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Groundwater travel time in the freshwater lenses of Samborombón Bay, Argentina

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Abstract The Samborombón Bay area (Argentina) is a coastal plain environment that contains groundwater resources with high salinity. In addition, there are local freshwater lenses associated with shell ridges and sand sheets in the region. In this work, the groundwater travel time in these freshwater lenses is estimated based on their geological conditions, which include hydraulic conductivity, recharge, morphology and discharge to surface freshwater or to saline groundwater. Groundwater travel times in the freshwater lenses were calculated from the equations developed by Chesnaux and Allen. The travel times estimated for the different scenarios were relatively short. The results indicate that the groundwater flow tends to be strongly dependent on the recharge conditions, with an excess of water in the water balance. The results can be applied to help design sustainable management methods to exploit this water resource system and also to assess the impact of contaminant plumes on this groundwater resource.

Key words groundwater flow; freshwater resource; Argentina

Temps de transfert hydrogéologique dans les lentilles d'eau douce de la Baie de Samborombón, Argentine
Résumé La zone de la Baie de Samborombón (Argentine) est un environnement de plaine côtière qui contient des ressources en eaux souterraines dont la salinité est élevée. En outre, il existe des lentilles d'eau douce locales associées aux crêtes de coquillages et feuilles de sable dans la région. Dans ce travail, le temps de transfert des eaux souterraines dans ces lentilles d'eau douce est estimé en fonction de leurs conditions géologiques, notamment la conductivité hydraulique, la recharge, la morphologie et la décharge vers les eaux de surface ou vers les eaux souterraines salines. Les temps de transfert des eaux souterraines dans les lentilles d'eau douce ont été calculés à partir des équations développées par Chesnaux et Allen. Les temps de transfert estimés pour les différents scénarios sont relativement faibles. Les résultats indiquent que l'écoulement des eaux souterraines a tendance à être fortement dépendant des conditions de recharge, avec un excès d'eau dans le bilan hydrologique. Les résultats peuvent être appliqués pour aider à concevoir des méthodes de gestion durable pour l'exploitation de ce système de ressources en eau et aussi pour évaluer l'impact de panaches de contaminants sur cette ressource en eaux souterraines.

Mots clefs écoulement hydrogéologique; ressources en eau douce; Argentine

INTRODUCTION

The time interval between recharge and discharge points is defined as the travel time of groundwater flow (Etcheverry & Perrochet, 2000). Travel time is used in several applications, such as designing exploitation and monitoring systems, identifying areas affected by contaminant migration and assessing the potential for natural attenuation of pollutants (Bair *et al*., 1990; Frind *et al*., 2002; Zhan & Sun, 2007).

Analytical solutions to estimate the travel time of groundwater flow have been developed by several authors for confined aquifers with regional flow (Bear & Jacobs, 1965; Grubb, 1993), unconfined aquifers with pumping conditions and without recharge (Simpson *et al*., 2003; Chapuis & Chesnaux, 2006), unconfined aquifers without pumping conditions and with recharge by infiltration (Chesnaux *et al*., 2005), and unconfined aquifers without pumping and with recharge by infiltration in oceanic islands and inland

