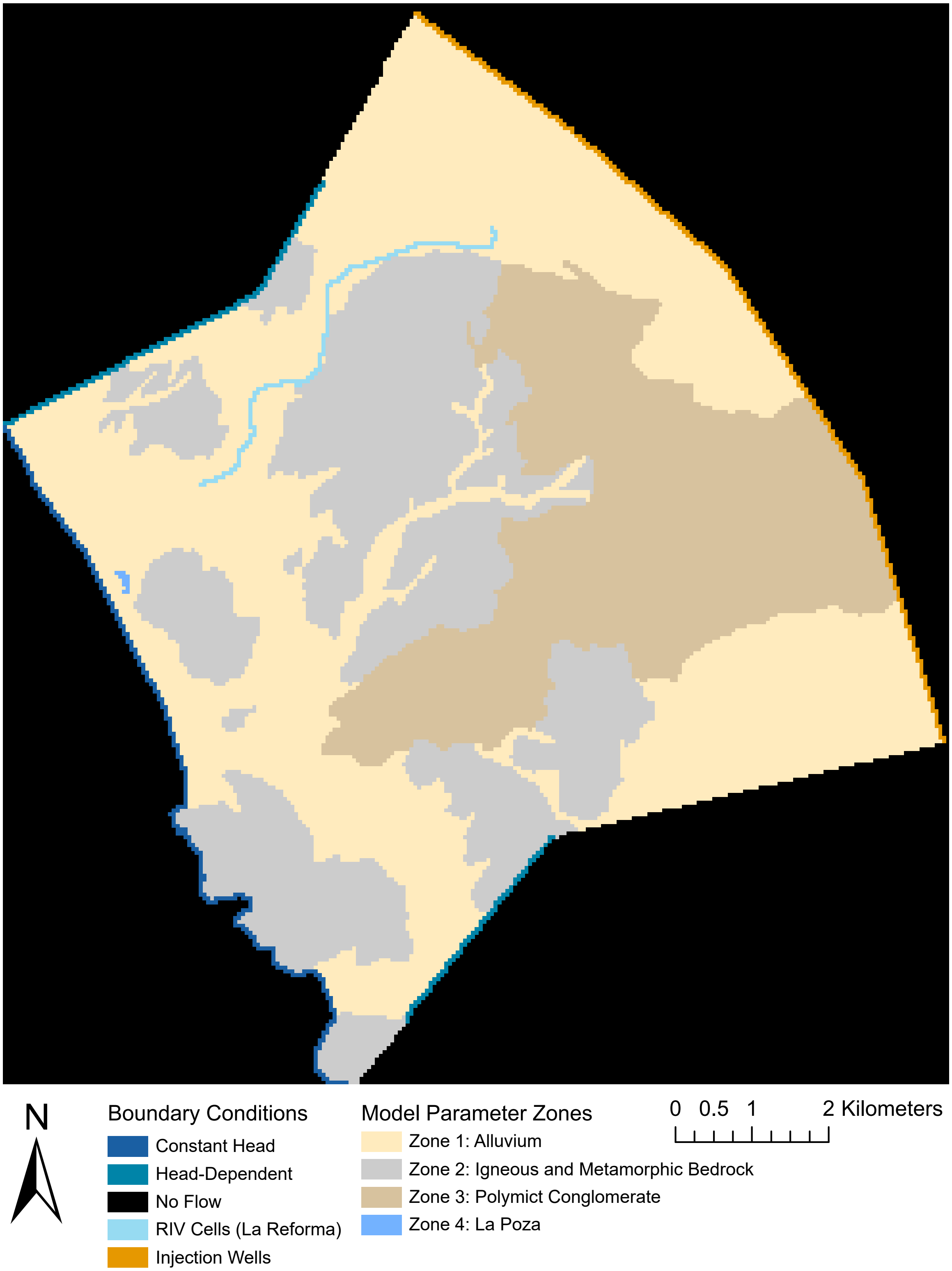
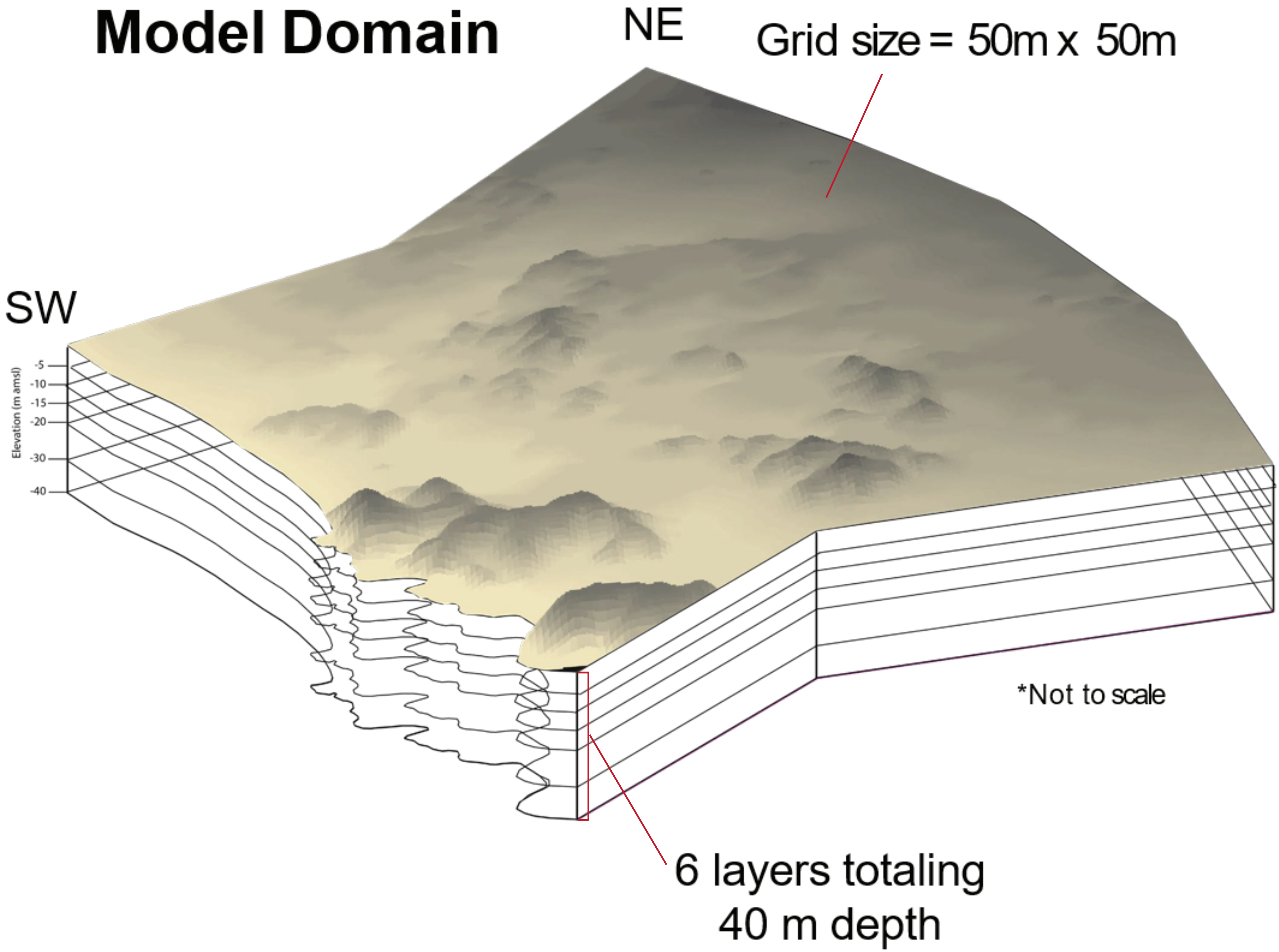


Figure 8: Boundary conditions and model parameters for SEAWAT model setup. Parameter zones are constructed based on the geologic map of the area (Calera et al. 2001). Aquifer connection with the Pacific Ocean is simulated with constant head cells, connection with surrounding aquifers is simulated with head-dependent flux cells, Arroyo La Reforma is simulated with RIV cells, and aquifer recharge is simulated by injection wells on the northeast boundary.

Model Domain



The models constructed and completed are listed below:

(1) **Model calibrated to 2007 hydrologic conditions**: Model inputs for boundary conditions and initial conditions were principally based on information published in CONAGUA's 2007 study (a very detailed explanation of these inputs are in the methods section of my thesis). This information included hydraulic head values and specific conductance values published for the Todos Santos aquifer as well as for the surrounding aquifers (Canada Honda, Pescadero), and pumping rates and durations for wells. In summary, the model utilized GHB cells to account for connection with surrounding aquifers, injection wells on the inland boundary to simulate upgradient recharge, ET cells to simulate areas of evapotranspiration, Constant Head cells to simulate the ocean boundary, and RIV cells to simulate Arroyo La Reforma. The model parameters calibrated included hydraulic conductivities and streambed conductance values. Three geologic hydraulic conductivity zones were calibrated, including the principal aquifer material (fine-med grained sand), polymict conglomerate, and igneous and metamorphic bedrock. Resulting values were 5 m/d for fine-med grained sand, 2 m/d for the polymict conglomerate, and 0.0146 m/d for the igneous/metamorphic bedrock.

