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Impact of sea-level rise on saltwater intrusion length into the coastal aquifer, Partido de La Costa, Argentina

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ABSTRACT

The impact to water resources of a potential 1-m rise in sea level against the low-lying coast of Partido de La Costa, Argentina was modeled using two scenarios. The first scenario was calculated under the assumption of a constant lateral flux of freshwater. A constant water-table elevation was assumed in the second scenario. Maintaining the lateral flux of freshwater from the land (the first scenario) resulted in an approximately linear increase of the inland extent of saltwater intrusion with rising sea level; saltwater penetrated landward between 25 and 40 m. Meanwhile holding the water-table elevation constant (the second scenario), caused the movement of the saltwater interface to be non-linear. In this case, landward migration in excess of 200 m or more might be expected. The second scenario is more likely to be the situation in Partido de La Costa. The variation of hydrogeological parameters from north to south along the barrier conspire to make the southern reaches, where both the hydraulic conductivity and aquifer thickness are greater, more sensitive to saltwater intrusion from sea-level rise than the northern part of the barrier. These findings may be applicable to similar sandy coastal aquifers in other parts of the global coastline.

1. Introduction

The International Panel on Climate Change (IPCC) considered seawater intrusion into aquifers to be an important future impact of sea-level rise (Kundzewicz et al., 2007). Several studies have quantified the change in worldwide aquifer recharge pending under various, global, climate predictions (Döll, 2009; Döll and Flörke, 2005; Kundzewicz and Döll, 2009; Ranjan et al., 2009; Werner and Simmons, 2009). Werner and Simmons (2009), in particular, explored two limiting conditions to forecast changes in the seawater intrusion length into aquifers based on common global parameters. The first model allows for the vertical upward migration of the inland water-table to keep pace with sea-level rise. This is known as the flux-controlled scenario (Werner and Simmons, 2009). In this case, the hydraulic gradient remains constant causing the flow of fresh groundwater under the shoreline (i.e. the underflow) to remain invariant. If the underflow is constant, the upper limit of sea water intrusion was found to be limited to "no greater than 50 m for typical values of recharge, hydraulic conductivity and aquifer depth" (Werner and Simmons, 2009). The second model does not allow for the vertical migration of the water table and, therefore, any rise in sea level directly translates to a lowering of the hydraulic gradient across the shoreline. This is known as the head-controlled scenario (Werner and Simmons, 2009). Under an invariant, inland water table, the saltwater intrusion can be greater by an order of magnitude, or more, than that forecast by the flux-controlled scenario (Werner and Simmons, 2009). Head-controlled reductions have actually occurred in areas where recharge is less than consumption. Where groundwater is being mined, withdrawals are not replenished completely by recharge leading to a falling water table. Such conditions have been found, for example, in southern California and at several locations along the Mediterranean coastline (e.g. Antonellini et al., 2008).

Only by modeling can coastal groundwater conditions be anticipated in the face of climate change. However, "further work is required to assess the effects of spatial (geologic heterogeneity) and temporal heterogeneity of the sea-level rise intrusion problem" (Werner and Simmons, 2009). Either the constant-head or the constant-flux scenario, or a combination of both, may be valid in any particular setting. Thus, the manifestation of these changes in particular settings can provide clues to managers of water

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resources (Werner and Simmons, 2009). Site-specific forecasts of saltwater intrusion into the coastal zone must assess both models. Progress will be based on a combination of both observational and modeling studies on a local to regional scale (Antonellini et al., 2008; Bobba, 2002; Oude Essink, 1999; Sherif and Singh, 1999; Werner and Gallagher, 2006). While the physical mechanisms involved are well-defined, we will show that the response of any particular system to these mechanisms is sensitive to the basic controlling variables. In this article, we have applied these two scenarios to the coast of Partido de La Costa, Argentina.

The projection of future saltwater intrusion lengths are influenced by the change of precipitation, temperature and evapotranspiration, which are not manageable by regional authorities. However, they are also impacted by manageable factors like land-use (Pousa et al., 2011), population growth and other factors that increase water consumption. Low-lying coastal beaches, like Partido de La Costa, are especially sensitive to the effect of sea-level rise. In many cases, if not most, the water table cannot migrate freely but, any change in the water-table elevation will lead eventually to a change in the volume of the freshwater lens. In such places too, groundwater from the freshwater lens is often the only source of potable water for inhabitants. By alternately applying the flux-controlled and the head-controlled scenarios to a low-relief coast in Argentina we hope to demonstrate the sensitivity of such systems to sea-level rise. Managers of water resources on the barrier must respond to local, natural conditions that vary from north to south over even this local section of the coast.

2. Study site

The climate of this coastal region of Argentina is marked by a dry season, which coincides with the coldest months (April–September), and a rainy season during the warmest months (October–March). Most precipitation occurs during months which have the highest potential evapotranspiration (Carretero and Kruse, 2012). Hence, the majority of the recharge occurs during the dry season. It is generally accepted that average annual precipitation in Argentina rose during the 20th century (Barros et al., 2006), however, current climate trends show a reduction in rainfall during the dry season while rainfall is projected to increase during the rainy season (Carretero and Kruse, 2011). This change in climate patterns will likely lead to a net reduction in recharge, further stressing aquifer exploitation.

The Partido de La Costa, (36°44.36′S; 56°41.1′W), is one of the most important tourist destinations in the country. This sandy barrier is home to the sea-side resorts of San Clemente del Tuyú, Las Toninas, Santa Teresita, San Bernardo and Mar de Ajó (Fig. 1). The beach-dune, barrier system extends continuously for 60 km from San Clemente del Tuyú in the north to Punta Médanos at the southern end of the study area. The width of the barrier beach varies between two and four kilometers. More than 75,000 permanent residents inhabit Partido de La Costa many of whom are concentrated in the middle third of the barrier (Table 1). The population increases considerably during the austral summer due to tourism. The entire population is dependent upon the shallow aquifer for their potable water supply (Carretero and Kruse, 2010) and the average rate of consumption per inhabitant is 200 L/d (Planas et al., 2000).