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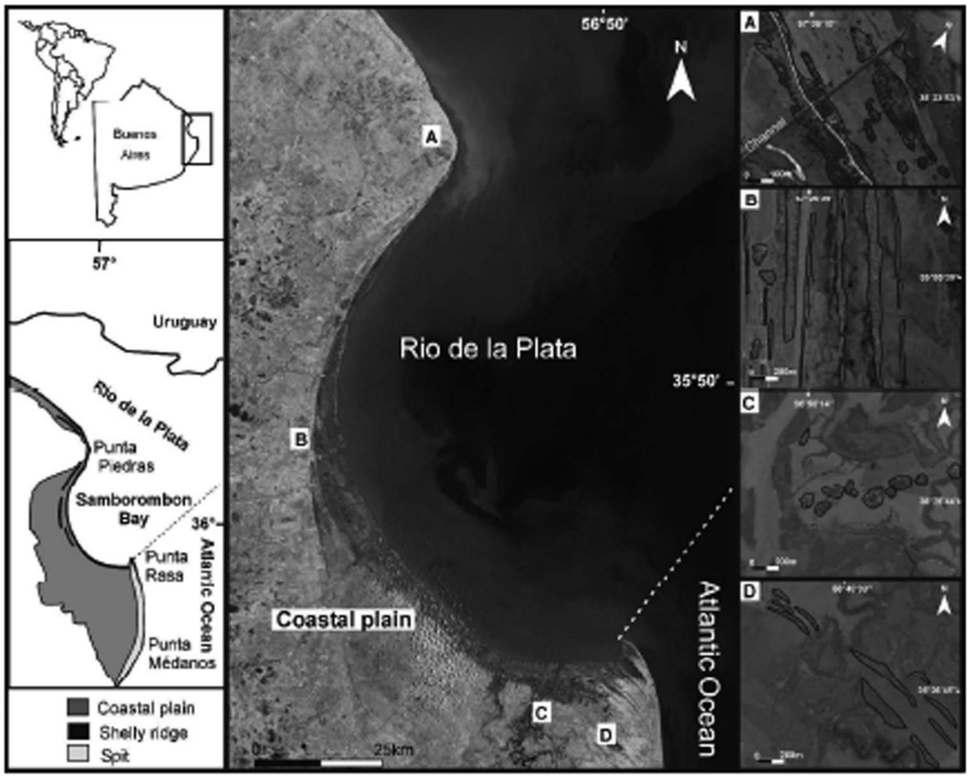

Fig. 1 Location of the study area. (a) area with a predominance of strip-shaped sand sheets; (b) area with a predominance of shell ridges; (c) area with a predominance of circular sand sheets; and (d) area with a predominance of strip-shaped sand sheets.

islands with both circular and strip morphology (Chesnaux & Allen, 2008).

Samborombón Bay is located in eastern Buenos Aires Province, Argentina (Fig. 1), in a coastal plain environment that contains groundwater resources with high salinity. Along this plain are shell ridges and sand sheets where low-salinity water accumulates in the form of lenses.

The aim of this work is to estimate the groundwater travel time in these freshwater lenses by using the model developed by Chesnaux & Allen (2008) for oceanic and inland islands. The use of this analytical method is suggested in order to describe the hydrological dynamics in the actual system studied.

In the study area, the assessment of groundwater system exploitation and conservative pollutant migration are important issues to consider for groundwater management. The calculation of groundwater travel time has direct bearing on this matter. The exploitation of freshwater lenses requires well designs suitable for the flow volumes. In relation to the contamination of the lenses by conservative pollutants, the study of the propagation of the contaminant plume is directly related to the velocity and travel time of groundwater.

The implementation of this type of model becomes relevant in the region, both to the socio-economic development and the preservation of the environmental conditions. The only source of potable water supply available is related to the freshwater lenses. The economy is based on cattle farming (bovine) and mining (extraction of shell debris and sand). Significant volumes of water are used in mining, extraction being done in an unplanned manner from the freshwater lenses. The dynamics and quality of the water also have a direct influence upon the preservation of ecosystems; it should be highlighted that the study area has been designated as a Ramsar site.

The water dependence of these environments requires balanced hydrological management, and techniques that can provide fast assessment of the travel time of freshwater lenses are very useful analytical tools for managing groundwater.

STUDY AREA

Geology and geomorphology

Samborombón Bay is located between Punta Piedras and Punta Rasa (Buenos Aires Province, Argentina) and comprises a shoreline of approximately 180 km. It is an extensive coastal plain dominated by shell ridges and sand sheets (Fig. 1). The formation of the bay took place during the Pleistocene–Holocene as a consequence of successive displacements of the coastline due to oscillations in the sea level. Its origin is related to the simultaneous development of a sand spit in the southeast sector and barrier systems in the north sector. The sand spit migrated northward (from Punta Médanos to Punta Rasa) and the barrier systems migrated southward. To the west of these environments there is a coastal plain with marshes and tidal channels (Fig. 1) (Violante *et al*., 2001).