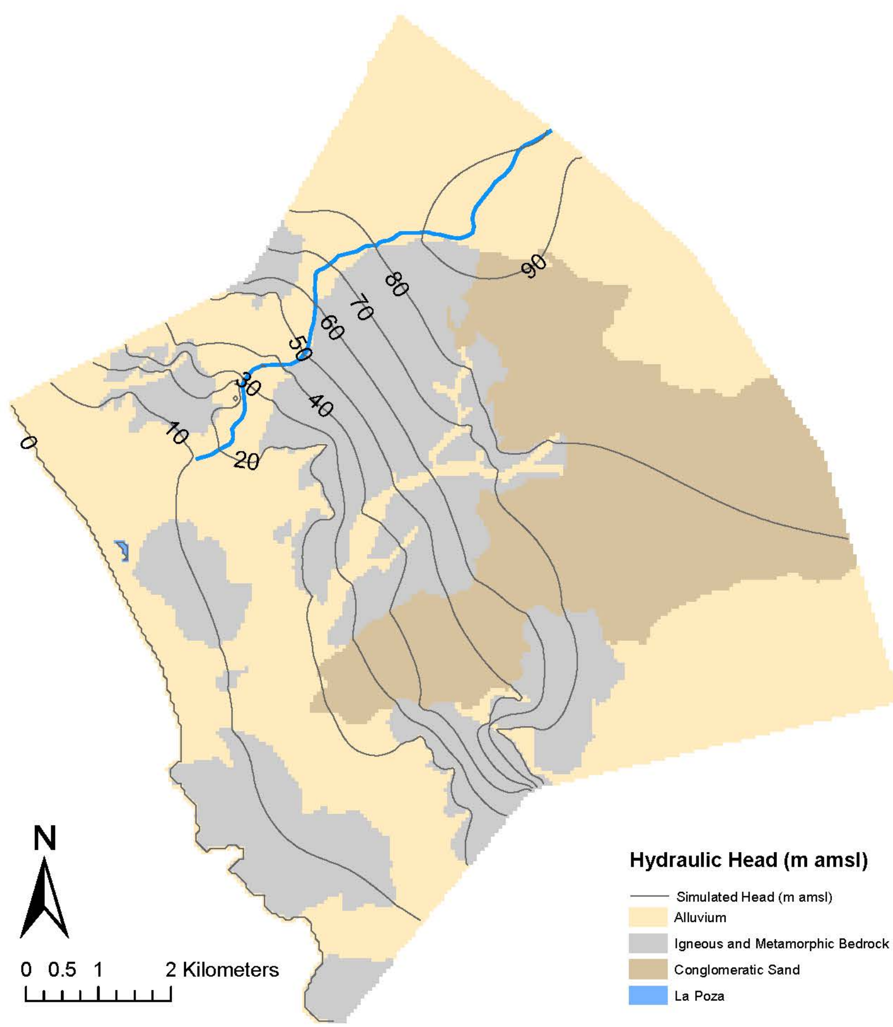


Figure 18: Simulated hydraulic head potentiometric surface map displaying 2007 hydrogeologic conditions. Groundwater flow is from northeast to southwest, consistent with topographic driven flow from the Sierra de la Laguna mountains to the Pacific Ocean.

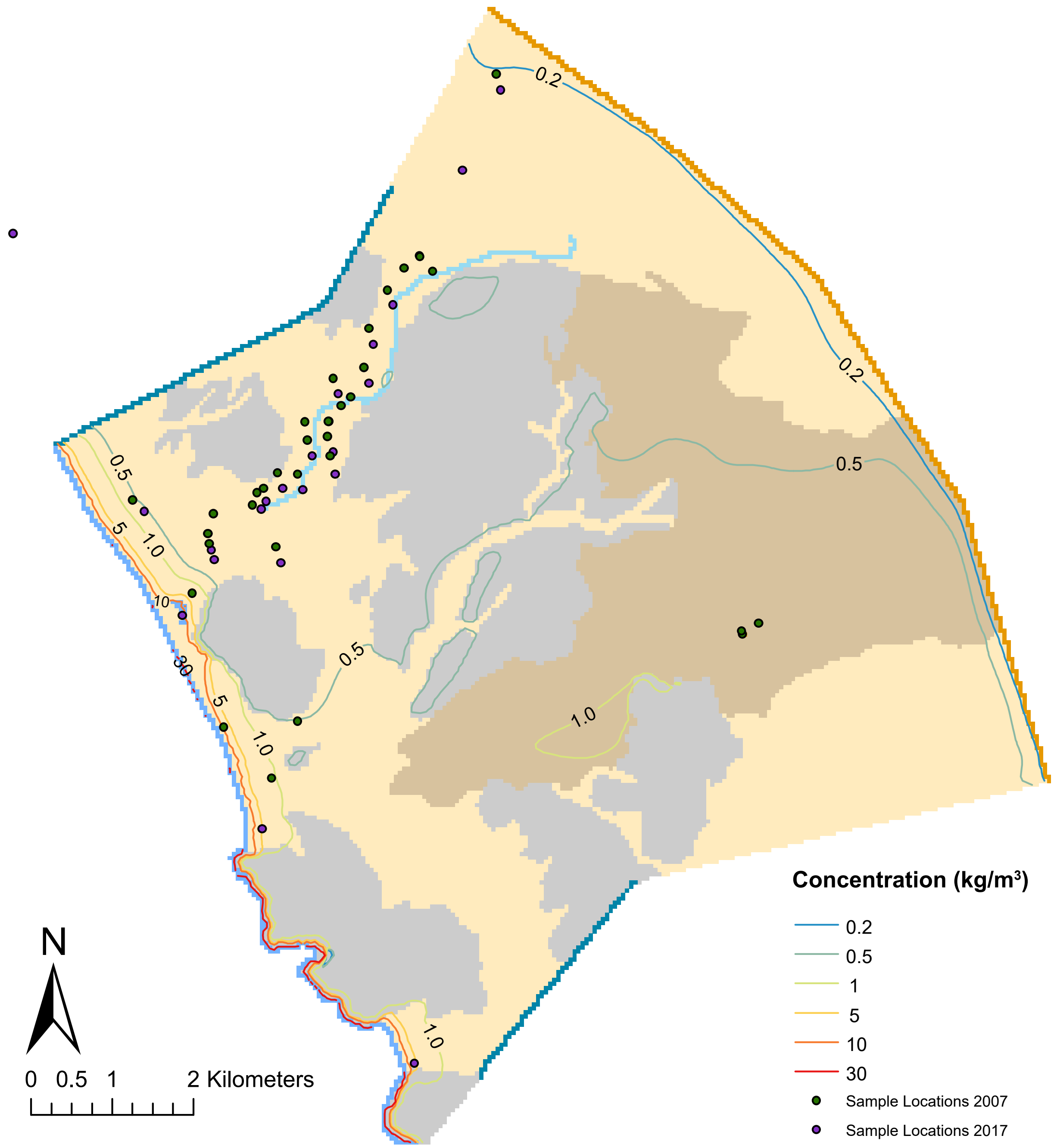


Figure 19: Simulated salinity contour map displaying results from layer 5 of the steady-state SEAWAT simulation. The seawater-freshwater interface, located at contour 1.0 kg/m³, reaches up to 607 meters inland. A high salinity gradient can be seen near the coastline. Six sample locations can be seen having already experienced salinities higher than 1.0 kg/m³ by 2007.

Table 2: Calibrated model parameters from steady-state SEAWAT simulation

Zone No.	Material	Porosity	Specific Yield	Longitudinal Dispersivity (m)	Horizontal Transverse Dispersivity (m)	Vertical Transverse Dispersivity (m)	Hydraulic Conductivity (m/d)
1	Alluvium	0.25	0.1	100	10	0.005	5
2	Igneous and Metamorphic Basement	0.1	0.05	20	5	0.0008	0.0146
3	Polymict Conglomerate	0.2	0.1	100	10	0.005	2
4	La Poza Estuary	1.0	0.5	100	10	0.005	820

Table 3: Salinity values, converted from collected specific conductance values, for 2007 and 2017. 2007 salinity values were used in steady-state model calibration. 2017 salinity values were used in calibrating the first transient model, simulating the 10 year time span from 2007 to 2017.

2007	
Sample	Salinity (kg/m^3)
07-1	1.27
07-2	0.66
07-3	1.17
07-4	0.35
07-8	0.51
07-9	0.35
07-13	0.32
07-14	0.29
07-15	0.29
07-16	0.29
07-17	0.28
07-18	0.27
07-19	0.83
07-20	0.19
07-21	0.16
07-24	0.39
07-25	0.78
07-26	0.18
07-27	0.15
07-28	0.47
07-29	0.25
07-30	0.30
07-31	0.38
07-32	0.37
07-33	0.43
07-35	0.43
07-36	0.51

2017	
Sample	Salinity (kg/m^3)
17-1	51.41
17-2	0.65
17-3	0.44
17-4	0.22
17-5	0.19
17-6	0.22
17-7	0.21
17-8	0.29
17-9	0.57
17-10	0.68
17-11	0.60
17-12	1.29
17-13	0.66
17-14	0.36
17-15	0.59
17-16	0.45
17-17	0.53
17-18	0.60
17-19	0.80
17-20	2.56
17-21	0.46

Table 4: Pumping rates, pumping durations, and assigned model layer for wells published by CONAGUA (2007). Pumping rates are listed for different model scenarios.

Well No.	Use	Location		Operation Time		Steady-State	Transient final (2007-2017)	Forecast Scenario 1	Forecast Scenario 2	Forecast Scenario 3	Forecast Scenario 4, 5	Assigned Model Layer
		Northing (m)	Easting (m)	(hrs/day)	(days/yr)	Q (m^3/d)	Q (m^3/d)					
07-1	Domestic	2592040	584642	0.5	365	1.8	1.8	1.8	3.6	1.8	1.8	1
07-5	Potable	2594011	579159	12	365	1555.2	1555.2	1555.2	3110.4	1555.2	1555.2	4
07-6	Potable	2594027	578913	10	365	432	432	432	864	432	432	4
07-7	Domestic	2595193	579595	10	365	576	576	576	1152	576	576	2
07-8	Domestic	2593116	578891	2	365	28.8	57.6	57.6	57.6	57.6	57.6	5
07-13	Domestic and Agriculture	2594235	579557	4	180	28.8	57.6	57.6	57.6	57.6	57.6	4
07-14	Agriculture	2594478	579524	20	26	166.4	332.8	332.8	332.8	332.8	332.8	4
07-16	Domestic and Agriculture	2594660	579538	8	180	57.6	115.2	115.2	115.2	115.2	115.2	3
07-17	Domestic and Agriculture	2594855	579693	4	180	57.6	115.2	115.2	115.2	115.2	115.2	2
07-18	Canal	2594962	579812	24	365	10368	10368	10368	20736	10368	10368	2
07-19	Domestic and Agriculture	2595326	579974	3	26	97.2	194.4	194.4	194.4	194.4	194.4	2
07-20	Domestic and Agriculture	2595807	580037	20	180	2880	5760	5760	5760	5760	5760	2
07-21	Agriculture	2596279	580265	24	180	4320	8640	8640	8640	8640	8640	1
07-22	Agriculture	2596697	580662	12	180	3456	6912	6912	6912	6912	6912	1
07-27	Agriculture	2598939	581603	18	180	2332.8	4665.6	4665.6	4665.6	4665.6	4665.6	1
07-28	Industrial	2593784	578658	4	180	129.6	259.2	259.2	259.2	259.2	259.2	5
07-29	Canal	2594655	579247	24	365	12096	12096	12096	24192	12096	12096	4
07-30	Canal	2594432	579276	24	365	12096	12096	12096	24192	12096	12096	4
07-31	Canal	2593635	578602	12	365	4320	8640	8640	8640	8640	8640	5
07-32	Agriculture	2593157	578070	8	180	115.2	230.4	230.4	230.4	230.4	230.4	5
07-33	Agriculture	2593279	578050	4	180	230.4	460.8	460.8	460.8	460.8	460.8	5
07-35	Domestic and Agriculture	2593528	578120	6	180	194.4	388.8	388.8	388.8	388.8	388.8	5
07-36	Domestic and Agriculture	2593697	577123	3	180	97.2	194.4	194.4	194.4	194.4	194.4	5

Table 5: Steady-state calibration target locations and values.

