

# Relationship between precipitation and water-table fluctuation in a coastal dune aquifer: northeastern coast of the Buenos Aires province, Argentina

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**Abstract** The water-table fluctuation (WTF) method is one of the most widely used means to estimate aquifer recharge. In the northeastern coast of the Buenos Aires province, Argentina, the geomorphological and climatic characteristics, as well as the presence of a shallow, homogeneous unconfined aquifer, make it possible to apply this methodology. The relationship between water-table fluctuations and precipitation in a humid climate, considering its seasonal variations, is assessed. Water tables were measured monthly between February 2008 and September 2010 in a monitoring network; rainfall data were analysed. The water table rises when the accumulated precipitation between measurements is more than 53mm/month in the dry season and more than 97mm/month in the rainy season. The index, relating water-table fluctuations and precipitation occurring between measurements, shows that values below 0 suggest no increase in the water reserves, whereas higher values entail an increase. In the study area, where there is a lack of historical data, finding out the relationship between water-table fluctuations and precipitation will constitute a tool for groundwater use and management, and set up an early warning system for dry periods. It could also be extrapolated to other regions with similar hydrological conditions lacking in data.

**Keywords** Groundwater recharge/water budget · Coastal aquifers · Groundwater management · Water-resources conservation · Argentina

## Introduction

Water-table fluctuation analysis is a conventional method to estimate recharge and water storage in an unconfined aquifer (Castany 1971; Todd 1958; Custodio and Llamas 1996). Its possible applications depend on data availability, hydrogeological conditions and scale of work. Recharge values obtained on the basis of water-table fluctuations are frequently compared to other methods such as chloride mass balance, Darcy flow models, radiocarbon dating and mathematical modelling. Even though the current trend is towards the use of mathematical models (Chiew et al. 1992; Rai and Singh 1995; Rai and Manglik 1999; Bekesi and McConchie 1999; Manglik et al. 2004), water-table fluctuation data are necessary for their validation.

Healy and Cook (2002) and Healy (2010) undertook a revision of recharge estimation methods based on their association with water-table fluctuations and specific yield, which becomes particularly important when examining the response to individual storms in regions with shallow aquifers (Scanlon et al. 2002). The analysis of the fluctuations in the water table makes it possible to identify, on the basis of extensive time series data, the variations in groundwater recharge resulting from changes in land use or climate change (de Vries and Simmers 2002). Park and Parker (2008) and Cuthbert (2010) have developed analytical solutions which aim at improving the water-table fluctuation method (WTF method), by taking into consideration the different variables intervening in the recharge phenomenon. Even though the uncertainty in the estimates is usually related to the limited precision of the evaluation of specific yield, the regrettable fact that groundwater recharge is only rarely well defined must be taken into consideration (Voss 2011).

Among the advantages of the WTF method are its simplicity and its independence of the water displacement mechanism in the unsaturated zone, as well as the possibility of integrating the result areally, and not only

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as isolated data. Sibanda et al. (2009) state that for the semi-arid Nyamandhlovu area, Zimbabwe, this method was not effective to estimate areal recharge, although it could be used to determine local recharge, which varies between 2 and 50 mm/year due to the variations in the specific yield. Risser et al. (2009) highlight the importance of recharge estimation based on this method when applied to the mid-eastern area of Pennsylvania, USA, as other methods applied (i.e., lysimeter, hydrological budget and modelling) only provide an estimate of the potential recharge (i.e., the percolation below the root zone that reaches the aquifer) or net recharge (i.e., recharge minus evapotranspiration or discharge to a deeper aquifer).

Missstear et al. (2009) came across a limitation to the application of this method in the estimation of recharge for the Curragh aquifer in Ireland, where they also used the hydrological budget, methods involving soil moisture budgeting and numerical modelling due to the complexity of the aquifer and the variability of the specific yield. Abdalla and Al-Abri (2010) used the WTF method to establish the preferential recharge areas, in order to calculate the recharge induced by tropical storms and cyclones in the Sultanate of Oman.

In general, different contributions on recharge estimation have shown a strong correlation with precipitation (Bradford et al. 2002; Döll and Fiedler 2008), establishing that more precipitation means more recharge to the aquifer. Hsu et al. (2007) determined the relationship between precipitation and recharge as the first step towards assessing the impact of climate change in the groundwater system of the Pingtung Plain in Taiwan.

In the northeastern coast of the Buenos Aires province, Argentina, freshwater reserves are limited and restricted to the groundwater of the coastal sand-dune barrier, whose regime strongly depends on the weather conditions (Kruse and Carretero 2010). The only natural source of recharge is the infiltration of precipitation water surplus.

Due to the scarcity or lack of historical data on available freshwater reserves, determining the relationship between water-table fluctuations and precipitation is central in order to characterise the recharge process and, on such a basis, define a tool which could be useful in the management of groundwater exploitation.

