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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^2/d in the north (Carretero, 2011) and from 400 to 490 m^2/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):

$$q_i(x_i) = q_0 - Wx_i = K(h + \alpha h)(\mathrm{d}h/\mathrm{d}x) \quad (1)$$