Sample No.	Coordinates		Hydraulic Head (m amsl)	Salinity (kg/m^3)	Assigned Layer
	Easting (m)	Northing (m)			
07-1	584642	2592040	107.36	1.27	1
07-2	584841	2592175	-	0.66	1
07-3	584634	2592079	-	1.17	1
07-4	578736	2593836	15.97	0.35	5
07-5	579159	2594011	21.037	-	4
07-8	578891	2593116	6.998	0.51	5
07-9	577859	2592546	-	0.35	5
07-13	579557	2594235	27.749	0.32	4
07-14	579524	2594478	-	0.29	4
07-15	579543	2594663	-	0.29	4
07-16	579538	2594660	-	0.29	3
07-17	579693	2594855	40.082	0.28	2
07-18	579812	2594962	-	0.27	2
07-19	579974	2595326	58.974	0.83	2
07-20	580037	2595807	-	0.19	2
07-21	580265	2596279	61.604	0.16	1
07-22	580662	2596697	71.418	-	1
07-24	580468	2596547	-	0.39	1
07-25	580824	2596507	-	0.78	1
07-26	575320	2597948	-	0.18	5
07-27	581603	2598939	-	0.15	1
07-28	578658	2593784	-	0.47	5
07-29	579247	2594655	-	0.25	4
07-30	579276	2594432	27.014	0.30	4
07-31	578602	2593635	-	0.38	5
07-32	578070	2593157	-	0.37	5
07-33	578050	2593279	6.088	0.43	5
07-35	578120	2593528	6.81	0.43	5
07-36	577123	2593697	-3	0.51	5
P-43	586726	2590198	114.11	-	1

(2) **Transient model simulating time span from 2007-2017:** This was done because we had specific conductance data for 2017 and I wanted to attempt to calibrate any unknown changes in pumping rates to those values. Calibrating to specific conductance values is difficult and whether or not the results are meaningful is debated, but the transient run additionally functioned as an evaluation of model sensitivity to changes in pumping. Out of the three pumping scenarios simulated, the differences in calibration error were <1%, indicating very little model sensitivity to these changes over a ten year time period. The three pumping scenarios simulated were as follows:

   a. **Pumping rates and durations published in 2007**
   b. **2007 rates doubled in agricultural and coastal wells**
   c. **2007 rates doubled in all aquifer wells**

   Because of the lack of difference between the three simulations, I decided to use the second pumping scenario (doubled in agricultural and coastal wells) to account for population increase. These rates were used as the base case in forecasting scenarios.

(3) **Forecasting Scenarios:** These scenarios are outlined in the thesis – they model different pumping and sea-level rise scenarios. Upgradient recharge was kept constant at 6 mm/yr. Cyclone recharge was simulated in the lower elevations of the watershed through La Reforma (RIV cells) – this rate varied between scenarios, but overall it simulated recharge amounts equivalent to roughly 2-4 cyclones a year (depending on amount of precipitation per cyclone), which is pretty high considering TS has had very little cyclone precipitation recently to my knowledge.

The seawater-freshwater interface was identified at a salinity value of 1.0 kg/m^3 which is the USGS definition of brackish water, however a salinity value of 0.5 kg/m^3 is the permissible limit in both the US and Mexico. The simulated interface was plotted at depth for two different locations within the aquifer, for years 2007, 2017, 2022, 2027, and 2037, and for all five forecasting scenarios, to evaluate the migration inland in response to different hydrologic stresses. In summary, even with roughly 150 mm of recharge simulated, seawater intrusion is exacerbated in all scenarios. The extent is dependent on the simulated hydrologic stresses, with the most important factor being recharge in the lower watershed elevations. One forecasting simulation involved drying up lower reaches of La Reforma, which resulted in the most severe seawater intrusion in the Todos Santos town area (nearly 60 m of intrusion between 2007 and 2037). Punta Lobos experienced around 45-50 meters of intrusion between 2007 and 2037 according to the simulation in all scenarios, indicating possible negative implications for the desalination plant recently constructed in that area, as higher density water requires more energy to desalinate. The consistency in simulated intrusion for Punta Lobos was an effect of the geology of the area and its distance from La Reforma (recharge source).

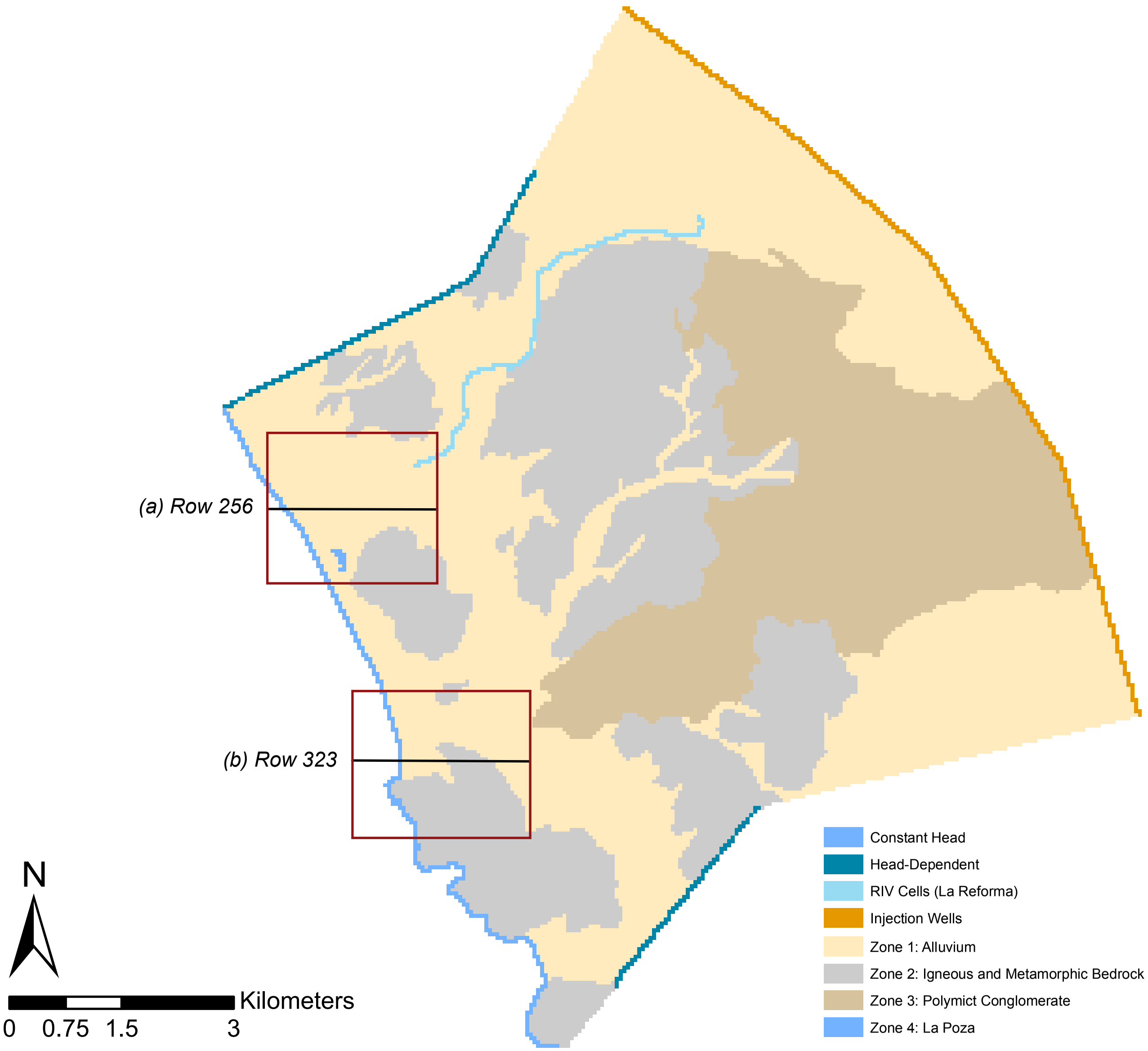


Figure 22: Locations of cross-section profiles for area (a) Todos Santos and (b) Punta Lobos, where simulated seawater-freshwater interface was plotted with depth (Fig. 23). Red boxes show extent of plan view salinity contour maps displayed in Figure 23.