The coastal plain is a topographically low area with a maximum height of about 5 m a.s.l. and gentle slopes with values close to 10^{-4}. It is composed of clayey silt sediments of low hydraulic conductivity. The shell ridges associated with the barriers developed in the coastal plain from the middle of the bay towards the north, and constitute the remains of marine regression. They form ridges parallel to the coastline, which are 50–120 m in width and from a few hundred metres to about 10 km in length (Fig. 1(a) and (b)). They consist of loose remains of marine shells, which alternate in sectors with layers of sand and clay.

Among the sand sheets, those with a circular shape are differentiated from those with a strip shape. Both types were deposited on the coastal plain, have an aeolian origin and are composed of fine to medium-coarse sands. The strip-shaped sheets lie parallel to the coastline to the west of the sand spit. They are about 100 m wide and between 300 m and 1 km long (Fig. 1(a) and (d)). The circular sheets are distributed at random in the environment of the coastal plain and have a limited aerial expression with radii that are rarely larger than 50 m (Fig. 1(c)).

Both the shell ridges and the sand sheets constitute geoforms that are elevated above the coastal plain by about 3 m on average.

Hydrogeology

The climate of the region is sub-humid to humid with a mean annual rainfall of 930 mm (period 1887–2002). Monthly rainfall data show a relatively regular pattern with a maximum of 91 mm in March and a minimum of 67 mm in June (Table 1). Annual values indicate the presence of alternating dry and wet cycles: the highest annual rainfall was 1634 mm in 1914, and the lowest was 421 mm in 1925 (Carol, 2008).

Table 1 Mean monthly rainfall in the period 1887–2007.

Months	Mean rainfall (mm)
January	87.6
February	72.8
March	90.9
April	85.1
May	77.7
June	67.1
July	71.2
August	68.9
September	69.5
October	81.6
November	79.3
December	78.9

The coastal plain is a hydrogeological unit of low hydraulic conductivity that contains an unconfined aquifer. The water table is very close to the surface, with a depth of between 0.3 and 1.0 m and a hydraulic head usually lower than 1.5 m a.s.l. The regional flow moves towards the Río de la Plata and can discharge locally into ponds and surface water. The water in this hydrogeological unit is Na-Cl with high salinity values of up to 10 g/L (Sala *et al*., 1978; Carol *et al*., 2008, 2009).

The shell ridges and sand sheets constitute recharge areas where rainfall accumulates, forming freshwater lenses over the coastal plain with saline groundwater. In these environments the lithological and morphological characteristics, as well as the lack of surface runoff, favour the infiltration of rainfall excess. Due to the relative monthly regularity of rainfall events (Table 1), monthly recharge is assumed to be constant. The water excess that feeds the freshwater lenses depends mainly on rainfall and evapotranspiration. According to the daily hydrological balances (period 1990–2006) carried out in the region (Deluchi *et al*., 2006), and calculating reference evapotranspiration by the Penman-Monteith equation (Allen *et al.*, 2004), it is estimated that, for the years with an annual rainfall close to the mean value (e.g. 2006 with 952 mm), the annual real evapotranspiration is 502 mm and the excess recharging the lenses is 450 mm. For dry years (e.g. 1996 with 802 mm), the annual real evapotranspiration is 553 mm and the excess is 250 mm, whereas for wet years (e.g. 1993 with 1380 mm) the annual real evapotranspiration is 575 mm and the excess is 805 mm.

These variations in the recharge produce oscillations in the water table of the lenses, which can be found at a depth of between 1.0 and 2.5 m, with hydraulic head values between 1.0 and 4.5 m a.s.l., depending on the thickness of the lens.

The water in the lenses is of low salinity – between 300 and 1200 mg/L in the case of the shell ridges, and between 300 and 1600 mg/L in the case of the sand sheets (Sala *et al*., 1978; Carol *et al*., 2008, 2009). The groundwater flows from the higher topographical areas (3–6 m a.s.l.) towards the saline coastal plain (<1 m a.s.l.) forming saltwater-bound lenses (Fig. 2(a)).