The beach area is rectilinear – with a width ranging from 50 to 150 m –, accretional and there is no escarpment. Both the beach and the dunes are characterized by fine-grained sands with the grain size gradually increasing from north to south (Spalletti and Mazzoni, 1979). Low-elevation dunes are fixed by sparse vegetation. The continental plain to the west is marked by elevations less than 5 m surrounding Samborombon Bay, which lies immediately behind this coastal barrier (Fig. 1; Consejo Federal de Inversiones, 1989). The bay itself is heavily vegetated and extends about 30 km to the west. It is connected to the sea through tidal channels which drain extensive marshland.

The study area lies in the Costera Region (González, 2005). Average precipitation in the coastal region is 1000 mm/y and recharge has been estimated to be 230 mm/y (Carretero, 2011). Groundwater is recharged on the barrier mainly along the crests of the sand dunes and discharges both to the east towards the sea and to the west towards Samborombon Bay (Carretero, 2011). The main freshwater aquifer (phreatic aquifer) is a Holocene layer of silty sand. The freshwater lens is bounded by a brackish water–freshwater transition zone toward the bay and freshwater–saltwater towards the ocean. The volume of freshwater in the aquifer has been calculated to be approximately 1.2×10^8 m^3 based on the length, width, average thickness, and porosity of the aquifer zone. The underlying aquitard is composed of clay and sandy clay with a thickness of between 2 and 2.5 m. This aquitard overlies a deeper, semiconfined aquifer complex. The sequence is capped by a surficial layer of well-drained sandy soils (Consejo Federal de Inversiones, 1990). Water consumption for the current total population was calculated to be 5.6×10^6 m^3/y.

There are important hydrogeological differences from north to south along this barrier (Table 1). The phreatic aquifer thickness depends on the dune elevation and varies between 7 and 18 m, with higher elevations towards the south. The hydraulic conductivity of the barrier increases from 7 to 30 m/d from north to south. The transmissivity varies from 100 to 150 m^3/d in the north (Carretero, 2011) and from 400 to 490 m^3/d in the south (Consejo Federal de Inversiones,1990). The semiconfined aquifer contains freshwater only in the south, while, towards the north, the semiconfined aquifer contains saltwater. Towards the north, however, the semiconfined aquifer pinches out between Las Toninas and Punta Rasa, although it remains possible to find an aquitard or aquiclude that contains some aquifer levels with high-salinity water (Consejo Federal de Inversiones, 1990). This high-salinity water was not taken into account in our analysis of water resource availability. The groundwater divide was taken as the inner boundary of our study area. The isophreatic map (Fig. 2) shows a groundwater watershed whose isolines grow progressively larger from north to south following the increasing height of the dune. The groundwater flux map was drawn using data taken from Consejo Federal de Inversiones (1990) based on manual measurements of around 250 wells which were homogeneously distributed along the sand-dune barrier. Additional wells from San Clemente del Tuyú area were also used (Carretero, 2011). As we shall show, even along this short section of coastline, such differences have important management implications.

3. Material and methods

For a homogeneous, isotropic, unconfined aquifer receiving a constant recharge, steady-state analytical solutions describing the freshwater lens (Custodio, 1987; Falkland, 1991) were utilized by Werner and Simmons (2009) to forecast saltwater intrusion lengths. The forecasts were based on Darcy's Law with the assumptions of (a) the Ghyben–Hertzberg relationship for immiscible, hydrostatic equilibrium in one dimension between saline groundwater and fresh groundwater, and (b) the Dupuit–Forchheimer approximation of horizontal flow. The horizontal flux of fresh groundwater (q_i) at any inland position (x_i) was thereby calculated in this case as Falkland (1991):

