Determination of heterogeneities in the hydraulic properties of a phreatic aquifer from tidal level fluctuations: a case in Argentina

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Abstract A well-known analytical solution of Jacob (1950) for groundwater flow due to tidal-wave propagation, together with field measurements along a complete tidal cycle and geological data, were used to evaluate the heterogeneities in the hydraulic properties of a phreatic aquifer located next to the River Ajo in the coastal plain environment of the southern sector of the Samborombon Bay wetland, Argentina. From the analysis of water-table fluctuations in a set of monitoring wells located along a riverbank-normal transect, it was possible to quantify the piecewise spatial variations of the hydraulic diffusivity of the phreatic aquifer. The results show the strong lateral variations of the sedimentary environment due to the influence of the different transport and deposition agents that characterize the coastal plain. The known thickness of the phreatic aquifer and the estimated range of the specific yield allowed the hydraulic conductivity to be identified as the most influential factor. [Jacob CE (1950) Flow of ground water. In: Rouse H (ed) Engineering Hydraulics. Wiley, New York]

Received: 25 April 2008 / Accepted: 29 April 2009
Published online: 20 May 2009

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Keywords Coastal aquifers · Tidal effects · Hydraulic properties · Samborombon Bay · Argentina

Introduction

Coastal zones under the influence of tide develop complex natural hydrological dynamics. Tidal fluctuations periodically modify the relationship between surface waters and groundwater. Tidal-wave propagation in coastal aquifers affects groundwater flux direction and the relative location of recharge and discharge zones. Changes in the chemical quality of groundwater can also be observed. The social and economic development of coastal zones, together with the preservation of the environment, requires a detailed knowledge of the hydrological conditions of the area to evaluate and predict its behavior in the light of changes due to human activities.

Tidal-wave propagation in coastal aquifers for different hydrological conditions has been investigated by different authors. A well-known one-dimensional differential equation (Jacob 1950), cited also in classical hydrological texts (e.g. Todd and Mays 2005), describes the influence of the tide in confined and unconfined aquifers in contact with an idealized vertical beach face. Later developments considered the coastal slope (Nielsen 1990, Teo 2003, Teo et al. 2003, Jeng et al. 2005), the effect of waves (Turner et al. 1996), two-dimensional flux (Sun 1997, Li et al. 2000), multi-layered aquifers (Li and Jiao 2002, Jeng et al. 2002), leaky confined aquifers (Chuang and Yeh 2007), and the effect of an aquifer's submarine outlet being covered by a thin layer of sediment of properties different to those of the aquifer (Li et al. 2007, Xia et al. 2007, Ren et al. 2008). Several models have also been used to describe tidal-wave propagation and its effects on aquifers graphically (Ateie-Ashtiami et al. 1999, Mao et al 2006, Vandenbohede and Lebbe 2007). In all these cases, the hydraulic conditions of the aquifer are supposed to be homogeneous. For heterogeneous conditions, Li and Jiao (2003) analyze a case with a vertical variability due to a stratified column of sediments with different properties. Trefry (1999) presents algebraic solutions for tidal propagation in spatially heterogeneous one-dimensional aquifers.

The analysis of tidal-wave propagation has been applied to homogeneous aquifers for calculating hydraulic properties such as transmissivity (Ferris 1951, Erskine 1991), mean hydraulic gradient (Serfes 1991), and

 DOI 10.1007/s10040-009-0478-3

hydraulic diffusivity and specific yield (Zhou 2007, Kolja and El-Kadi 2008). In the latter case, the hydraulic diffusivity of a confined aquifer is determined from estimations of the tidal efficiency and time lag of groundwater fluctuations relative to the beach face for a set of wells arranged without any preferential distribution. The specific yield is calculated assuming a homogeneous behavior alongshore and a constant hydraulic conductivity and thickness of the aquifer.