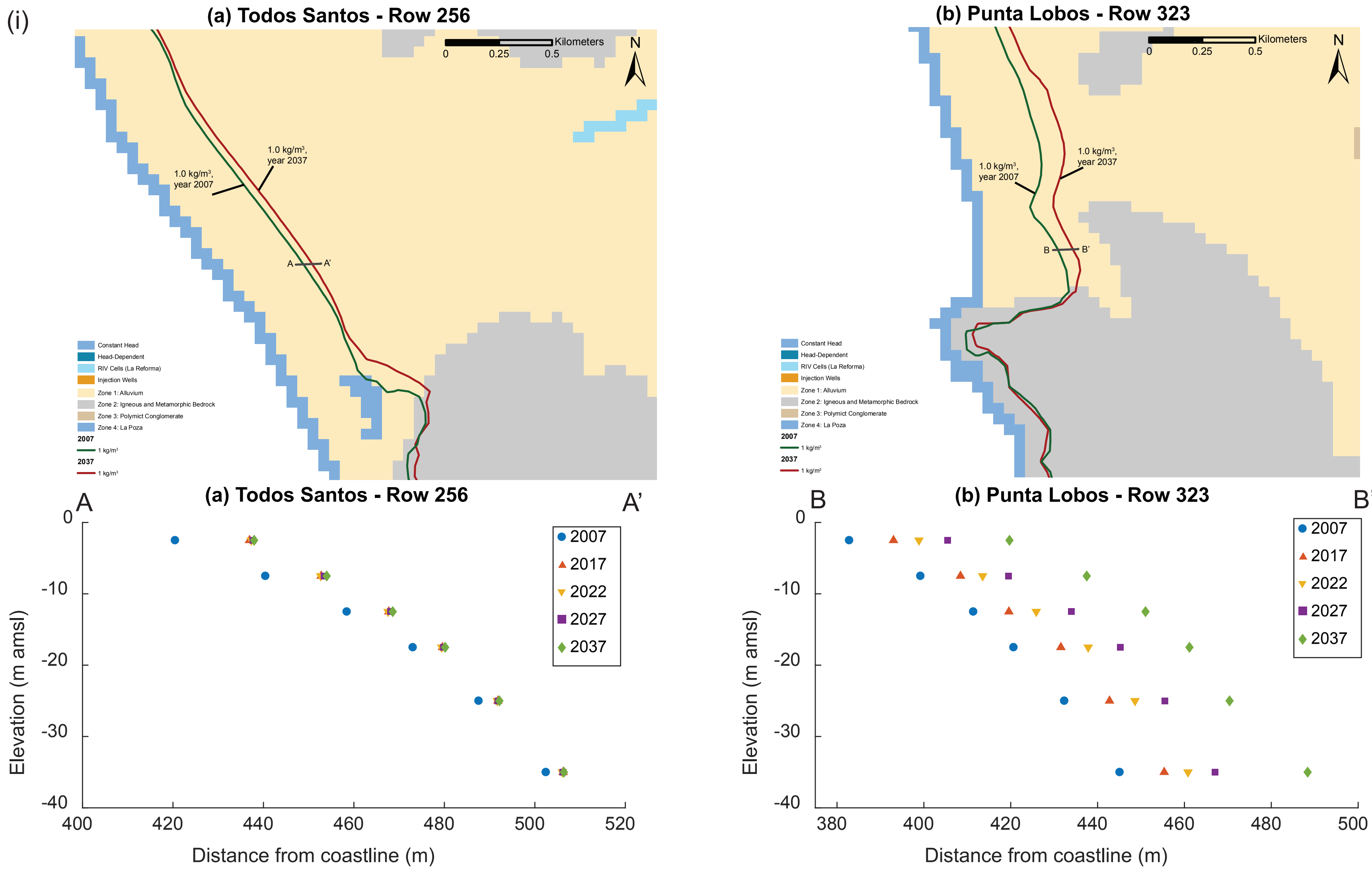


Figure 23: Simulated seawater-freshwater interface location (identified at salinity value of 1.0 kg/m3) in plan view for years 2007 and 2037, model layer 5, and with depth at the end of years 2007, 2017, 2022, 2027, and 2037 for locations (a) Todos Santos town and (b) Punta Lobos beach (Fig. 22). Results for the following five forecasting scenarios are displayed: (i) Pumping rates remain at 2007 conditions, (ii) Pumping rates are doubled in all wells, (iii) Pumping rates remain at 2017 conditions, sea-level rise of 4 mm/yr, (iv) Pumping rates remain at 2017 conditions, Arroyo La Reforma is overexploited in lower reaches, and (v) Pumping rates remain at 2017 conditions, sea-level rise of 25 mm/yr.

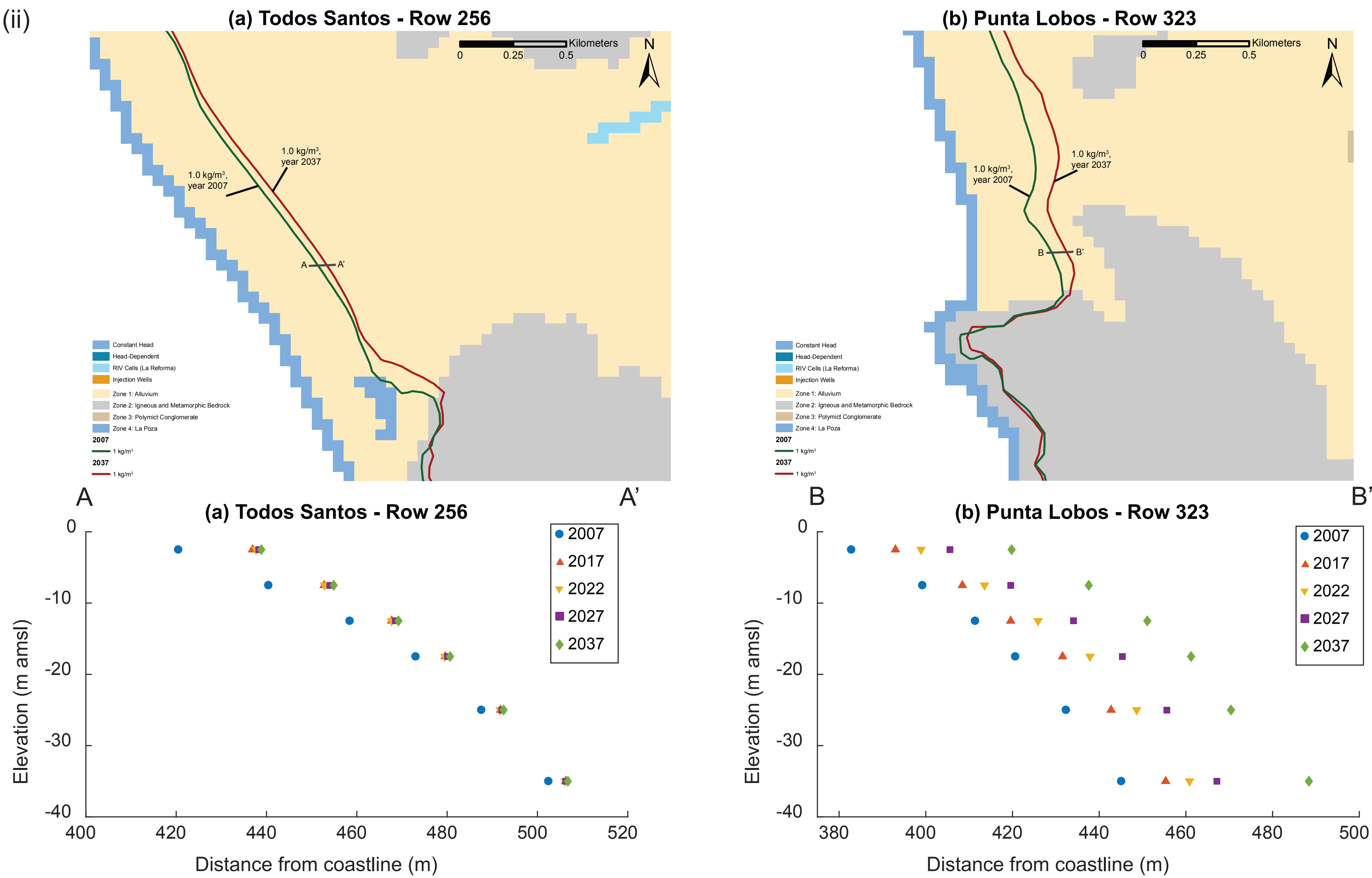


Figure 23: Simulated seawater-freshwater interface location (identified at salinity value of 1.0 kg/m3) in plan view for years 2007 and 2037, model layer 5, and with depth at the end of years 2007, 2017, 2022, 2027, and 2037 for locations (a) Todos Santos town and (b) Punta Lobos beach (Fig. 22). Results for the following five forecasting scenarios are displayed: (i) Pumping rates remain at 2007 conditions, (ii) Pumping rates are doubled in all wells, (iii) Pumping rates remain at 2017 conditions, sea-level rise of 4 mm/yr, (iv) Pumping rates remain at 2017 conditions, Arroyo La Reforma is overexploited in lower reaches, and (v) Pumping rates remain at 2017 conditions, sea-level rise of 25 mm/yr.