The bay is an area where the waters of the Río de la Plata and the Atlantic Ocean mix, and where salinity varies between 3 g/L in the northern sector and 12 g/L in the southern sector (Guerrero *et al*., 1997). Different salinity values (between 1 and 14 g/L) are found in the channels and surface water that discharge into the bay (Carol, 2008). The coastal area is susceptible to flooding from the waters in the bay, the channels and the water courses. The groundwater of the sand sheets sometimes comes into contact with these water courses and tidal channels that contain low-salinity water. In these cases, there is no freshwater/saltwater interface in the discharge area and the groundwater flow discharges directly into low-salinity water courses (freshwater-bound lenses) (Fig. 2(b)).

ESTIMATION OF TRAVEL TIME

The travel time of the groundwater flow through the freshwater lenses was calculated according to the solutions proposed by Chesnaux & Allen (2008) for oceanic and inland islands.

The lenses studied were modelled as lenses with a symmetrical morphology and homogeneous lithology, with a constant recharge after rainfall events (Table 1). These characteristics were taken into consideration in the equations applied.

Solutions for shell ridges and sand sheets that discharge to the coastal plain (saltwater-bound lenses)

The equations developed for oceanic islands were applied to the shell ridges and sand sheets whose

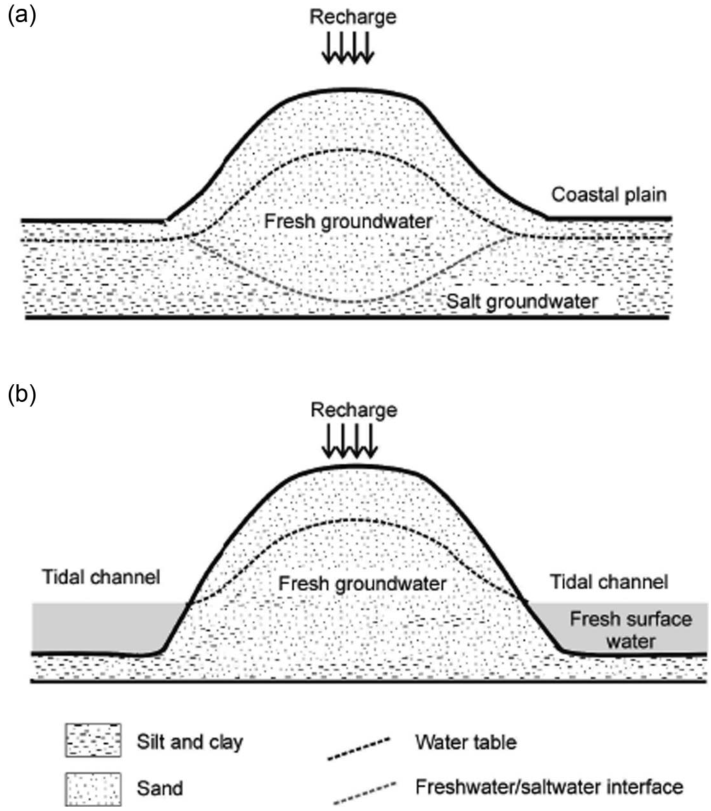

Fig. 2 Profiles of circular or strip-shaped sand sheets for: (a) saltwater-bound lenses; and (b) freshwater-bound lenses. Adapted from Chesnaux & Allen (2008).

groundwater flow discharges to the saline coastal plain. The boundary represented by the freshwater/saltwater interface between the oceanic island and the ocean is homologous to that between the freshwater lenses located in the shell ridges and sand sheets, and the saline aquifer of the coastal plain (Fig. 2(a)). As the freshwater–saltwater interface is regarded as an impermeable boundary, the medium into which freshwater lenses discharge – either a saline surface water body or a porous saline aquifer – has no influence on the calculation of travel time.