Sedimentary environments associated with coastal plains are often characterized by strong lateral grain-size variability within short distances. This modifies the hydraulic properties of the aquifer. Due to this strong grain-size variability, the use of pumping tests for the determination of the hydraulic properties (Fetter 1994) would seem to give homogeneous results that would not reflect satisfactorily the characteristics of the sedimentary environment. The objective of this work is to use an analytical solution for groundwater flow due to tidal-wave propagation, together with field data to evaluate the heterogeneities of a phreatic aquifer associated with an estuarine environment from variations in the hydraulic diffusivity.

Study area

The study area is located in the southern sector of the Samborombon Bay wetland in the Province of Buenos Aires, Argentina (Fig. 1). The Samborombon Bay is a remarkable coastal feature of the most prominent estuarine environment in Argentina, the Rio de la Plata, a water body of about 35,000 km^2 shared by Argentina and Uruguay. Due to the influence of the Atlantic Ocean, the Samborombon Bay waters become progressively more brackish southwards. As reported by the Servicio de Hidrografía Naval [Naval Hydrographic Service] (SHN), tides are mixed, predominantly semidiurnal, with tidal ranges less than 2 m (SHN 2008). Because the principal semidiurnal lunar tide (M_2) has been shown to contain more than 70% of the total energy of the astronomical tide in the Rio de la Plata (SHN 2001), the period of this tidal constituent (12.42 h) was used in subsequent analytical calculations.

In its trajectory towards the Samborombon Bay, the tidal wave coming from the southern Atlantic enters the River Ajo and the numerous tidal channels distributed all over the area (Fig. 1). The main course of the River Ajo has a variable width, ranging from 100 m at its head to 500 m at its outlet in the Samborombon Bay, and a depth between 3 m near its outlet and 6 m at about 3 km upstream. The riverbanks are semi-cliffy, with heights between 0.5 and 1.5 m, and flanked by salt marshes, rushes and brackish ponds with numerous crabs.

The study area is a coastal plain environment in which a phreatic aquifer develops in accumulated Holocene sediments (Carol et al. 2008). At a regional scale, these sediments are composed of alternating silts, silty clays, and sands of 3 to 5 m thick (Parker 1979). Over the whole coastal plain, there are isolated sand sheets of aeolian origin, with a small area and thicknesses less than 3 m. The processes of sediment transport and deposition in the coastal zone of the Samborombon Bay have highly changing geological dynamics due to several factors. Storm episodes dominate sediment transport and deposition between the Rio de la Plata, the River Ajo and the tidal channels. Heavy rains carry sediments from the highest to the lowest topographic areas, whereas wind accumulates sediments in sand sheets. The prevalence of one or the other of the above agents determines the type of