$$q_i(x_i) = q_0 - Wx_i = K(h + \alpha h)(\mathrm{dh}/\mathrm{dx}) \tag{1}$$

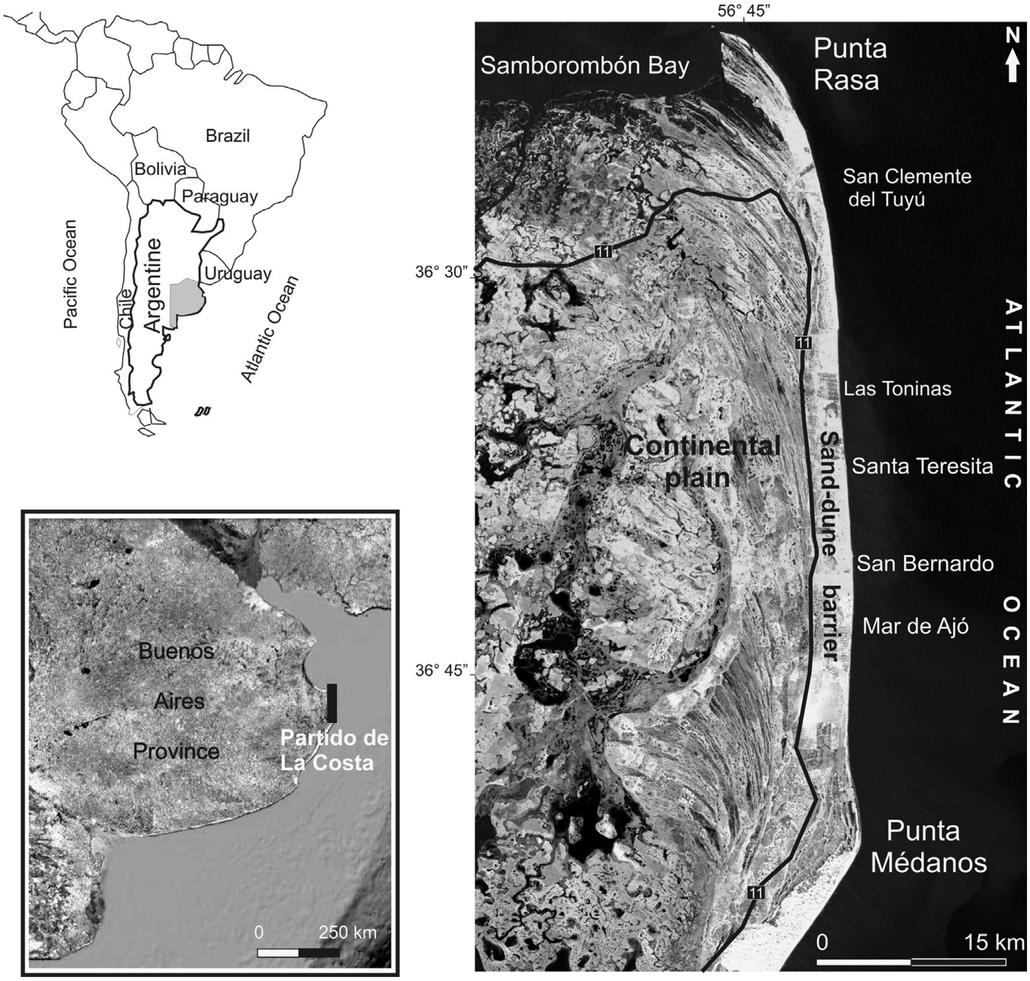

Fig. 1. Study Area: sea-side resorts location and geomorphological environments can be observed.

Table 1
Phreatic aquifer parameters and population according to different areas.

Area (from north to south)	Thickness [m]	Depth below sea level of the aquifer bottom (z_0) [m]	Transmissivity (T) [m^2/d]	Hydraulic conductivity (K) [m/d]	Population
San Clemente del Tuyú	7–10	5	100–150	7	15,000
Las Toninas-Mar de Ajó	15	7	90–120	7–15	60,000
Punta Médanos	18	10	400–490	25–30	0 (Rural area)

which can be integrated to yield (Custodio, 1987):

$$h_i{}^2 = \frac{2q_0x_i - Wx_i{}^2}{K(1+\alpha)} \tag{2}$$

where x_i is the distance inland from shore, and h_i is the elevation of the water table at inland position x_i, W is the recharge, q_0 is the (horizontal) fresh groundwater flow under the shoreline per unit length of shoreline and K is the hydraulic conductivity. The groundwater density ratio, α, is $\rho_f/(\rho_s - \rho_f)$, where ρ_f is the density of freshwater and ρ_s is the density of seawater. The groundwater density ratio, α, is usually assumed to be 40.

In both the flux-controlled and head-controlled scenarios (Fig. 3), the position of the saltwater–freshwater interface length of the saltwater wedge at the base of the aquifer from under the shoreline to the toe of the saltwater wedge is designated as x_T and calculated as (Custodio, 1987):

$$x_T = \frac{q_0}{W} - \sqrt{\frac{q_0{}^2}{W^2} - \frac{K(1+\alpha)z_0{}^2}{W\alpha^2}} \tag{3}$$

where z_0 is the depth of the base of the aquifer below the instantaneous sea level. z_0 will change as sea-level rises. In dynamic equilibrium with a rising sea level, the water-table elevation (h_i) inland of the furthest inland penetration of saltwater at the base of the aquifer, which is to x_T, was determined by a mass balance to be (Werner and Simmons, 2009):

$$h_i = \sqrt{\left(\frac{2}{K}(x_i - x_T)\left(q_0 - \frac{W}{2}(x_i + x_T)\right) + (h_T + z_0)^2\right)} \tag{4}$$