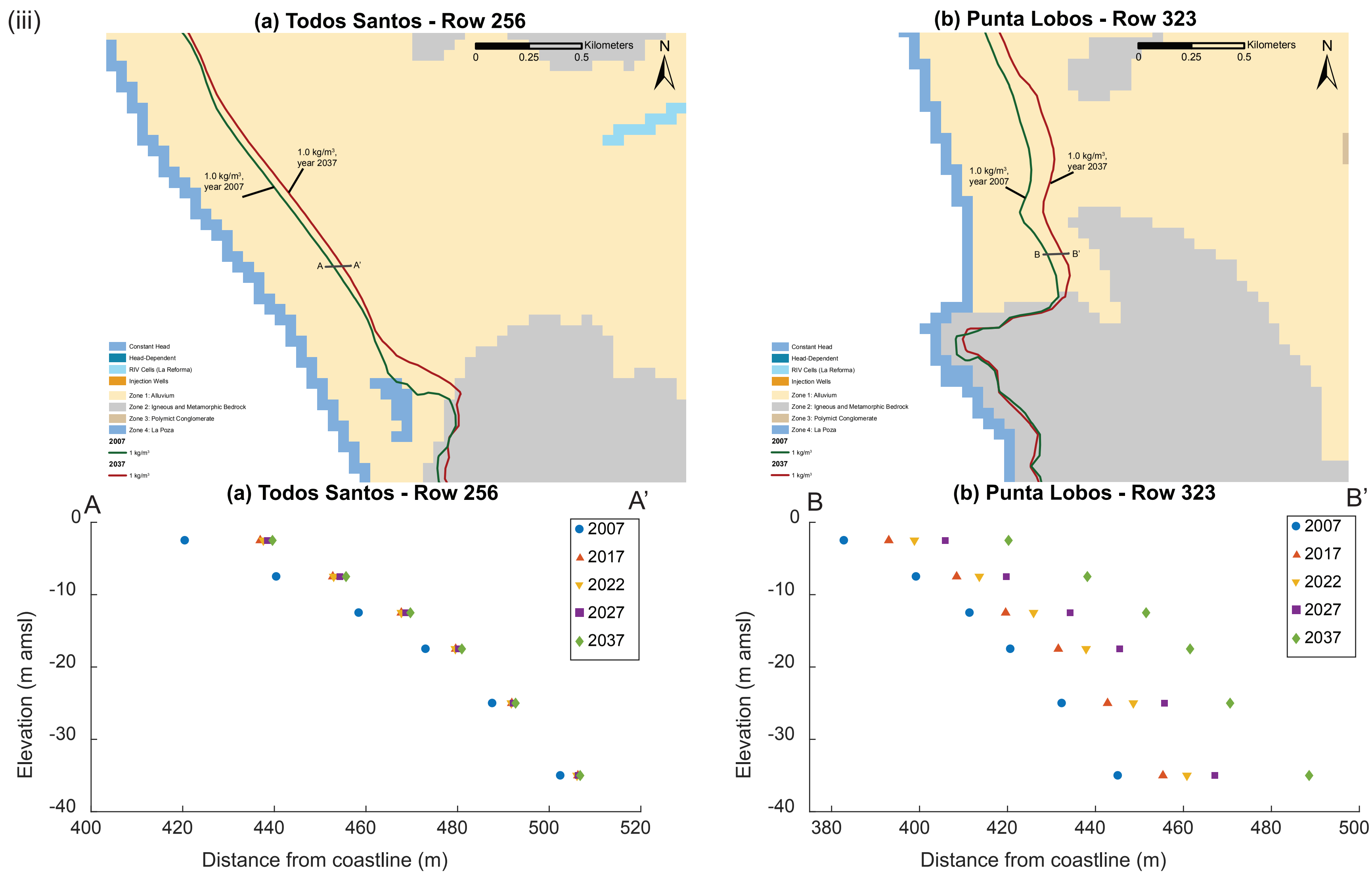


Figure 23: Simulated seawater-freshwater interface location (identified at salinity value of 1.0 kg/m3) in plan view for years 2007 and 2037, model layer 5, and with depth at the end of years 2007, 2017, 2022, 2027, and 2037 for locations (a) Todos Santos town and (b) Punta Lobos beach (Fig. 22). Results for the following five forecasting scenarios are displayed: (i) Pumping rates remain at 2007 conditions, (ii) Pumping rates are doubled in all wells, (iii) Pumping rates remain at 2017 conditions, sea-level rise of 4 mm/yr, (iv) Pumping rates remain at 2017 conditions, Arroyo La Reforma is overexploited in lower reaches, and (v) Pumping rates remain at 2017 conditions, sea-level rise of 25 mm/yr.

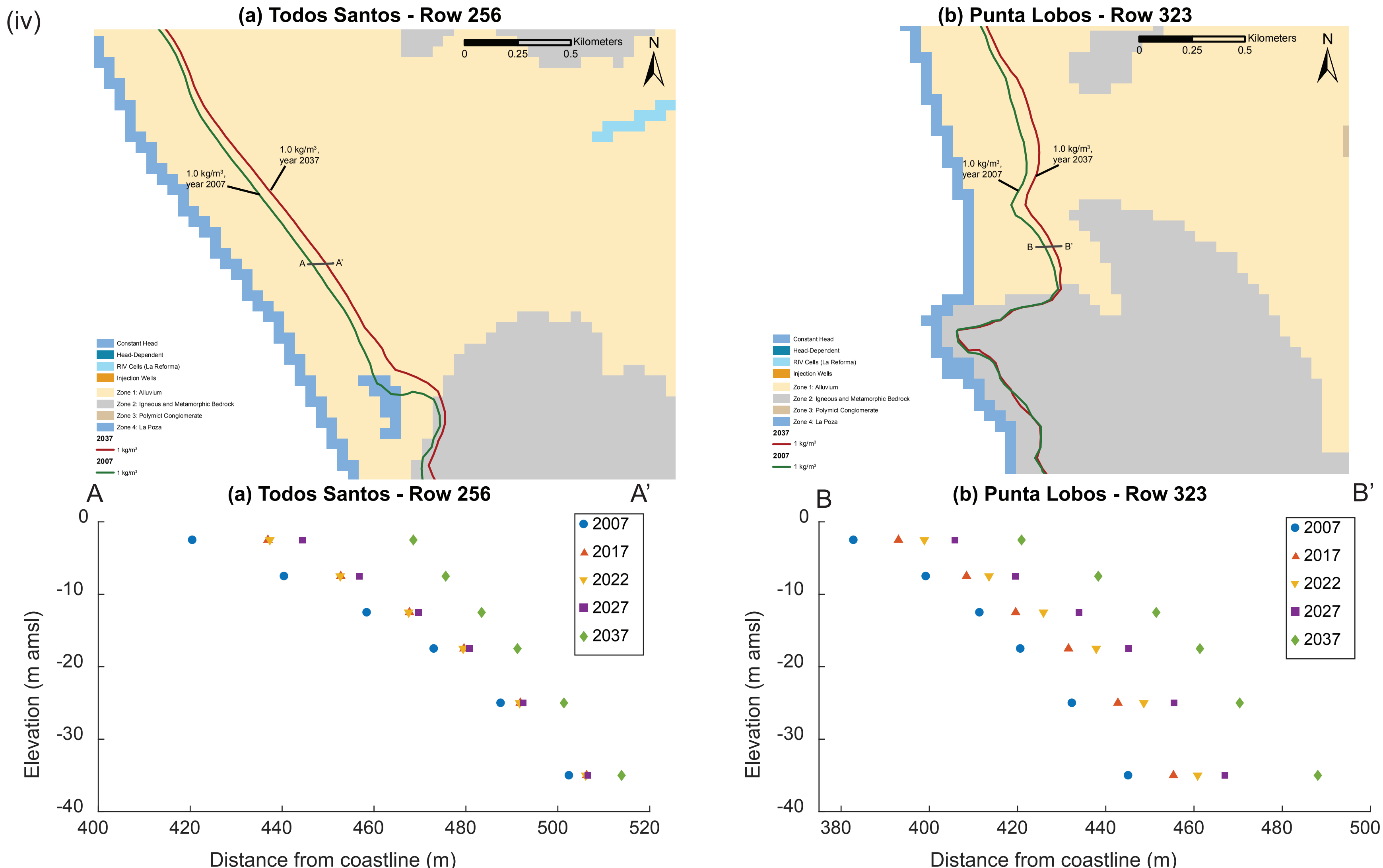


Figure 23: Simulated seawater-freshwater interface location (identified at salinity value of 1.0 kg/m3) in plan view for years 2007 and 2037, model layer 1, and with depth at the end of years 2007, 2017, 2022, 2027, and 2037 for locations (a) Todos Santos town and (b) Punta Lobos beach (Fig. 22). Results for the following five forecasting scenarios are displayed: (i) Pumping rates remain at 2007 conditions, (ii) Pumping rates are doubled in all wells, (iii) Pumping rates remain at 2017 conditions, sea-level rise of 4 mm/yr, (iv) Pumping rates remain at 2017 conditions, Arroyo La Reforma is overexploited in lower reaches, and (v) Pumping rates remain at 2017 conditions, sea-level rise of 25 mm/yr.

(v)