The objective of this contribution is to evaluate the relationship between water-table fluctuations and precipitation, considering the seasonal variations. Due to the great scarcity of hydrogeological data in the region, this work does not strictly focus on the accuracy of the estimation of recharge values, but on the practical usefulness of finding out the relationship between easily measurable variables (i.e., water-table levels and precipitation) in the assessment of groundwater behaviour.

## Study area

The study area is located in the coastal region of the Atlantic Ocean in the Buenos Aires province, Argentina

(36° 22' S latitude, 56° 44' W longitude). It is a 2-km-wide coastal fringe which extends over an area of 15 km<sup>2</sup> (Fig. 1). Tides are mixed, predominantly semidiurnal, with tidal ranges of less than 2 m (SHN 2008).

The climate is humid temperate, regionally homogeneous, with an average annual rainfall on the order of 900 mm and an average temperature of 14.6 °C. The rainfall pattern shows that 65 % of the annual rainfall occurs in the rainy season (October–March), whereas 35 % occurs in the dry season (April–September) (Fig. 2). In the rainy season the highest temperatures occur, with an average maximum of 22.2 °C in January. The dry season is the coldest, with an average minimum temperature of 7.6 °C in July.

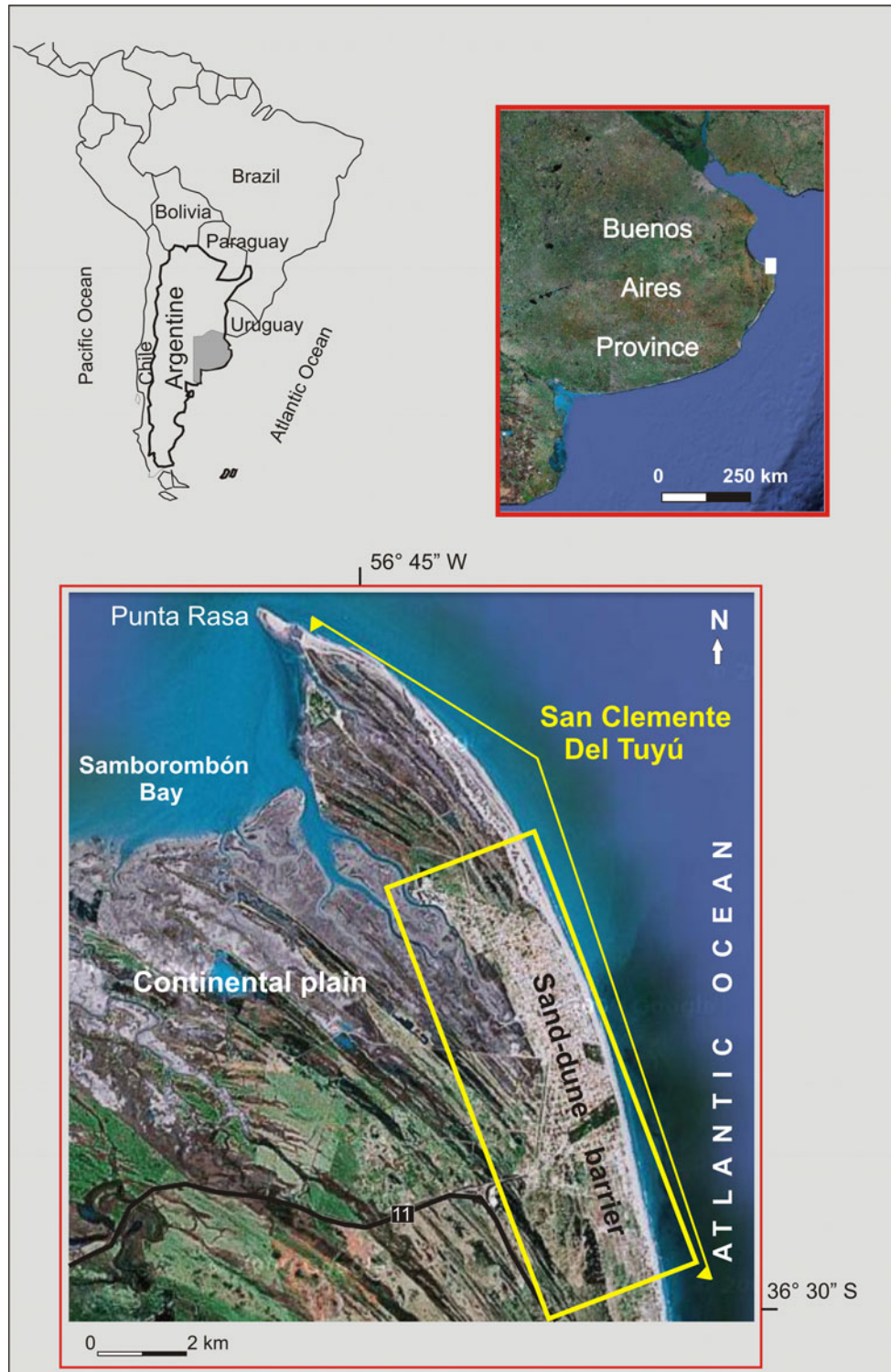
The study area comprises a sand-dune barrier and its adjacent continental plain. The sand-dune barrier extends over 180 km, uninterrupted from Punta Rasa to the south, with a width of 2–4 km. It is a constructional coast, without cliffs, with low sand dunes between 3 and 10 m above sea level (asl), composed of fine sand and scarcely covered by vegetation. The continental plain extends to the west of the sand-dune barrier, with heights below 5 m asl.