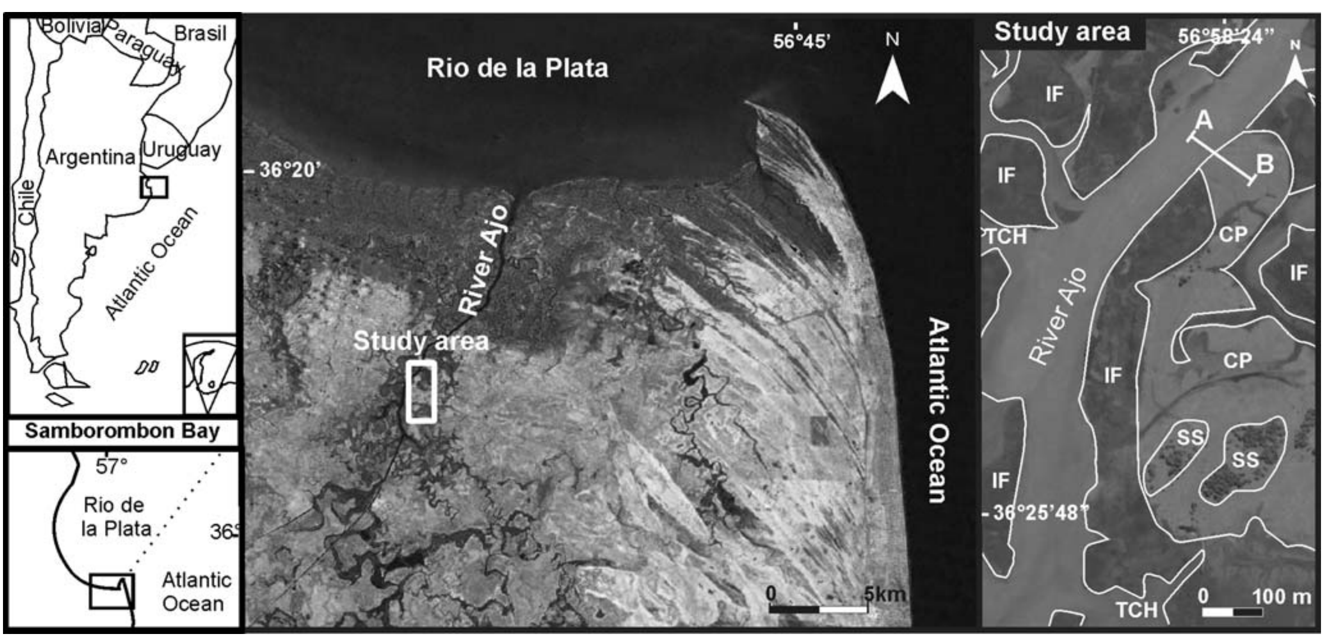

Fig. 1 Location map and the geomorphologic characteristics of the study area with the location of the AB transect. *TCH* tidal channel; *IF* intertidal flat; *CP* coastal plain; *SS* sand sheet

 DOI 10.1007/s10040-009-0478-3

sedimentation. This is the reason why sediment deposits have a marked spatial sedimentary variability.

A portion of the phreatic aquifer within the study area was chosen for field study. This portion includes the AB transect and develops on the shore of the River Ajo, where depositional sediments associated with fluvial and coastal plain environments predominate (Fig. 1). During a complete tidal cycle, hourly water levels were simultaneously measured on the river surface and within five monitoring wells located along the riverbank-normal AB transect at 2, 5, 10, 15 and 20 m from the riverbank (Fig. 2). The wells were drilled with a hand auger up to a depth of 2 m. A slotted PVC screen was placed inside every well and backfilled with gravel. Every point along the AB transect was geometrically leveled with a Pentax Automatic Model AL-240 level, with an accuracy of ±2 mm.

Materials and methods

For a simple harmonic tide of amplitude (half-range) h_0 and period t_0, the analytical solution of Jacob (1950) for one-dimensional groundwater flow due to tidal-wave propagation within an unconfined aquifer is

$$h = h_0 e^{-x\sqrt{\pi S/t_0 T}} \sin\left(\frac{2\pi t}{t_0} - x\sqrt{\pi S/t_0 T}\right) \tag{1}$$

where h is the amplitude of the water-table oscillation with respect to the mean level, x is (in this case) the distance from the bank of the River Ajo (where tide is present), S the specific yield, T the transmissivity, and t the time.

The amplitude of the water-table oscillation at a distance x from the riverbank, h_x, is thus

$$h_x = h_0\, e^{-x\sqrt{\pi S/t_0 T}} \tag{2}$$

If the amplitude h_0 of the tide, and the amplitude of the water-table fluctuation h_x at a distance x from the riverbank are known from field measurements (Fig. 2), it is possible to calculate the diffusivity D of the aquifer by

$$D = \frac{T}{S} = \frac{KZ}{S} = \frac{\pi x^2}{t_0\left[\ln\left(\frac{h_0}{h_x}\right)\right]^2} \tag{3}$$

where K and Z are the hydraulic conductivity and the thickness of the aquifer, respectively.