where h_T is the water-table elevation at the toe of sea water wedge

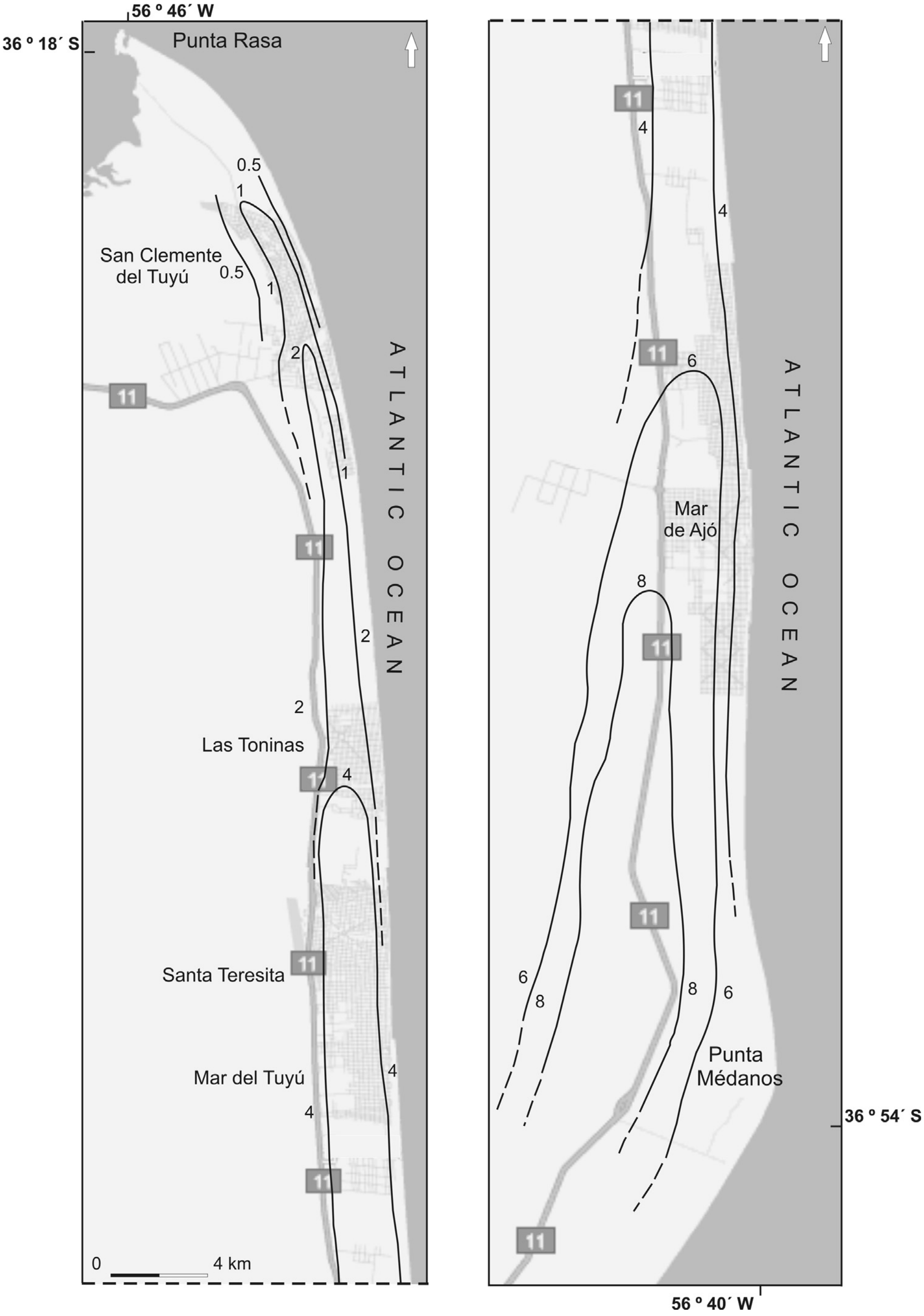

Fig. 2. Isophreatic map. Curves are in meters above sea level (m asl) based on measurements of approximately 250 wells (Consejo Federal de Inversiones, 1990) as well as additional wells from San Clemente del Tuyú (Carretero, 2011).

($h_T = z_0/\alpha$), and x_T is the distance inland of the toe of the saltwater–freshwater interface.

In the flux-controlled scenario, q_0 is constant and controls the position of the sea water-fresh water interface despite a rise in sea level. The water-table elevation level (h_i) rises at the same rate as the sea level changes to maintain this constant underflow. In the head-controlled scenario, the water-table position is invariant despite sea-level rise, that is, the depth of the water table below the land surface remains constant as sea-level rises. For the current application to Partido de La Costa this situation is considered at $x_i = 1$ km which is a reasonable point to define the boundary condition. The control of the water-table elevation is assumed to be due to the balance among evapotranspiration, streams/rivers, wetlands and/or drains and groundwater extraction. In this case, the seaward flow of freshwater is diminished due to a reduction in the hydraulic gradient as sea-level rises. The hydrological parameters for Partido de La Costa (Table 1) were used to calculate the future saltwater intrusion length using both scenarios pending a sea-level rise up to one meter, including forecasts of population growth (INDEC, 2010).

4. Results

Table 2 summarizes the results in the flux-controlled and the head-controlled scenarios and lists parameters used in the equations.

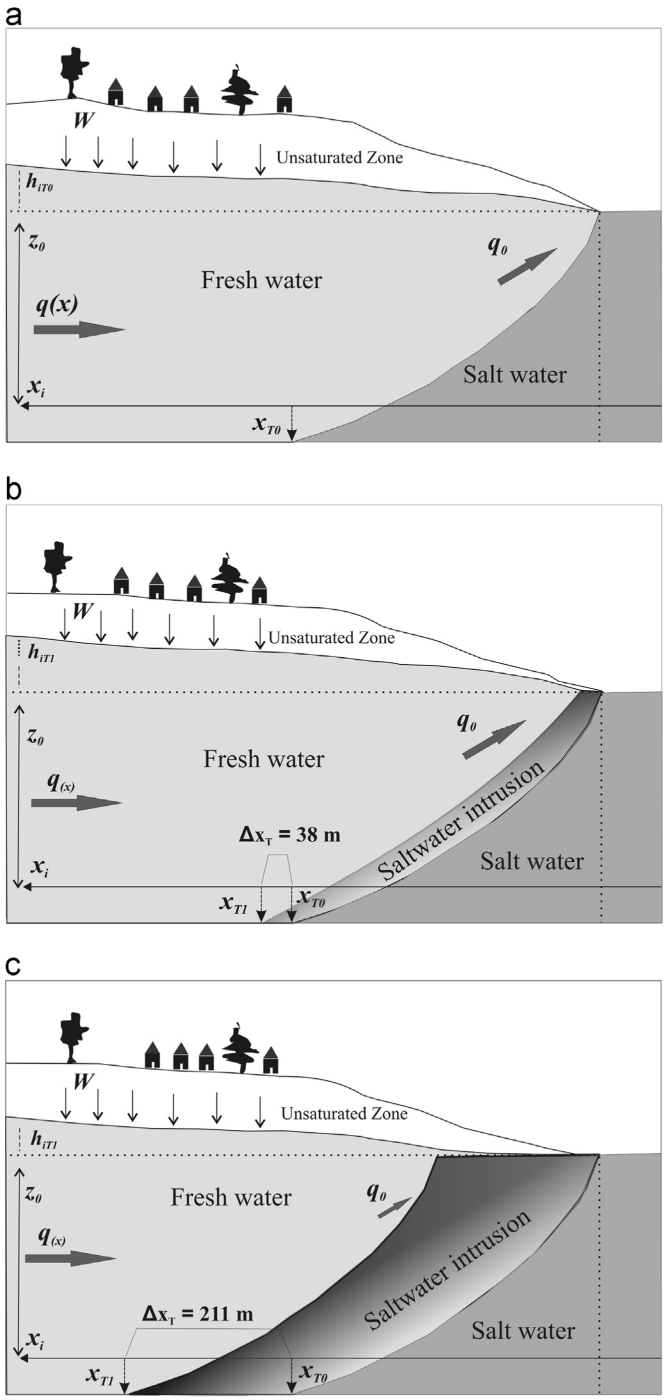

Fig. 3. Schematic diagram of the modeled cross-section and the variables for two scenarios: (a) no sea-level rise (SLR). (b) Flux-controlled scenario in which the maximum Δx_T was 38 m for a one-meter rise in sea level. (c) Head-controlled scenario in which the maximum Δx_T was 211 m for a 1-m rise in sea level. W is the recharge, q_0 is the fresh groundwater flow under the shoreline per unit length of shoreline, x_i is the distance inland from shore, and h_i is the water table at inland position x_i, z_0 is the depth of the base of the aquifer below the instantaneous sea level, x_T is the location of the toe of the saltwater wedge and Δx_T is the variation in the position of the toe of the saltwater wedge due to changes in sea level in both (b) and (c).