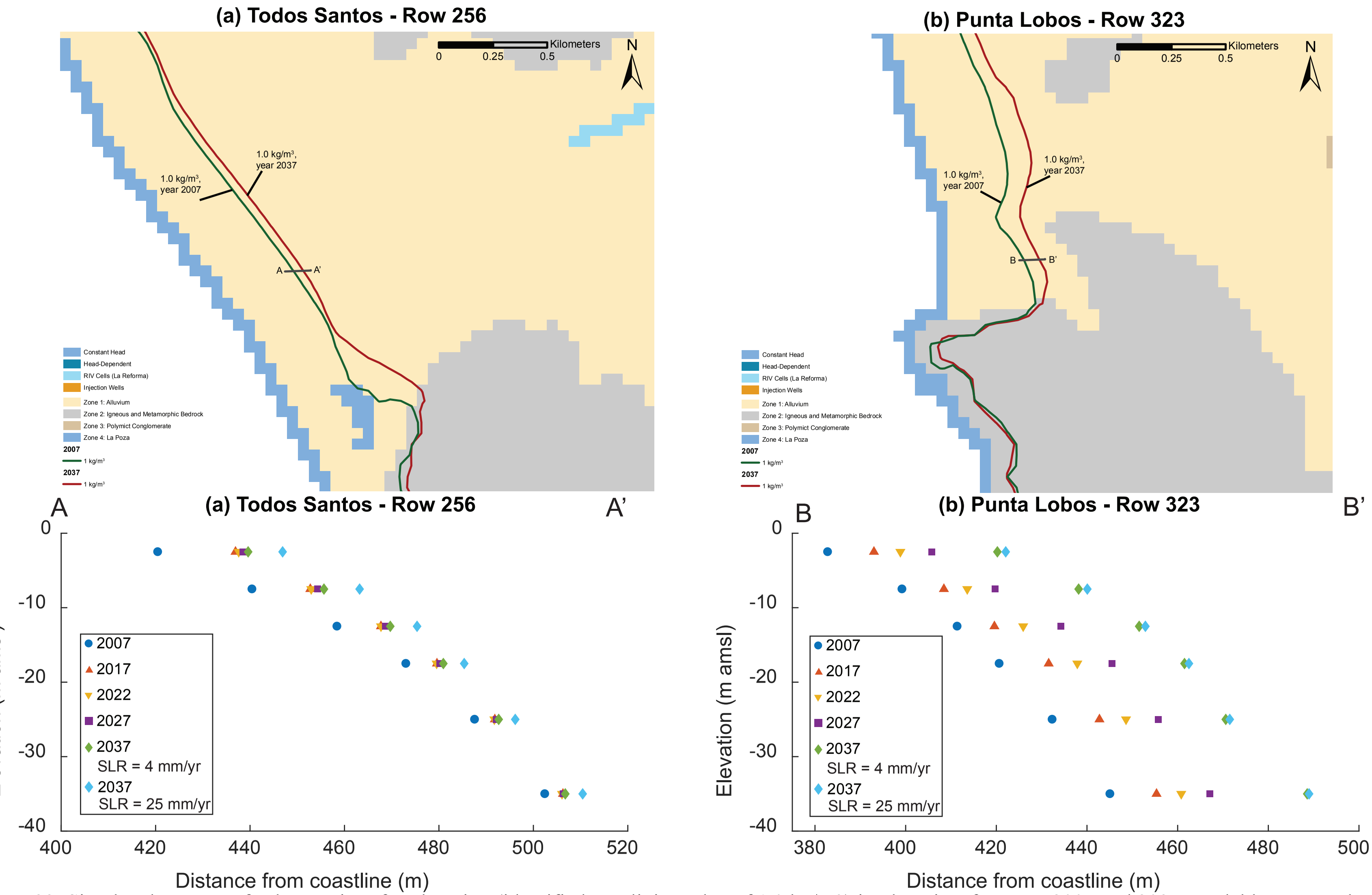


Figure 23: Simulated seawater-freshwater interface location (identified at salinity value of 1.0 kg/m3) in plan view for years 2007 and 2037, model layer 5, and with depth at the end of years 2007, 2017, 2022, 2027, and 2037 for locations (a) Todos Santos town and (b) Punta Lobos beach (Fig. 22). Results for the following five forecasting scenarios are displayed: (i) Pumping rates remain at 2007 conditions, (ii) Pumping rates are doubled in all wells, (iii) Pumping rates remain at 2017 conditions, sea-level rise of 4 mm/yr, (iv) Pumping rates remain at 2017 conditions, Arroyo La Reforma is overexploited in lower reaches, and (v) Pumping rates remain at 2017 conditions, sea-level rise of 25 mm/yr.

Table 12: Simulated seawater-freshwater interface model results for steady-state, transient ('07-'17), and forecasting scenarios for 5, 10, and 20 years. Results are listed for the following locations: (a) Todos Santos town area, and (b) Punta Lobos beach, and for the following forecasting scenarios: (i) Pumping rates remain at 2007 conditions, (ii) Pumping rates are doubled in all wells, (iii) Pumping rates remain at 2017 conditions, sea-level rise of 4 mm/yr, (iv) Pumping rates remain at 2017 conditions, Arroyo La Reforma is overexploited in lower reaches, and (v) Pumping rates remain at 2017 conditions, sea-level rise of 25 mm/yr.

(i)

(a) Todos Santos - Row 256

Year	2007	2017	2022	2027	2037
Simulated Depth (m amsl)	Simulated distance from coastline (m)				
-2.5	420.47	436.92	437.33	437.64	437.94
-7.5	440.43	452.76	452.65	453.43	453.98
-12.5	458.43	467.72	467.55	468.09	468.59
-17.5	473.02	479.58	479.41	479.77	480.17
-25	487.58	491.84	491.69	491.88	492.17
-35	502.44	506.26	506.08	506.15	506.42
Average Distance from Coastline (m)	463.73	472.51	472.45	472.83	473.21

Simulated Depth (m amsl)	Evolution from 2017 to 2022 (m)	Evolution from 2017 to 2027 (m)	Evolution from 2017 to 2037 (m)
-2.5	0.41	0.72	1.02
-7.5	-0.11	0.67	1.22
-12.5	-0.17	0.38	0.87
-17.5	-0.18	0.19	0.59
-25	-0.15	0.05	0.33
-35	-0.19	-0.12	0.15
Average Migration Inland (m)	-0.06	0.31	0.70

(b) Punta Lobos - Row 323

Year	2007	2017	2022	2027	2037
Simulated Depth (m amsl)	Simulated distance from coastline (m)				
-2.5	382.81	393.00	398.88	405.51	419.71
-7.5	399.22	408.43	413.53	419.47	437.51
-12.5	411.39	419.58	425.87	433.94	451.04
-17.5	420.66	431.55	437.84	445.27	461.16
-25	432.34	442.75	448.62	455.53	470.39
-35	445.09	455.34	460.83	467.05	488.37
Average Distance from Coastline (m)	415.25	425.11	430.93	437.79	454.70

Simulated Depth (m amsl)	Evolution from 2017 to 2022 (m)	Evolution from 2017 to 2027 (m)	Evolution from 2017 to 2037 (m)
-2.5	5.87	12.50	26.71
-7.5	5.10	11.04	29.07
-12.5	6.30	14.36	31.46
-17.5	6.29	13.72	29.61
-25	5.87	12.78	27.64
-35	5.48	11.71	33.03
Average Migration Inland (m)	5.82	12.68	29.59

(ii)

(a) Todos Santos - Row 256

Year	2007	2017	2022	2027	2037
Simulated Depth (m amsl)	Simulated distance from coastline (m)				
-2.5	420.47	436.92	437.70	438.32	438.84
-7.5	440.43	452.76	452.88	454.05	454.88
-12.5	458.43	467.72	467.68	468.51	469.22
-17.5	473.02	479.58	479.50	480.08	480.65
-25	487.58	491.84	491.74	492.09	492.51
-35	502.44	506.26	506.11	506.32	506.73
Average Distance from Coastline (m)	463.73	472.51	472.60	473.23	473.81

Simulated Depth (m amsl)	Evolution from 2017 to 2022 (m)	Evolution from 2017 to 2027 (m)	Evolution from 2017 to 2037 (m)
-2.5	0.78	1.40	1.92
-7.5	0.12	1.29	2.12
-12.5	-0.04	0.79	1.50
-17.5	-0.09	0.50	1.07
-25	-0.09	0.26	0.68
-35	-0.15	0.06	0.46
Average Migration Inland (m)	0.09	0.71	1.29

(b) Punta Lobos - Row 323

Year	2007	2017	2022	2027	2037
Simulated Depth (m amsl)	Simulated distance from coastline (m)				
-2.5	382.81	393.00	398.90	405.61	419.80
-7.5	399.22	408.43	413.55	419.55	437.59
-12.5	411.39	419.58	425.90	434.04	451.09
-17.5	420.66	431.55	437.86	445.37	461.19
-25	432.34	442.75	448.64	455.62	470.41
-35	445.09	455.34	460.84	467.13	488.37
Average Distance from Coastline (m)	415.25	425.11	430.95	437.89	454.74

Simulated Depth (m amsl)	Evolution from 2017 to 2022 (m)	Evolution from 2017 to 2027 (m)	Evolution from 2017 to 2037 (m)
-2.5	5.90	12.61	26.79
-7.5	5.11	11.12	29.15
-12.5	6.32	14.47	31.51
-17.5	6.31	13.82	29.64
-25	5.89	12.87	27.66
-35	5.50	11.79	33.03
Average Migration Inland (m)	5.84	12.78	29.63

Table 12 cont.:

(iii)

(a) Todos Santos - Row 256

Year	2007	2017	2022	2027	2037
Simulated Depth (m amsl)	Simulated distance from coastline (m)				
-2.5	420.47	437.15	437.60	438.51	439.60
-7.5	440.43	453.02	452.95	454.33	455.65
-12.5	458.43	467.88	467.73	468.69	469.70
-17.5	473.02	479.68	479.51	480.18	480.93
-25	487.58	491.89	491.74	492.13	492.66
-35	502.44	506.27	506.07	506.30	506.76
Average Distance from Coastline (m)	463.73	472.65	472.60	473.36	474.22

Simulated Depth (m amsl)	Evolution from 2017 to 2022 (m)	Evolution from 2017 to 2027 (m)	Evolution from 2017 to 2037 (m)
-2.5	0.45	1.36	2.44
-7.5	-0.06	1.31	2.63
-12.5	-0.15	0.81	1.82
-17.5	-0.17	0.50	1.25
-25	-0.15	0.24	0.77
-35	-0.20	0.03	0.49
Average Migration Inland (m)	-0.05	0.71	1.57

(b) Punta Lobos - Row 323

Year	2007	2017	2022	2027	2037
Simulated Depth (m amsl)	Simulated distance from coastline (m)				
-2.5	382.81	393.03	398.83	405.80	420.23
-7.5	399.22	408.51	413.59	419.77	438.16
-12.5	411.39	419.63	425.93	434.27	451.51
-17.5	420.66	431.61	437.87	445.52	461.51
-25	432.34	442.77	448.61	455.68	470.61
-35	445.09	455.34	460.80	467.12	488.58
Average Distance from Coastline (m)	415.25	425.15	430.94	438.03	455.10

Simulated Depth (m amsl)	Evolution from 2017 to 2022 (m)	Evolution from 2017 to 2027 (m)	Evolution from 2017 to 2037 (m)
-2.5	5.80	12.77	27.20
-7.5	5.08	11.25	29.64
-12.5	6.30	14.64	31.88
-17.5	6.26	13.92	29.91
-25	5.84	12.91	27.84
-35	5.45	11.78	33.24
Average Migration Inland (m)	5.79	12.88	29.95

(iv)

(a) Todos Santos - Row 256

Year	2007	2017	2022	2027	2037
Simulated Depth (m amsl)	Simulated distance from coastline (m)				
-2.5	420.47	436.92	437.33	444.43	468.56
-7.5	440.43	452.76	452.65	456.76	475.60
-12.5	458.43	467.72	467.55	469.72	483.42
-17.5	473.02	479.58	479.41	480.79	491.22
-25	487.58	491.84	491.69	492.44	501.33
-35	502.44	506.26	506.08	506.54	513.87
Average Distance from Coastline (m)	463.73	472.51	472.45	475.11	489.00