The equations that govern the travel times of the groundwater flow in the circular and strip-shaped freshwater lenses are, respectively:

$$t_{\mathrm{ccp}_{(r)}} = n_e \sqrt{\frac{2\left(\rho_f + \Delta\rho\right)}{WK\Delta\rho}} \left[\sqrt{R^2 - r^2} - \sqrt{R^2 - r_i^2} - R \ln\left(\frac{R + \sqrt{R^2 - r^2}}{R + \sqrt{R^2 - r_i^2}} \frac{r_i}{r} \right) \right] \tag{1}$$

$$t_{\mathrm{scp}_{(x)}} = n_e \sqrt{\frac{\rho_f + \Delta\rho}{WK\Delta\rho}} \left[\sqrt{L^2 - x^2} - \sqrt{L^2 - x_i^2} - L \ln\left(\frac{L + \sqrt{L^2 - x^2}}{L + \sqrt{L^2 - x_i^2}} \frac{x_i}{x} \right) \right] \tag{2}$$

where t is time; n_e the effective porosity; W the recharge; K the hydraulic conductivity; r and R the radial distances; x and L the longitudinal distances; ρ_f the density of freshwater; and $\Delta\rho$ the difference between the densities of saltwater (ρ_s) and freshwater (ρ_f). In this manner, the travel time between two positions located along the flow line may be calculated, r_i and x_i being the initial position (time = 0), and r and x, the position of the water particle at time t. For circular lenses, the problem is solved between $r_i = 0$ to $r = R$, whereas for the longitudinal ones it is between $x_i = 0$ to $x = L$. The thickness of the freshwater lens is given by the addition of the height of the water table (h) and the depth of the interface (z) (Chesnaux & Allen, 2008). Abbreviations ccp and scp indicate circular and strip lenses, respectively, discharging to the coastal plain. A density value of 1.000 g/cm^3 (ρ_f) was used for freshwater and 1.025 g/cm^3(ρ_s) for saline water.

Solutions for sand sheets that discharge into tidal channels (freshwater-bound lenses)

The solutions developed for inland islands were applied to the sand sheets that discharge into tidal channels and surface water courses, since both represent geoforms with a similar hydrological behaviour (Fig. 2(b)).

For these sand sheets, the travel time of the groundwater flow for circular and strip lenses, respectively, is given by:

$$t_{\mathrm{ctc}_{(r)}} = n_e \sqrt{\frac{2}{WK}} \left[\sqrt{C_{\mathrm{ctc}}^2 - r^2} - \sqrt{C_{\mathrm{ctc}}^2 - r_i^2} - C_{\mathrm{ctc}} \ln\left(\frac{C_{\mathrm{ctc}} + \sqrt{C_{\mathrm{ctc}}^2 - r^2}}{C_{\mathrm{ctc}} + \sqrt{C_{\mathrm{ctc}}^2 - r_i^2}} \frac{r_i}{r} \right) \right] \tag{3}$$

$$t_{\mathrm{stc}_{(x)}} = n_e \sqrt{\frac{1}{WK}} \left[\sqrt{C_{\mathrm{stc}}^2 - x^2} - \sqrt{C_{\mathrm{stc}}^2 - x_i^2} - C_{\mathrm{stc}} \ln\left(\frac{C_{\mathrm{stc}} + \sqrt{C_{\mathrm{stc}}^2 - x^2}}{C_{\mathrm{stc}} + \sqrt{C_{\mathrm{stc}}^2 - x_i^2}} \frac{x_i}{x} \right) \right] \tag{4}$$

where $C_{\mathrm{ctc}} = \surd(R^2 + 2Kb_R{}^2/W)$ in the case of circular lenses, and $C_{\mathrm{stc}} = \surd(L^2 + 2Kb_L{}^2/W)$ in the case of strip lenses; b is the saturated thickness of the lens, which, according to the Dupuit equation, is a function of r or x; and the subscripts ctc and stc indicate circular and strip lenses, respectively, discharging into tidal channels. For circular lenses, the problem is solved between $r_i = 0$ and $r = R$, and for longitudinal ones between $x_i = 0$ and $x = L$ (Chesnaux & Allen, 2008).

Hydrogeological parameters

The hydrogeological parameters used for the calculation of travel times were obtained from pumping tests and field measurements carried out in the area, together with previously collected information. The mean value of hydraulic conductivity, K, for the shell ridges was 1.2×10^{-3} m/s, whereas that for the sand sheets was 2.3×10^{-4} m/s. In both cases, the effective porosity, n_e, was 0.30.