4.1. Flux-controlled scenario

The rise in h_i [4] at $x_i = 1$ km required to keep q_0 constant despite sea-level rise was calculated to be 0.99 m for a sea-level rise of one meter. As expected, when the flux of groundwater into the coastal zone was held constant, the penetration of saline groundwater into the aquifer is relatively small. Although the forecast inland migration of the toe of the saltwater–freshwater interface are relatively small, conditions in the southern part of Partido de La Costa were worsened because of the variation in hydraulic conductivity (K; Fig. 4). At San Clemente del Tuyú, where $K = 7$ m/d, the toe of the saltwater–freshwater interface was calculated to migrate inland five meters for a 1-m rise in sea level. Between Las Toninas and Mar de Ajó, where $K = 15$ m/d, Δx_T was found to be 11 m. For a sea-level rise of one meter, Δx_T, reached 25 m only for the highest value of hydraulic conductivity considered ($K = 30$ m/d; Fig. 4).

Similar values of Δx_T were found with variation of the depth of the aquifer below mean sea level of the aquifer bottom (z_0) (Fig. 5). z_0 was five meters at San Clemente del Tuyú, seven meters from Las Toninas to Mar de Ajó, and 10 m in Punta Médanos. With these differences, Δx_T was forecast to be 11, 16 and 25 m, respectively, with a 1-m sea-level rise (Fig. 5). Δx_T was 25 m for the highest z_0 considered here ($z_0 = 10$ m) which aggravates the conditions in the south.

The largest migration of the toe of the saltwater wedge was seen with variations in recharge (W; Fig. 6). With no consumption, that is when W was set to 230 mm/y, the toe of the saltwater–freshwater interface migrated 25 m inland due to a 1-m level rise. Therefore, even in the absence of humans, sea-level rise will lead to a small increase in saltwater intrusion length. With the current consumption by 75,000 inhabitants, recharge was reduced to 203 mm/yr and the Δx_T was 33 m. When population reaches a projected value of 100,000 inhabitants, the recharge will be reduced to 194 mm/y and Δx_T was forecast to increase to 38 m (Fig. 6). This is the maximum value forecast in the constant-flux scenario considered here.

4.2. Head-controlled scenario

Given the permeable sands, low elevation, and general inability for the water table to migrate vertically, it is likely that this is a head-controlled system. When the water table inland stays at a constant elevation as sea-level rises the hydraulic gradient decreases. The resulting decrease in q_0 [1] due to the reduction of h_i, at $x_i = 1$ km, was calculated to be 0.84% for a ten centimeter sea-level rise and 77.4% for a sea-level rise of one meter. The change in the length of the toe of the saltwater wedge (Δx_T) goes asymptotically to infinity as sea level approaches a critical value for the fixed water table position. Of course, such a situation produces large excursions of the salt-water wedge. For example, in the head-controlled scenario with no consumption, that is for a recharge of 230 mm/y, the toe of the saltwater wedge migrated inland 193 m for a 1-m rise in sea level (Fig. 7). When the current consumption was included, that is, with a decrease in recharge to 203 mm/y, Δx_T rises to 199 m. When considering a change in recharge pending population growth, the recharge was calculated to become 194 mm/y; in this situation, Δx_T reaches 211 m (Fig. 7).

Differences in the hydraulic conductivity from north to south ($K = 7$, 15, 30 m/d) resulted in a variation in Δx_T of 123, 169 and 193 m, respectively (Fig. 8). In other words, as the hydraulic conductivity increased over four-fold from north to south (Table 1), the penetration of saltwater, as measured by x_T, increased about 40%. Likewise, the depth of the aquifer below mean sea level of the aquifer bottom (z_0) in the south also led to a 40% increase in the intrusion length. Varying z_0 from north to south ($z_0 = 5$, 7, 10 m) changed the value of Δx_T to 139, 154 and 193 m (Fig. 9). A summary of the results with respect to differences in the hydogeological parameters (K, z_0 and W) in different coastal areas is presented in Fig. 10. The amount of saltwater penetration in the aquifer increases from north to south in both scenarios but the coastal barrier is much

Table 2
Results (Δx_T) and values of the parameters required in the equations.

	Variation in:	K (m/d)	z_0 (m)	SLR (m)	q_0 (m^2/d)	W (mm/y)	Δx_T **(m)**
Flux-controlledcase	***W*** **(mm/y)**						
	230[a]	30	10–11	0–1	0.4		25
	203[b]	30	10–11	0–1	0.4		33
	194[c]	30	10–11	0–1	0.4		38
	K **(m/d)**						
	7		10–11	0–1	0.4	230	5
	15		10–11	0–1	0.4	230	11
	30		10–11	0–1	0.4	230	25
	z_0 **(m)**						
	5	30	5–6	0–1	0.4	230	11
	7	30	7–8	0–1	0.4	230	16
	10	30	10–11	0–1	0.4	230	25
	Variation in:	K (m/d)	z_0 (m)	SLR (m)	q_0 (m^2/d)	W (mm/y)	Δx_T **(m)**
Head-controlled case	***W*** **(mm/y)**						
	230 [a]	30	10–11	0–1	0.400–0.187		**193**
	203[b]	30	10–11	0–1	0.324–0.207		**199**
	194[c]	30	10–11	0–1	0.301–0.202		**211**
	K **(m/d)**						
	7		10–11	0–1	0.400–0.110	230	**123**
	15		10–11	0–1	0.400–0.157	230	**169**
	30		10–11	0–1	0.400–0.223	230	**193**
	z_0 **(m)**						
	5	30	5–6	0–1	0.400–0.110	230	**139**
	7	30	7–8	0–1	0.400–0.157	230	**154**
	10	30	10–11	0–1	0.400–0.223	230	**193**

[a] Recharge = 230 mm/y (no consumption).
[b] Recharge = 203 mm/y (75,000 inhabitants, 2010).
[c] Recharge = 194 mm/y (100,000 inhabitants, projection).