Although Jacob's (1950) solution is based on the assumption of a homogeneous aquifer, it can be applied in this case, if it is assumed that the aquifer is piecewise homogeneous between adjacent wells. Jacob's solution would thus be piecewise valid for the aquifer between adjacent wells. If the piecewise estimated hydraulic diffusivity does not change much, the aquifer may be classified as nearly homogeneous; however, if, on the contrary, the variations in the hydraulic diffusivity are significant, the aquifer is characterized by its heterogeneity. The degree of this heterogeneity depends on both the specific yield and the transmissivity, the latter associated with changes in the hydraulic conductivity and the thickness of the aquifer. If the degree of variation of these properties is known, at least approximately, it would be possible to define which one mostly determines the heterogeneity of the aquifer.

A more involved, closed-form solution for tide-induced water level fluctuations in an unconfined aquifer with a vertical beach has been derived by Teo (2003). This solution has the form of a second-order perturbation expansion,

$$\begin{aligned} H = {} & \left(1 + \alpha H_{01} + \alpha^2 H_{02} + \alpha^3 H_{03}\right) \\ & + \varepsilon^2\left(\alpha H_{21} + \alpha^2 H_{22}\right) \end{aligned} \tag{4}$$

where $H = h/D$ is the dimensionless water level fluctuation, D is the thickness of the aquifer, $\varepsilon = (D\, n_e\, \omega/2\, K)^{1/2}$ is the shallow water parameter, n_e is the soil porosity, ω is the angular frequency of tide, K is the hydraulic conductivity, $\alpha = A/D$ is the amplitude parameter, and A is the amplitude of the tide. The expressions

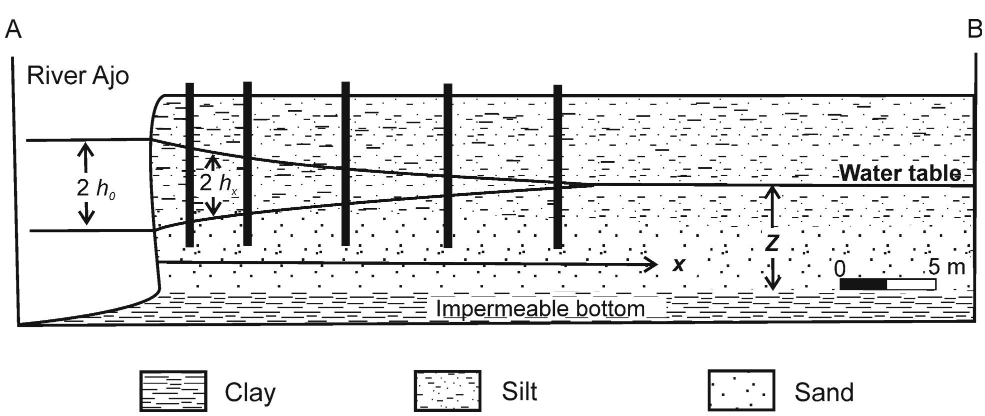

Fig. 2 Sedimentary cross section and location of monitoring wells (*vertical black bars*) along the AB transect. Z thickness of the aquifer; $2h_0$ tidal range at the River Ajo; $2\ h_x$ range of water-table fluctuations at a distance x from the riverbank

DOI 10.1007/s10040-009-0478-3

for H_{ij} are given in Teo (2003). In any case, the departure of the observed values from those estimated assuming homogeneous conditions throughout the aquifer is an indication of its heterogeneity.

Results and discussion

Successive field measurements show that the water-table height changes as the tidal-wave propagates along the River Ajo. Groundwater flux reverses direction according to the height of the water table with respect to the river surface. At low water, groundwater flows from the aquifer to the River Ajo, whereas at high water the direction is the opposite.