Simulated Depth (m amsl)	Evolution from 2017 to 2022 (m)	Evolution from 2017 to 2027 (m)	Evolution from 2017 to 2037 (m)
-2.5	0.41	7.51	31.64
-7.5	-0.11	4.00	22.84
-12.5	-0.17	2.00	15.70
-17.5	-0.18	1.21	11.63
-25	-0.15	0.60	9.50
-35	-0.19	0.27	7.61
Average Migration Inland (m)	-0.06	2.60	16.49

(b) Punta Lobos - Row 323

Year	2007	2017	2022	2027	2037
Simulated Depth (m amsl)	Simulated distance from coastline (m)				
-2.5	382.81	393.00	398.88	405.77	420.91
-7.5	399.22	408.43	413.53	419.48	438.30
-12.5	411.39	419.58	425.87	433.91	451.44
-17.5	420.66	431.55	437.84	445.24	461.34
-25	432.34	442.75	448.62	455.49	470.36
-35	445.09	455.34	460.83	467.02	488.07
Average Distance from Coastline (m)	415.25	425.11	430.93	437.82	455.07

Simulated Depth (m amsl)	Evolution from 2017 to 2022 (m)	Evolution from 2017 to 2027 (m)	Evolution from 2017 to 2037 (m)
-2.5	5.87	12.76	27.90
-7.5	5.10	11.04	29.87
-12.5	6.30	14.33	31.87
-17.5	6.29	13.69	29.79
-25	5.87	12.74	27.61
-35	5.48	11.67	32.73
Average Migration Inland (m)	5.82	12.71	29.96

Table 12 cont.

(v)

(a) Todos Santos - Row 256

Year	2007	2017	2037		
Simulated Depth (m amsl)	Simulated distance from coastline (m)			Simulated Depth (m amsl)	Evolution from 2017 to 2037 (m)
-2.5	420.47	436.92	446.90	-2.5	9.98
-7.5	440.43	452.76	463.20	-7.5	10.44
-12.5	458.43	467.72	475.37	-12.5	7.65
-17.5	473.02	479.58	485.35	-17.5	5.77
-25	487.58	491.84	496.16	-25	4.33
-35	502.44	506.26	510.44	-35	4.18
Average Distance from Coastline (m)	463.73	472.51	479.57	Average Migration Inland (m)	7.06

(b) Punta Lobos - Row 323

Year	2007	2017	2037		
Simulated Depth (m amsl)	Simulated distance from coastline (m)			Simulated Depth (m amsl)	Evolution from 2017 to 2037 (m)
-2.5	382.81	393.00	422.07	-2.5	29.07
-7.5	399.22	408.43	440.08	-7.5	31.64
-12.5	411.39	419.58	452.88	-12.5	33.31
-17.5	420.66	431.55	462.49	-17.5	30.94
-25	432.34	442.75	471.50	-25	28.75
-35	445.09	455.34	488.99	-35	33.65
Average Distance from Coastline (m)	415.25	425.11	456.33	Average Migration Inland (m)	31.23

Salinity concentration variablility:

Salinity concentration variability was evaluated temporally and spatially. Figures do the best job of summing up the differences in water concentration between 2007 and 2017. The figures below display specific conductance values for 2007 and 2017. Hydrochemical facies were compared between the two time periods by Piper Diagrams (also displayed below), using major ion concentration data published in CONAGUA's 2007 study and data from our 2017 field investigation. An interesting diagram is the Hydrochemical Facies Evolution Diagram which analyzes relative ion concentrations in the form of cation exchange reactions, and the corresponding indications of intrusion vs. freshening. Gimenez-Forcada (2010) created this diagram specifically for seawater intrusion evaluation. All hydrochemical figures and data are provided below. Figure captions are from my thesis. Any interpretations made are my own and feedback/critiques are welcome and encouraged for the sake of discussion.

It should be noted that seawater intrusion is a dynamic process, exacerbated by drought while mitigated by freshwater influx, to put it simply. According to precipitation data, years 2006 and 2007 experienced above average precipitation. It is my understanding that in 2017 Todos Santos was in the midst of a drought (and seems to still be experiencing drought currently, although I do not have annual precipitation data to corroborate this). Data from 2007 and 2017 seems to reflect the differences in freshwater influx. Although the groundwater model simulated the seawater-freshwater interface as a sharp boundary for display purposes, in reality the interface is expressed as a mixing zone that can vary in width (I've read anywhere from 1 km – 6 km, so fairly extensive). The geographic location of samples displaying cation exchange reactions indicative of seawater-freshwater mixing support the interpretation that groundwater up to 1.9 kilometers inland was affected by salinization in 2007, and groundwater up to 2.9 kilometers inland was affected in 2017. This increase in affected groundwater is likely due to lack of freshwater recharge as a result of drought conditions.

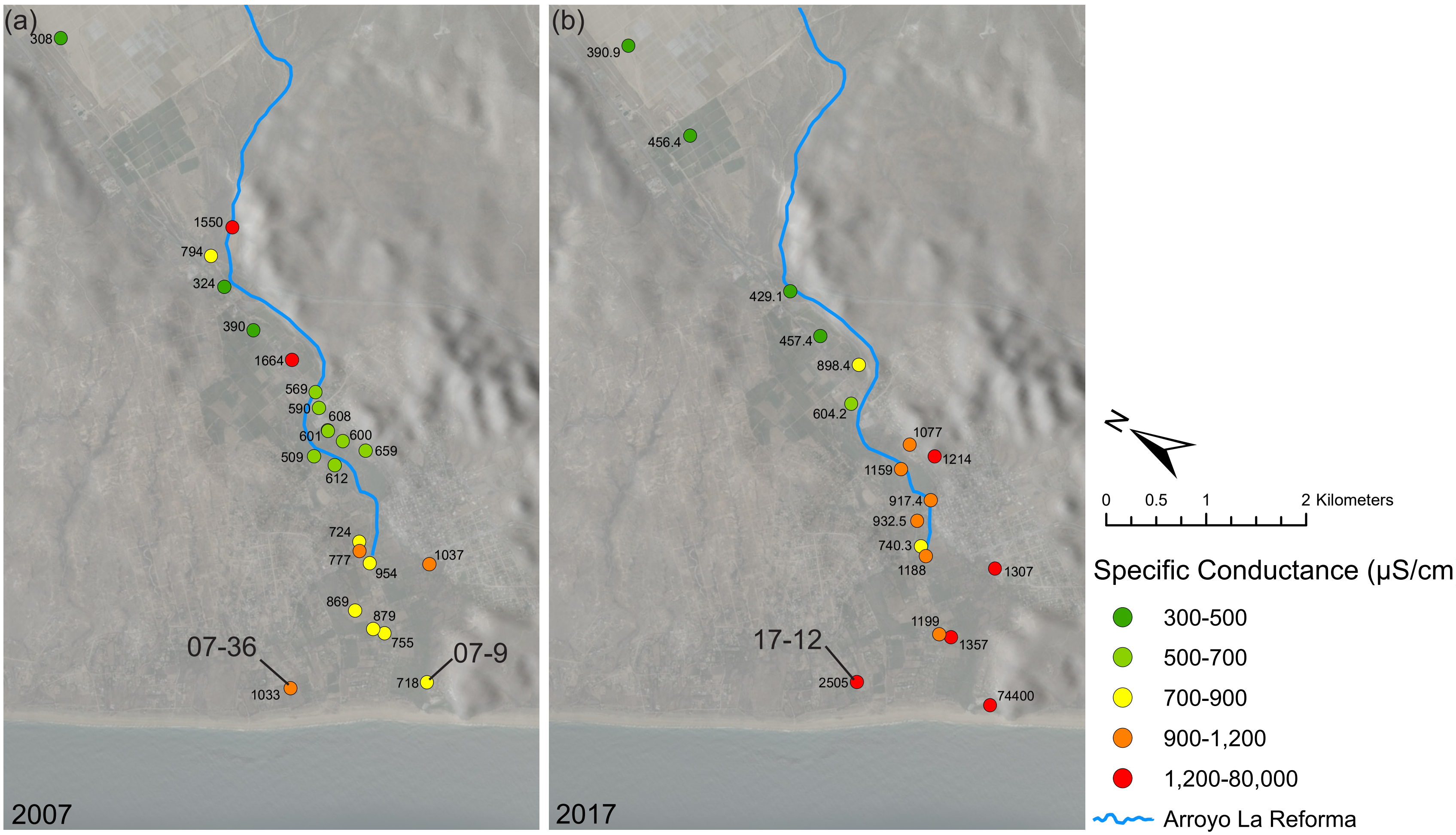


Figure 12: Comparison of specific conductance data collected in (a) 2007 and (b) 2017. Locations of interest include the cluster of wells closest to the coast, showing groundwater values up to 1037 uS/cm in (a) and showing groundwater values up to 2505 uS/cm in (b). Wells labelled 07-36 and 17-12 belong to Susana Mayu, who notified us in June 2017 that salinity in her wells was increasing. Sample location 07-9 was taken from a lower reach of Arroyo La Reforma which previously flowed into La Poza estuary.