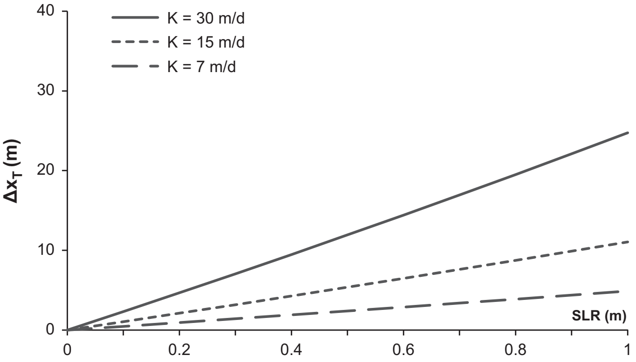

Fig. 4. Flux-controlled scenario: Δx_T vs. sea-level rise, with variation in recharge (W). x_T is the location of the toe of the sea water wedge.

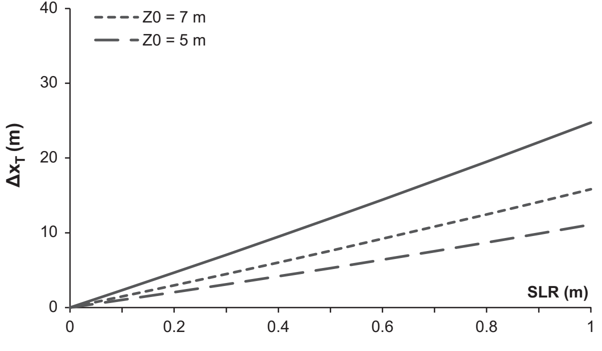

Fig. 5. Flux-controlled scenario: Δx_T vs. sea-level rise, with variation in hydraulic conductivity (K).

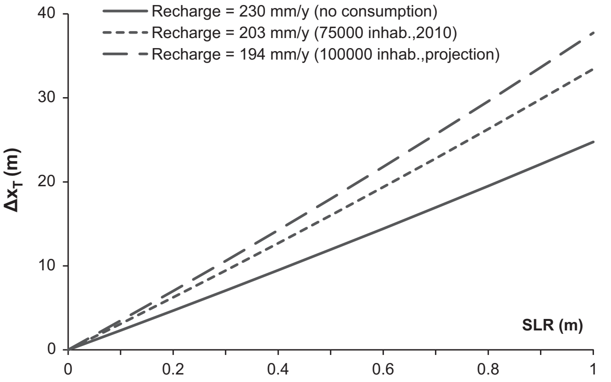

Fig. 6. Flux-controlled scenario: Δx_T vs. sea-level rise, with variation in z_0.

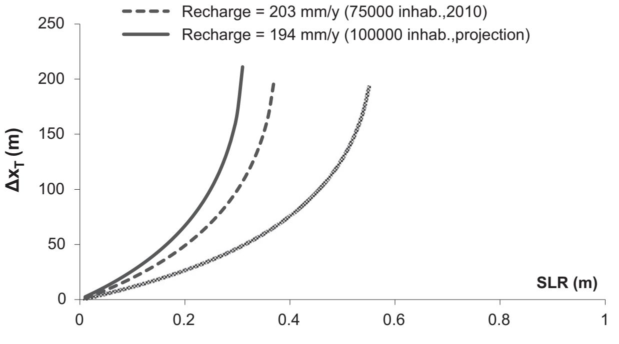

Fig. 7. Head-controlled scenario: Δx_T vs. sea-level rise, with variation in recharge (W).

more sensitive to the relatively small hydrogeological differences along its short length under the assumption of constant-head.

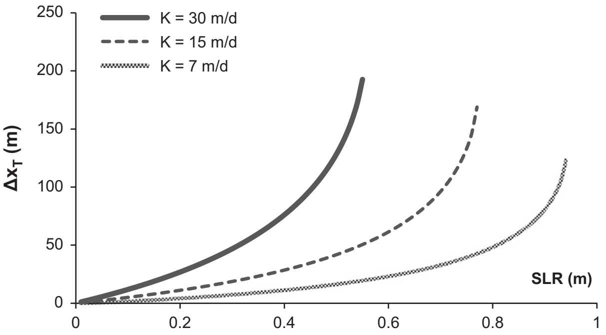

Fig. 8. Head-controlled scenario: Δx_T vs. sea-level rise, with variation in K.

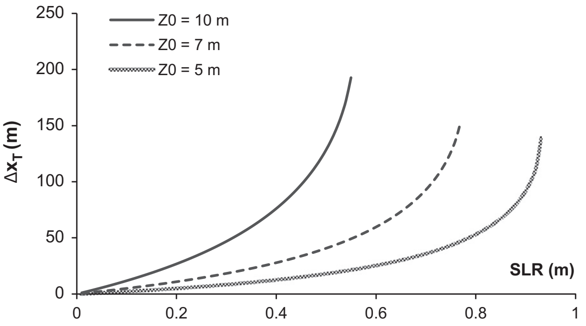

Fig. 9. Head-controlled scenario: Δx_T vs. sea-level rise, with variation in z_0.