The piecewise hydraulic diffusivity of the aquifer was estimated with the results from field measurements performed along the AB transect (Figs. 1 and 2) on 27 November 2006. On that occasion, the maximum tidal range (2 h_0) at the River Ajo was 1.47 m. The analysis was based upon the measurement of the difference between the maximum and minimum water-table levels (oscillation range, 2 h_x) at each monitoring well over a complete tidal cycle (12.42 h). The largest oscillation range, 0.19 m, was measured in the well at 2 m from the riverbank. Water-table oscillation ranges decreased landwards: 0.13 m at 5 m from the bank, 0.10 m at 10 m, 0.09 m at 15 m and 0.07 m at 20 m (Fig. 3). Table 1 illustrates the piecewise hydraulic diffusivity of the aquifer calculated with Eq. (3). It can be seen that the hydraulic diffusivity increases landwards. This reveals the heterogeneity of the aquifer, which can be due to changes in the transmissivity and/or the specific yield. Although these properties cannot be estimated simultaneously from measurements of the tidal level fluctuations, it is possible to use the geological knowledge of the study area to see which factors control the changes in the hydraulic diffusivity, and to what extent.

Table 1 Calculated hydraulic diffusivity D as a function of the distance x from the riverbank and the measured range (2 h_x) of water-table fluctuations for the tidal range (2 h_0) of 1.47 m of 27 November 2006

x (m)	$2h_x$ (m)	D (m^2/day)
2	0.19	5.79
5	0.13	379.02
10	0.10	2,202.68
15	0.09	13,658.55
20	0.07	2,400.63

According to Eq. (2), the amplitude h_x of the water-table oscillations in a homogeneous aquifer decays exponentially with the distance from its associated outcrop. This is clearly seen from Fig. 4 in which water-table fluctuation ranges from Eq. (2) are plotted semi-logarithmically against the distance from the riverbank, assuming that the hydraulic properties of the whole aquifer are equal to those from the well nearest to the riverbank. A similar behavior is observed for the measured values, but with a less decreasing rate for distances greater than 2 m from the riverbank. This departure from the analytical solution reveals a change in the hydraulic conditions of the aquifer within short distances near the riverbank. Measured water-table oscillations appear to have an asymptotic tendency against the distance from the riverbank. This can be attributed to the fact that the lithology of the same layer changes laterally increasing its sand proportion.

A better agreement arises from the comparison of measured ranges of water-table oscillations to those