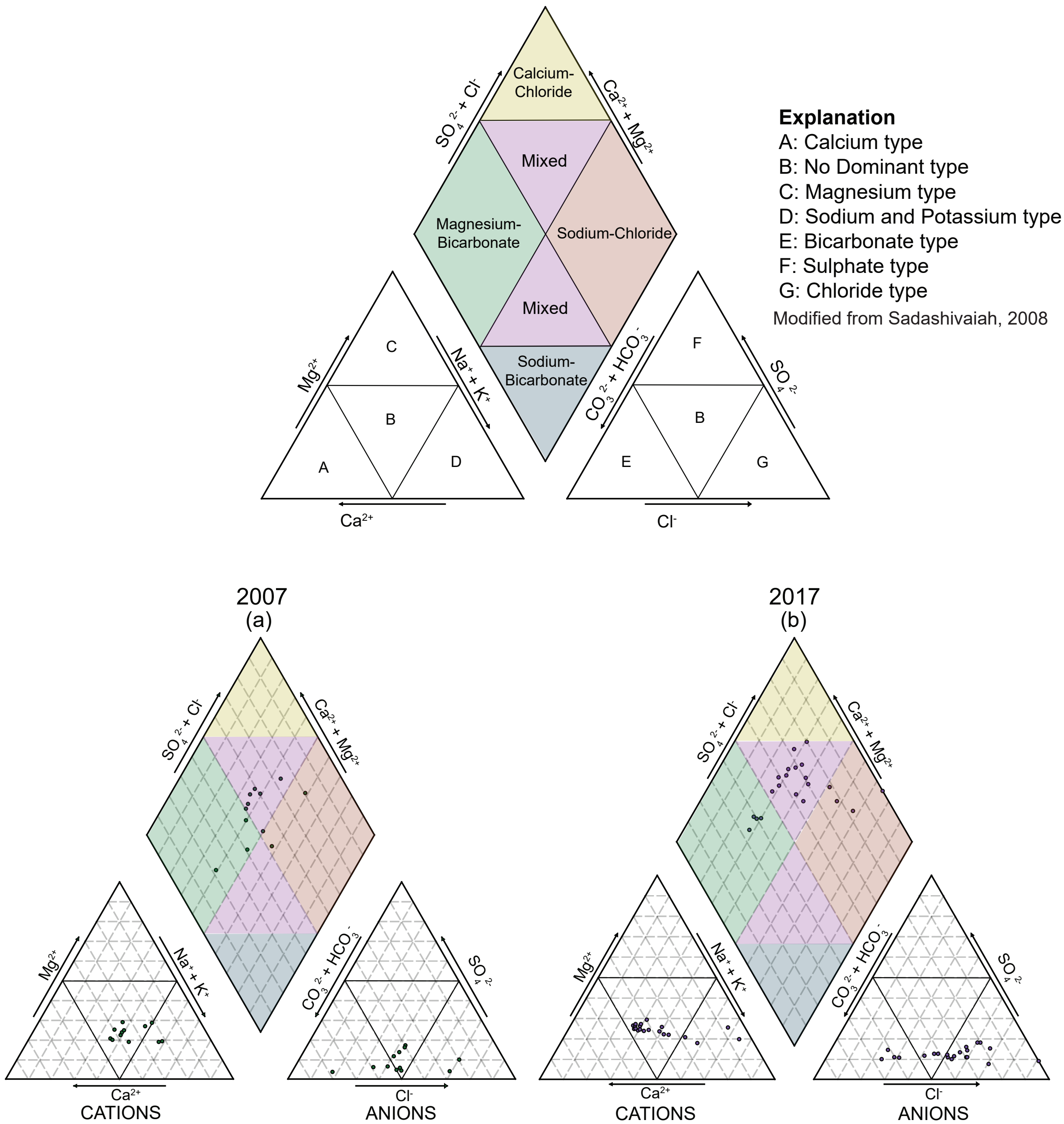


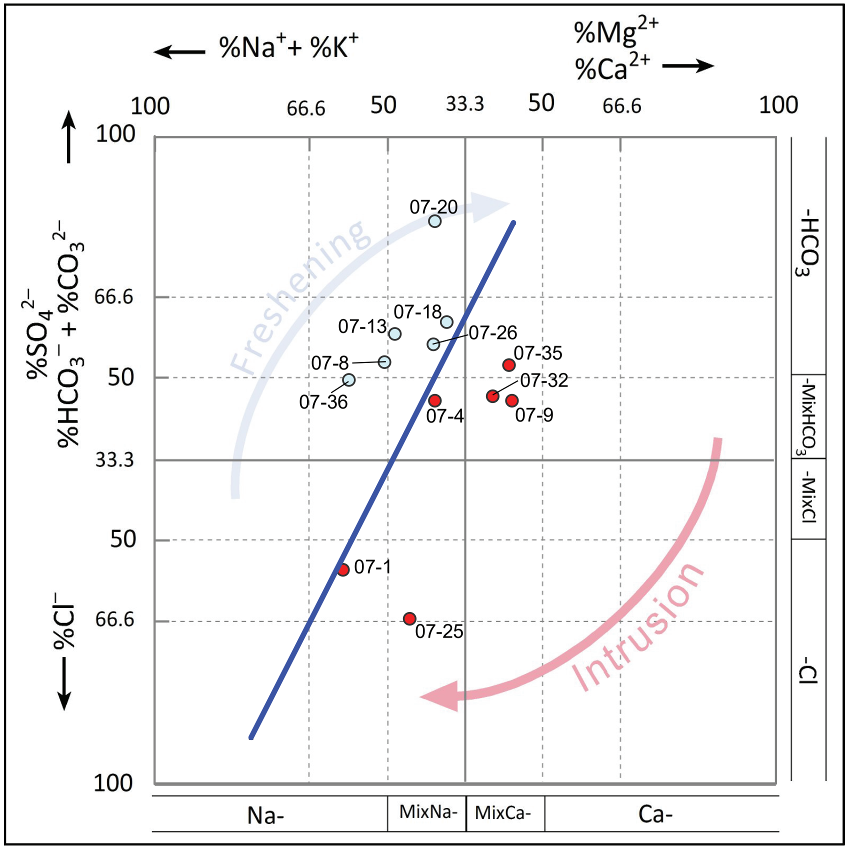
Figure 13: Piper diagrams and associated hydrochemical facies displaying results of major ion analysis for years (a) 2007 and (b) 2017. An increase in sodium-chloride type water can be seen from (a) to (b), as well as an increase in chloride-type water in anion ternary diagrams. Increasing chloride concentration can be seen in the anion ternary diagram displayed in (b). This increase correlates with proximity to the coastline, with the samples plotting with the lowest chloride concentration corresponding to those furthest inland, and samples plotting with the highest chloride concentration corresponding to those located closest to the coastline.

Table 6: Summary of specific conductance data for groundwater samples in 2007 and 2017. Surface water samples, including La Poza Estuary, Las Palmas wetlands, and springs, were not included in statistical calculations.

Specific Conductance Summary		
Year	**2007**	**2017**
Number of samples	22	18
Minimum Value (µS/cm)	308.0	390.9
Maximum Value (µS/cm)	2462.0	4786.0
Mean (µS/cm)	881.3	1209.9
Range (µS/cm)	2154.0	4395.1

Table 7: Hydrochemical facies categories by percentage for 2007 and 2017

Hydrofacies Classification, Todos Santos Aquifer			
Subdivision	**Subdivision Characteristic**	**2007** Percentage of samples in cateogory	**2017**
1	Magnesium-bicarbonate type	25.0	19.0
2	Sodium-chloride type	16.6	19.0
3	Mixed type	58.3	62.0
A	Calcium type	0.0	0.0
B	No Dominant type - (Cation, Anion)	83, 58.3	81, 14.3
C	Magnesium type	0.0	0.0
D	Sodium and potassium type	16.6	19.0
E	Bicarbonate type	25.0	19.0
F	Sulphate type	0.0	0.0
G	Chloride type	16.6	66.7



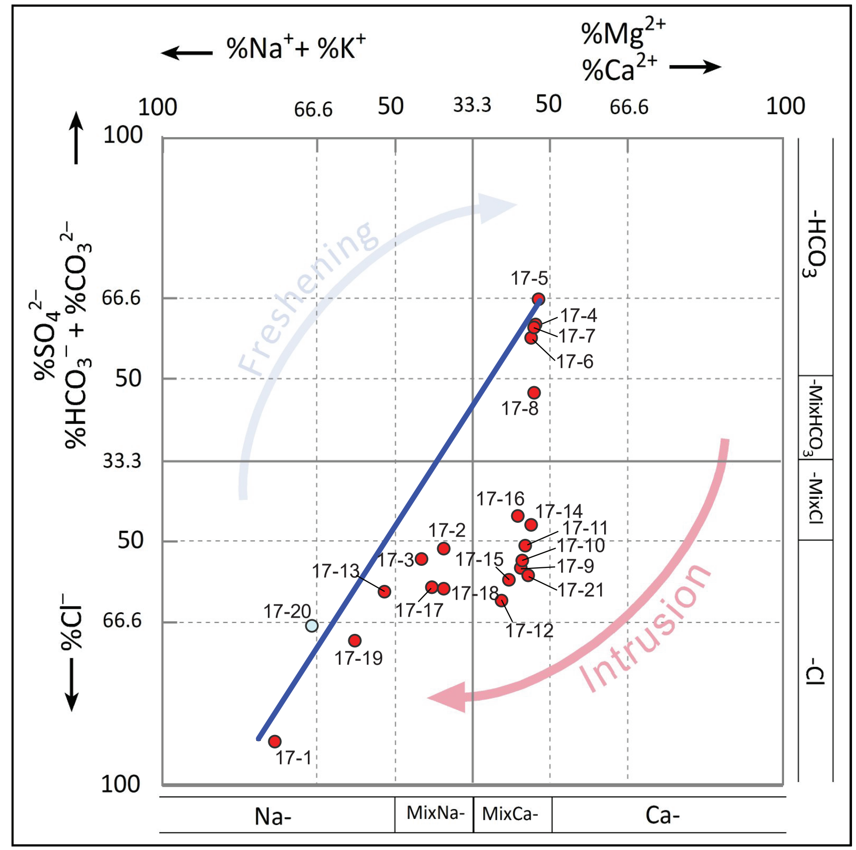


Figure 14: Hydrochemical facies evolution diagrams displayed for years (a) 2007 and (b) 2017 using the excel macro provided by Gimenez-Forcada (2015). Samples in (a) plotted 50% in the freshening phase and 50% in the intrusion phase, while 95% of 2017 samples (b) plotted in the intrusion phase. In (b), many samples plot in the CaCl facies, displaying the characteristic cation exchange of sodium with calcium indicating water which has experienced seawater intrusion. Also in (b), wells geographically located furthest inland (17-4, 17-5, 17-6, 17-7) correspond to samples plotting in the early stages of intrusion and in the freshwater facies, whereas samples from water sources geographically located closest to the coastline (17-1, 17-19, 17-20) correspond to samples plotting in the late stages of intrusion and in the seawater facies.