There were some local variations in the values of K. The lowest values (5.7×10^{-4} m/s) were observed when the shell deposits were cemented or had a higher percentage of silt. However, when these deposits were mixed with coarse sands, the values of K were near 2.3×10^{-3} m/s. In the case of sand sheets, the local variations in the percentage of fine and coarse sands led to minimum hydraulic conductivities of 1.2×10^{-4} m/s and maxima of 3.5×10^{-4} m/s.

The mapping of geoforms allowed us to distinguish a predominance of freshwater circular lenses with radii of 50 m and strip lenses with semi-widths of 50 m. In accordance with the measurements previously performed (Carol, 2008), the most frequent saturated freshwater depth for both types of lenses was 3 m. A mean annual recharge value of 0.45 m was used (Deluchi *et al*., 2006). In periods when the annual precipitation is less than the average value, the annual recharge decreases; for instance, in 1996 it decreased to 0.25 m. In that case, a decrease in the water table was registered, the saturated thickness having been reduced to approximately 2 m. In the wettest year (i.e. 1993), the annual recharge increased to 0.80 m. This led to an increase in the saturated thickness of the aquifer which reached a value of 3.5 m.

ANALYSIS OF THE RESULTS

The values for mean hydraulic conductivity and mean recharge obtained by comparing equal flow trajectories show that freshwater-bound lenses present longer travel times than saltwater-bound lenses. These times oscillate between 18 and 25 years for the former, and between 4.4 and 14 years for the latter (Fig. 3).

Among saltwater-bound lenses, the ones with a circular morphology presented longer travel times than those with a strip morphology: values of 14, 10 and 4.4 years, respectively. A similar situation was observed in freshwater-bound lenses, with values of 25 years for the circular ones and 18 years for the strip-shaped ones. The shell ridges showed considerably shorter travel times than the rest of the freshwater lenses analysed, with a maximum value of 4.4 years.

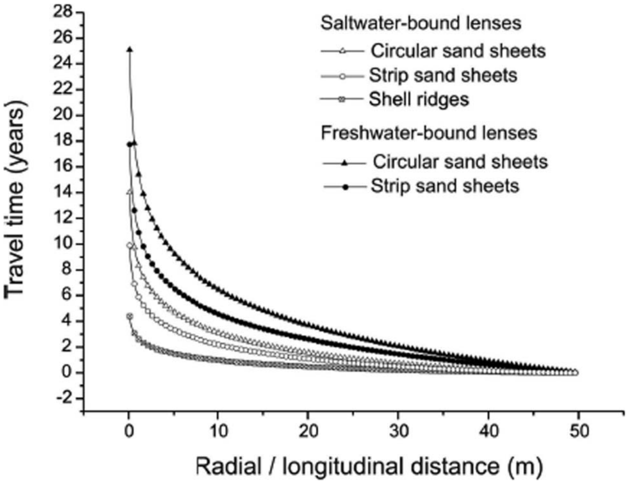

Fig. 3 Travel times estimated in relation to the distance travelled, for all the environments studied; $x = 0$ indicates the position of the lens ridge.

The local variations in hydraulic conductivity and recharge were analysed (Table 2). For the saltwater-bound lenses with a similar recharge, an increase in travel time was observed as the hydraulic conductivity decreased. When the hydraulic conductivity was the same, a decrease in travel time was observed as the recharge increased. However, the shell ridges presented travel times that were less affected by variations in hydraulic conductivity and recharge than those of the sand sheets. The travel times estimated for an annual recharge of 0.80 m (a wet year) and lower values of hydraulic conductivity were shorter than those estimated for a recharge of 0.25 m/year (a dry year) and higher values of hydraulic conductivity. In this case, a lower recharge reduced the saturated thickness of the freshwater in the lens, and, as a consequence, the hydraulic gradient decreased, which produced a reduction in the velocity of groundwater flow.

For the freshwater-bound lenses, local variations in the hydraulic conductivity of sediments did not produce significant modifications in the travel times. However, recharge variations did produce a significant difference, since the travel time for an annual recharge of 0.80 m is half of that corresponding to 0.25 m. Similar to what has been observed in previous cases, this decrease in travel time is related to a lower hydraulic gradient originating with a drawdown in the water table caused by a decrease in the recharge.