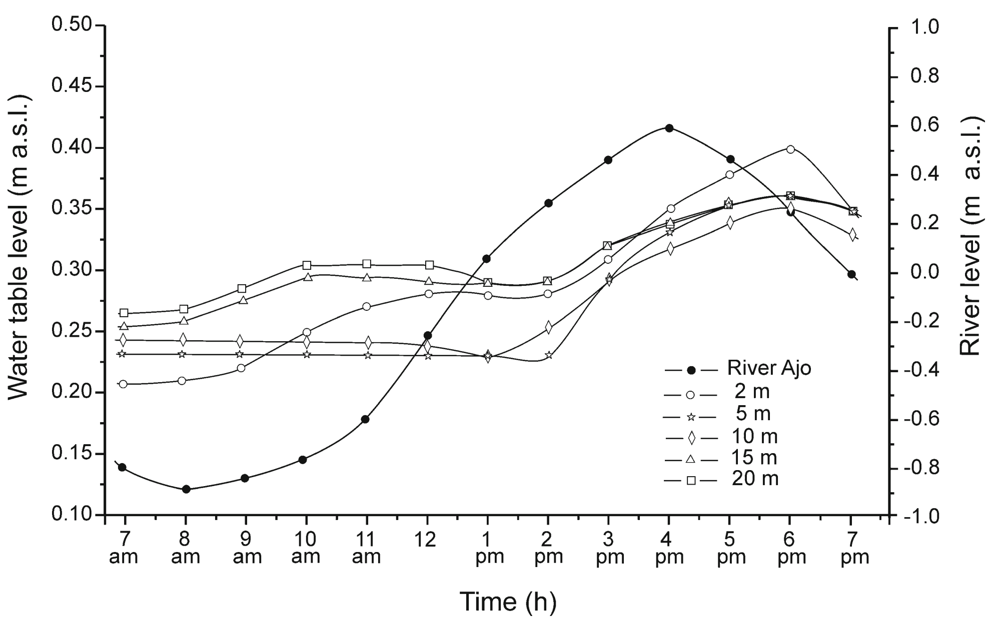

Fig. 3 Tide and water-table fluctuations as a function of time at the monitoring wells (at 2, 5, 10, 15 and 20 m from the riverbank) during a complete tidal cycle on 27 November 2006

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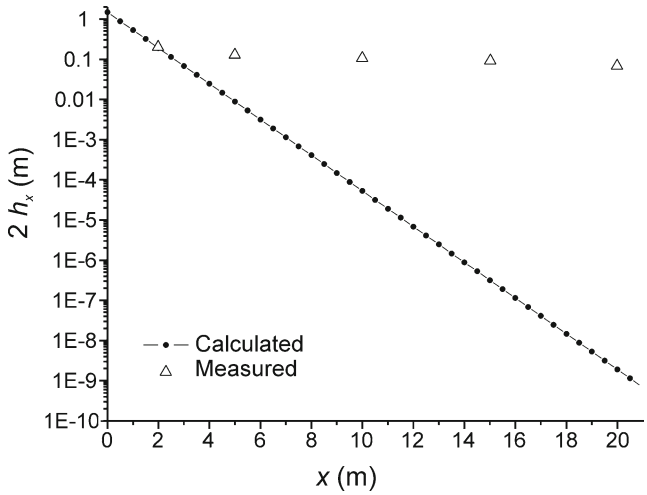

Fig. 4 Comparison between the range (2 h_x) of water-table fluctuations calculated from Jacob's solution (Jacob 1950) assuming homogeneous conditions and those from field measurements, as a function of the distance x from the riverbank

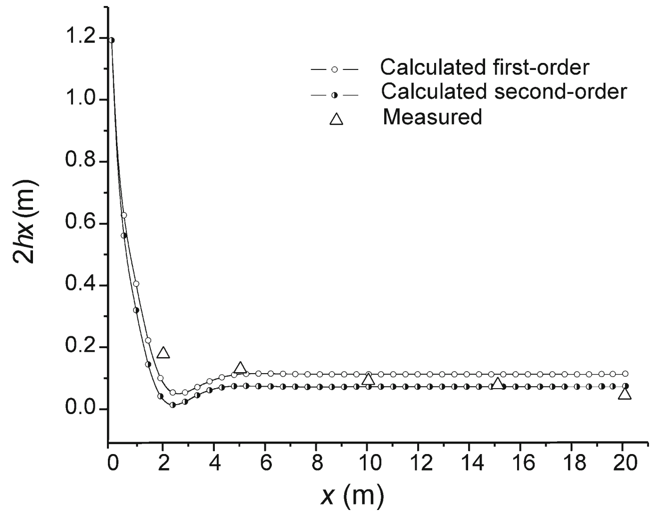

Fig. 5 Comparison between the range (2 h_x) of water-table fluctuations calculated from Teo's solution (2003) assuming homogeneous conditions and those from field measurements, as a function of the distance x from the riverbank

calculated with the first and second order analytical solutions given by Teo (2003; Eq. 4; Fig. 5). As in Fig. 4, the hydraulic properties of the whole aquifer are assumed to be equal to those from the well nearest to the riverbank.