5. Discussion

The freshwater resources of coastal zones depend on how the saltwater–freshwater interface will migrate with changing sea levels. The rise and fall of the tide across a sloping shorefront will elevate the water table referred to as tidal pumping (Nielsen, 1990). Although the magnitude will change with the slope of the land at the shoreline, this effect is manifest in the current water-table elevation and it will persist as seal level rises. It has not been explicitly parameterized here, because the coast of Partido de La Costa is microtidal (Servicio de Hidrografía Naval, 2008) and because of the morphology of the sand-dune barrier, the effects of the tides are limited to the subaerial beach. The discharge of groundwater will, of course be modulated by the variation of the tides, wave set up and a variety of sea level changes on time scales, but these variations are much shorter than the sea-level rise over decades (e.g. Valle-Levinson et al., 2011). The position of the saltwater interface, however, changes but slowly and these shorter-term variations will essentially be manifest as dispersion, increasing the width of the saltwater–freshwater interface in the aquifer. The condition is expected to remain the same as seal level gradually rises.

Under head-controlled conditions, saltwater intrusion will penetrate far inland with only a few tens of centimeters of sea-level rise

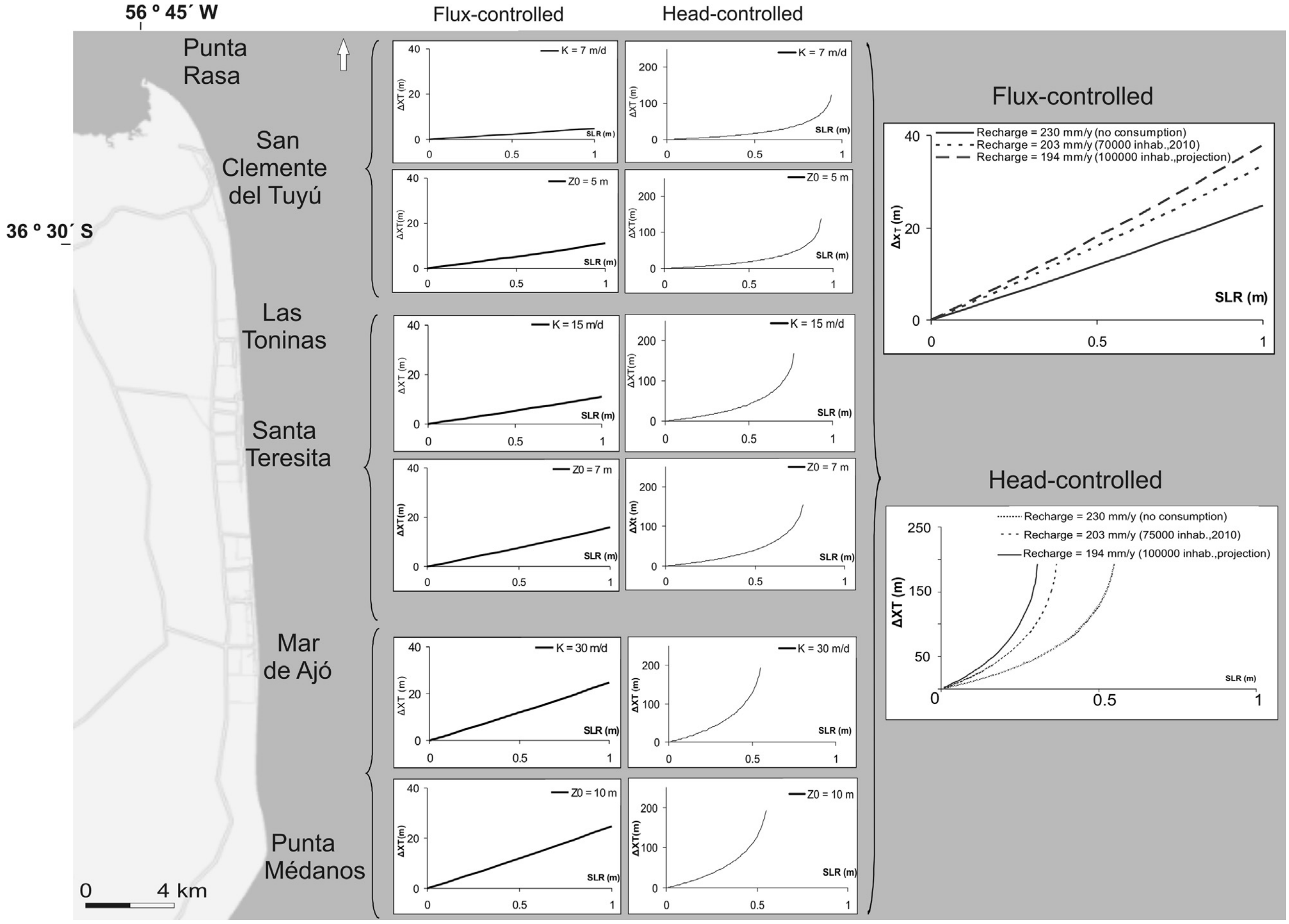

Fig. 10. Saltwater intrusion lengths into different coastal areas and the whole region pending different parameters.

while the situation is much less dire if the system is flux-controlled. If the position of the interface is controlled by the flux of freshwater, that is, in the flux-controlled scenario, the intrusion length is, to a good approximation, linearly increasing with sea-level rise. Essentially, the saltwater–freshwater interface migrates landward directly related to sea-level rise.

In head-controlled systems, there is a threshold sea level beyond which all coastal freshwater reserves will be lost and saltwater will penetrate throughout the aquifer. Under the conditions examined here, the critical value of sea-level rise decreases, directly and approximately linearly, as the recharge decreases or as the hydraulic conductivity increases. In the situations considered here, the migration of the saltwater–freshwater interface was greatest with reductions in recharge, but, in contrast to the conclusion of other studies (i. e. Ranjan et al., 2009), changes in consumption are not much more important than sea-level rise for determining the rate of saltwater penetration into coastal aquifers.