DISCUSSION

The model presented herein is a simplification of a more complex system that represents the natural conditions of groundwater flow. The simulations performed are based on ranges of variation in hydraulic conductivity, recharge and saturated thickness of freshwater derived from tests, measurements and field surveys, considering both the hydraulic and meteorological heterogeneities of the environment.

The recharge and saturated thickness values have proved to be the most relevant variables for the estimation of travel time in freshwater-bound lenses, the assessment of hydraulic conductivity being less influential. In saltwater-bound lenses, however, the variations in hydraulic conductivity are more significant.

Regardless of the simplifications and assumptions of the model, the results obtained were tested qualitatively on the basis of current groundwater characteristics

Table 2 Travel times (years) calculated for a 50-m radius or semi-width for variable hydraulic conductivity, *K* (m/s) and variable recharge, *W* (m/year).

W and T_{fw}	Saltwater-bound lenses									Freshwater-bound lenses					
	Shell ridges			Strip sand sheets			Circular sand sheets			Strip sand sheets			Circular sand sheets		
	K_{SR1}	K_{SR2}	K_{SR3}	K_{SS1}	K_{SS2}	K_{SS3}	K_{SS1}	K_{SS2}	K_{SS3}	K_{SS1}	K_{SS2}	K_{SS3}	K_{SS1}	K_{SS2}	K_{SS3}
0.25 m/year and 2 m	5.3	7.5	10.7	13.8	17.1	23.9	15.0	18.5	26.2	21.1	21.2	21.6	29.8	30.0	30.6
0.45 m/year and 3 m	4.0	4.4	8.0	10.3	10.0	17.8	11.2	14.0	19.5	17.4	17.9	17.6	24.6	24.8	24.9
0.80 m/year and 3.5 m	3.0	4.2	6.1	7.7	7.4	13.4	8.4	10.3	14.6	11.4	11.4	11.5	16.1	16.2	16.3

T_{fw}: thickness (m) of the freshwater lens or saturated thickness.
$K_{SR1} = 2.3 \times 10^{-3}$ m/s; $K_{SR2} = 1.2 \times 10^{-3}$ m/s; $K_{SR3} = 5.7 \times 10^{-4}$ m/s; $K_{SS1} = 3.5 \times 10^{-4}$ m/s; $K_{SS2} = 2.3 \times 10^{-4}$ m/s; and $K_{SS3} = 1.2 \times 10^{-4}$ m/s.

and environmental conditions. Both the variations in the water table and the evolution of nitrate content may be regarded as qualitative evidence for the verification of the model. The travel time of freshwater lenses is reflected in the dry seasons, or through the deterioration of the chemical quality due to the fast migration of the contaminant plumes.

The results indicate relatively short travel times, ranging between 3.0 and 30.6 years. In natural conditions, the travel time of groundwater is related to the stored volume and the recharge in freshwater lenses. Short travel times indicate that the stored volume (freshwater reserves) in the lenses needs constant recharge to avoid depletion due to discharge to the coastal plain or tidal channels. They are also indicators that the freshwater reserves in the lenses are replenished within a short period of time. A recharge deficit with respect to discharge (dry period) will be apparent in a lowering of the water table. Even though the existing data are limited, the variations in the water tables registered indirectly are indicators of the relationship between the volumes of water recharged and discharged by the lenses. For instance, 2007 was a wet year (with an annual rainfall of 1022 mm), in which there were no meaningful variations in the water tables. In contrast, in the dry year 2008 (annual rainfall of 664 mm), a mean lowering of 1.5 m took place in the saltwater-bound lenses of the unexploited shell ridges with a semi-width of 60 m. In the same years, in the saltwater-bound lenses of the circular sand sheets with a 50-m radius, a lowering of 1.1 m was registered**,** whereas in a circular freshwater-bound lens with a 50-m radius, it was 0.8 m.

These values indicate a short travel time and the need for adequate management of the available freshwater reserves, particularly in view of the fact that substantial volumes of water are used in mining. Exploitation systems with Ranney wells, or well points with low flow, are necessary to prevent a rapid decrease in the reserves, especially in the strip-shaped saltwater-bound lenses.