From Eq. (3), an increasing hydraulic diffusivity could be due to an increase in the hydraulic conductivity and/or the thickness of the aquifer, or to a decrease in the specific yield. Although with a changing sedimentary composition, the thickness of the study aquifer within the sedimentary layer is 3 m. Besides, the profiles of the monitoring wells have shown that the thickness of the sedimentary layer remains almost constant along the 20 m studied transect, so it may be disregarded as a contributing factor to the increasing diffusivity. On the other hand, the specific yield for unconfined aquifers ranges between 0.01 and 0.3 (Fetter 1994). According to Todd and Mays (2005), the values of the specific yield depend on grain size, shape and distribution of pores, compaction of the stratum and time of drainage. Taking into account all these factors, Carol (2008) has determined that the specific yield of the study aquifer can vary between 0.05 and 0.1. This range of variation cannot be the main cause of the observed increment in the hydraulic diffusivity. Therefore, the variations of the hydraulic diffusivity must be mostly attributed to an increase in the hydraulic conductivity of the aquifer. Table 2 shows a somewhat idealized situation in which the hydraulic conductivity is calculated from Eq. (3), assuming two different (but constant) specific yields along the AB transect. The increment in the hydraulic conductivity is clearly seen. These estimated values of the hydraulic conductivity are consistent with those given in tables for the lithology observed in the monitoring wells and depicted in Fig. 2 (see, for example, Castany 1963). Only the value corresponding to the well at 15 m from the riverbank is somewhat greater than those expected for sandy textures. On the whole, the estimated values of the hydraulic conductivity are consistent with the log information obtained during the drilling.

The inflow of water into the aquifer driven by the tidal-wave propagation, and the consequent rise of the water table, will thus be governed by the hydraulic conductivity of the aquifer. The more sandy layers at the bottom of the unconfined aquifer have a greater hydraulic conductivity than the surface layers, which are mostly of silty sandy to silty clayey character (Fig. 2). Therefore, the bottom sandy layers favor the tidal wave to enter the aquifer.

The rise of the water table above the bottom sandy sediments depends on the grain-size variations of the upper layers, as defined by their relative proportions of sand, silt and clay. The increasing hydraulic conductivity landwards would be related to an increment of the sand content in the uppermost sediments therein. Thus, the attenuation of the water-table fluctuations is

Table 2 Hydraulic conductivities calculated with Eq. (3) for two different values of the specific yield (S) and the same thickness (Z) of the aquifer

x (m)	D (m^2/day)	K (m/day)(for S=0.05 and Z=3 m)	K (m/day)(for S=0.1 and Z=3 m)
2	5.79	0.10	0.19
5	379.02	6.32	12.63
10	2,202.68	36.71	73.42
15	13,658.55	227.64	455.28
20	2,400.63	40.01	80.02

 DOI 10.1007/s10040-009-0478-3

greater at the banks of the River Ajo, where the hydraulic conductivity is lower because of a larger content of silts in the upper layers of the aquifer, than in the landward sectors, where the hydraulic conductivity is larger because of a larger content of sand in the upper layers of the aquifer.

Conclusions

The sedimentary heterogeneities and the hydraulic diffusivity of a typical unconfined aquifer in the southern sector of the Samborombon Bay wetland, Argentina, were determined through an analysis of the differences between calculated and measured water-table fluctuations due to tides. This helped to improve the evaluation of the aquifer dynamics in an environment characterized by the presence of sediments with lateral strong variability within short distances. However, only the hydraulic diffusivity can be quantified with this method. The transmissivity, the hydraulic conductivity and the specific yield can be qualitatively evaluated only if the geological characteristics of the aquifer are known from beforehand. In spite of this, the analysis of water-table fluctuations due to an incoming tidal wave is useful to verify the geological features of tidal zones lacking enough information. Every method leading to a better understanding of the hydraulic properties in this particular wetland is a valuable tool because freshwater resources are scarce and restricted to small thickness lenses. Any urban development must consider the assessment of these resources to satisfy the need for freshwater supply and a suitable sewage disposal system.

Acknowledgements The authors are very grateful to the Argentine National Agency for Scientific and Technological Promotion (PICT 38256/05) and National Council on Scientific and Technical Research (PIP 5632/05) of Argentina for funding this research.

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