The hydraulic conditions in the southern part of the study site make this area the most vulnerable. Whether using the flux-controlled or the head-controlled scenarios, the intrusion length is greater at any rate of sea-level rise in the southern part of Partido de La Costa than it is in the northern part. This was due to a combination of high hydraulic conductivity and a thicker aquifer. It would seem to be less harmful to the availability of fresh water if population increase occurs in the less-stressed northern side of the study site.

The shift of the interface has an important role in decreasing the freshwater reserves in the aquifer, because, in equilibrium the depth of the saltwater–freshwater interface is approximately 40 times the elevation of the water table above sea level. As sea level rises under the head-controlled scenario (Fig. 11) the saltwater–freshwater interface will migrate vertically. For the flux-controlled scenario, the water table and the saltwater–freshwater interface will rise with it. The fresh groundwater might be thought of as a bubble of freshwater floating in the saline groundwater and rising with it as sea level increases. The volume of freshwater lost due to rising sea level is then the product of the sea-level rise (SLR) and the length of the saltwater–freshwater interface, that is $\mathrm{SLR} \times x_T$. The permanent loss is due only to the loss of recharge area (subaearial land) due to the inland migration of the shoreline. Under the head-controlled scenario, the position of the water table stays fixed as sea level rises. As sea level rises, the elevation of the water table (h_f) above the instantaneous sea level decreases at the same rate as sea-level rise, and the depth to the saltwater–freshwater interface below the instantaneous sea level, decreases accordingly to maintain a depth of $40h_f$ (Fig. 11). As sea level rises an amount the saltwater interface rises a vertical distance of $41 \times \mathrm{SLR}$ (Fig. 11). The maximum forecast saltwater intrusion would reduce the freshwater reservoir by 5.2%, or 6.3×10^6 m^3. Although this exceeds the amount of fresh water necessary to supply the population for a year, or 5.6×10^6 m^3/y, it is likely that this is a minimum value because the freshwater lens will be able to migrate vertically to a certain extent.

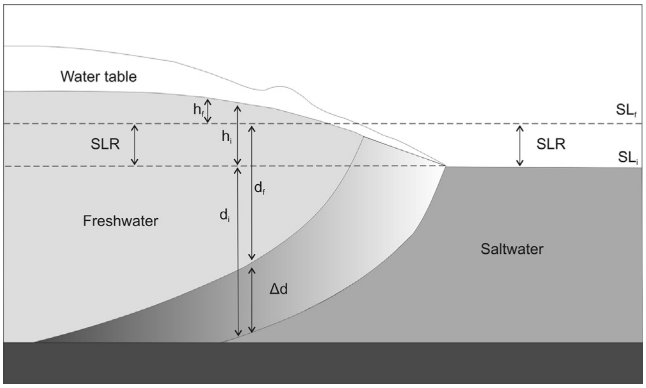

Fig. 11. The initial sea level is indicated by SL_i. After a rise of sea level of SLR the final sea level is SL_f. The position of the water table is assumed to be fixed at a certain point inland. The elevation of the water table is initially h_i above SL_i and changes to h_f above SL_f where $h_f = h_i - \mathrm{SLR}$. The initial depth of the saltwater–freshwater interface is $d_i = 40h_i$ below SL_i. At the final position of the sea the depth of the saltwater–freshwater interface is d_f below SL_f. At this location the saltwater–freshwater interface has risen an amount $\Delta d = d_i + \mathrm{SLR} - d_f$ or $40h_i + \mathrm{SLR} - 40h_f = -40h_i + \mathrm{SLR} - 40(h_i - \mathrm{SLR}) = 41 \times \mathrm{SLR}$.

Worldwide, sandy depositional terrain often underlain by unconfined aquifers and such terrains may account for more than 20% of the world's coastline (Bird, 1985). Due to conditions often found in these areas, a head-controlled scenario is expected to be most widely applicable. As a result, we anticipate a greater sensitivity to rising sea level for coastal areas in which (a) the hydraulic conductivity is greater than that at Partido de La Costa and/or (b) the aquifer thickness is greater and/or (c) consumption is greater than that in coastal Argentina. Therefore many barrier beaches such as those found in along the east coast of the United States, Northern Europe, and in Deltaic regions may be particularly sensitive to saltwater intrusion from sea-level rise. Meanwhile, the sensitivity of the coastal region would be expected to decrease if the hydraulic conductivity is less than that found at Partido de La Costa if the aquifer thickness is less, and population and hence consumption are lower than that found in Argentina.

6. Conclusions

In the flux-controlled scenario, an increase in saltwater intrusion length would reach a maximum of 38 m with a sea-level rise of one meter, but the coastal aquifer of Partido de La Costa, Argentina would be minimally affected by sea-level rise or by changes in water consumption. However, given the low elevation of the land surface, saltwater intrusion is more likely to be controlled by a water table at a fixed depth. With a 1-m rise in sea level in this case, an increase in saltwater intrusion length by more than 200 m will severely degrade the aquifer. Punta Médanos would be the most affected by sea-level rise; this is something to be considered because the area represents the main reservoir for Partido de La Costa due to the greater aquifer thickness. Any reduction in recharge, or, in other words, an increase in water consumption, will have the greatest impact on saltwater intrusion lengths into aquifers. If the population increases to 100,000 inhabitants, the aquifer would be strongly affected with a sea-level rise of only 0.31 m. A higher population growth rate associated with a higher water-consumption rate would affect the aquifer with a lower sea-level rise resulting in an earlier risk situation.

The reduction in the volume of fresh water may become equivalent to the annual population consumption. Coastal managers would need to develop a careful strategy for the water supply perhaps utilizing a different water source for their residents.

These findings may reflect patterns in similar coastal systems throughout the world and therefore we should heed the potential problem of sea-level rise as it pertains to coastal groundwater resources.

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