Traditionally, cattle farming is of the extensive type, although recently there has been a growing tendency towards the setting-up of feedlots with the aim of solving the problem of the lack of pastures. This type of operation is always set up in the highest topographic areas (shell ridges and sand sheets), and constitutes a source of nitrate contamination (Howarth *et al*., 2002). The evaluation of nitrate levels in groundwater indicates that the natural concentration in the lenses is below 5 mg/L, with values of 1 mg/L frequent.

Associated with a saltwater-bound lens located on a shell ridge with a semi-width of 70 m and a saturated thickness of 3.5 m, there is a feedlot of 10^4 m^2, which has been in operation for approximately 10 years. The evaluation of nitrate levels in a transect perpendicular to the ridge indicates concentrations of 18.4 mg/L in the shell ridge, 11.5 mg/L in the adjacent coastal plain and 0.7 mg/L in the coastal plain 100 m from the ridge. These data reveal the propagation of a contaminant plume in a period of less than 10 years. The permanent settlement of feedlots is a constant source of nitrate influx into the groundwater flow, which in its migration may affect the water quality of the whole lens. If cattle farming on feedlots were applied exclusively when the limited growth of pastures made these unsuitable for extensive cattle farming, the source of contamination would act temporarily and – given the short duration of the travel time – the lenses would be able to recover the quality of the water as a result of the migration of the contaminant plume towards the coastal plain.

The effects of climate change that may affect travel times in freshwater lenses are associated with a sea-level rise and the variations in the recharge of the subsurface system (precipitation – evapotranspiration).

Due to the low altitude of the coastal plain, a sea-level rise implies the flooding of the plain and tidal channels, with the ensuing advance of the coastline towards the continent. As sand sheets and shell ridges are more topographically elevated geoforms, they would form small islands discharging the subsurface flow towards the flooded plain area. Under these conditions, the travel time will be modified and the magnitude of such a change will depend on the salinity of the water produced by the flooding (discharge into saltwater or freshwater) and on the importance of the sea-level rise, which may affect the position of the discharge point and the thickness of the freshwater lens. Regarding the variations in the recharge, a reduction in rainfall will produce a lowering in the water table and, consequently, an increase in the travel time as a result of the decrease in the hydraulic gradient. In the case of an increase in the recharge, the process would be the inverse – an increase in water table levels and a reduction of the travel time due to the increased hydraulic gradient.

CONCLUSIONS

The factors that influence the groundwater travel time of the freshwater lenses along Samborombón Bay are hydraulic conductivity, recharge, morphology and discharge to surface freshwater or to saline groundwater.

The analytical solution of the model by Chesnaux & Allen (2008) for the estimation of travel time in freshwater lenses in oceanic islands can be adapted to suit the real conditions identified in freshwater lenses located in shell ridges and sand sheets discharging to a coastal plain (saltwater) or tidal channels (freshwater). Qualitative field observations, although limited, confirm that the short travel times estimated are coherent with the hydrological behaviour of the freshwater lenses. By means of gathering more detailed information – associated with an increase in the number of wells, records of the variations in the water tables and the adjustment of the hydrological balance, among others – a more precise verification of the model will be possible.

A local increase in the hydraulic conductivity of the sediments leads to a decrease in the travel time. This feature is more commonly observed in saltwater-bound lenses. The higher hydraulic conductivity of the shell ridges yields shorter travel times (between 3.0 and 10.7 years) than those obtained for the sand sheets (between 7.4 and 30.6 years). When the hydraulic conductivity is similar, there is a decrease in the travel time as the recharge increases. When the discharge type (freshwater- or saltwater-bound) is the same, the circular lenses present longer travel times than the strip-shaped ones. The sand sheets with freshwater-bound lenses have longer travel times than the saltwater-bound lenses.

Since the freshwater lenses are the only source of potable water in the region, the estimation of travel time is a useful tool in the assessment and management of the limited freshwater reserves that exist in Samborombón Bay. These reserves may be affected by excessive exploitation, contamination, or changes in the recharge conditions. In turn, travel time serves a fundamental role in the relationship between the volume of exploitation and the variation in groundwater reserves, as well as in the possibilities of remediation in case of chemical degradation.

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