In the sand-dune barrier, the soils do not show development—they are sandy, excessively drained and unstable. Due to the characteristics of the soil and the sediment, surface runoff is not considered in the area. Following a rainfall event, the response of the water table, which lies at a shallow depth (less than 2 m), is nearly immediate (within a day; Carretero 2011).

## Materials and methods

Hydrogeological surveys and the interpretation of the geological and geomorphological aspects of the area were carried out in order to define its general characteristics. The monthly rainfall in the town of San Clemente del Tuyú was analysed; the water surplus was determined by means of water budget following Thornthwaite and Mather (1955) and the mean monthly ET<sub>0</sub> values (reference crop evapotranspiration) following the Penman-Monteith method (Allen et al. 1998), using the AGROAGUA v.5.0 software (Forte Lay et al. 1995). This software makes it possible to carry out daily water budgets and continuously monitor the soil-water storage, using the daily rainfall, daily potential evapotranspiration and soil-field-capacity variables. In the case of immature, sandy soils with sparse vegetation and an effective depth for the water budget of 0.25 m—which characterise the coastal sand-dune barrier—a field capacity of 40 mm was assigned.

The water input into the groundwater system occurs through infiltration of the surplus of the water budget. Surface runoff, as a consequence of the morphological characteristics, of the lack of a drainage network and of the high permeability of the sediments in the coastal sand-dune barrier, tends to zero. Monthly manual measurements were carried out in a monitoring network set up in



**Fig. 1** Location of the study area. The outlined area (yellow) in the map shows the area where the monitoring network (Fig. 3) is located

2007, which comprises 43 wells drilled into the phreatic aquifer (with a density of 3 wells per km<sup>2</sup>; Fig. 3). These wells are 3 m deep with slotted pipe filters, 2 inches (5.1 cm) in diameter. The data were entered into a geographic information system (GIS), and monthly groundwater flow maps were made.

The water-table fluctuations between one measurement and the following were determined for each well. Then the average of the fluctuation between the 43 wells was calculated, thus obtaining a monthly average. The decision to use a monthly average value is due to the fact that the average value is regarded as

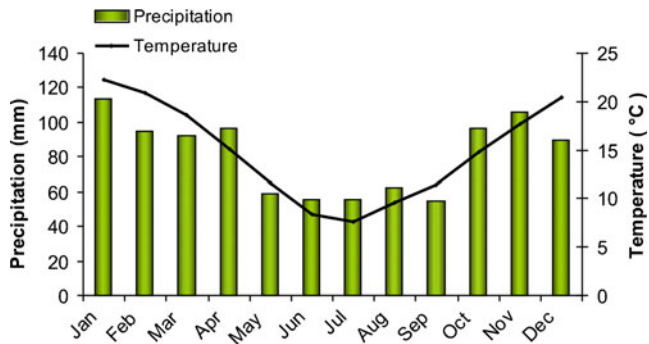


Fig. 2 Average monthly temperature and precipitation (1981–2010)

representative of the behaviour of the aquifer and that it makes data management simpler.

The population is supplied from a pumping field located to the south of the city. The two monitoring wells within the exploitation area have not been taken into consideration in order to avoid water extraction from having an influence on the analysis carried out. The cone of depression is barely discernible given the method of

areal exploitation used, as the pumping field comprises horizontal wells of the Ranney type and well-point systems (Carretero and Kruse 2010).

The experiments conducted on the basis of the recording of water tables have made it possible to verify (Carretero 2011) that the monitoring wells analysed are not affected by tidal influence. Due to the fact that the coast is microtidal (with a range of less than 2 m) and to the morphology of the sand-dune barrier, the effect of the tides can only be observed in the front beach. The average monthly water-table fluctuations were compared to the precipitation events for the same period. The fluctuations in level and the precipitation were analysed considering the rainy (October–March) and dry seasons (April–September) according to the climate variability of the area.

## Results

### Hydrogeological characteristics

A deep and a shallow hydrogeological system characterise the study area. Data on the deep system are scarce, limited

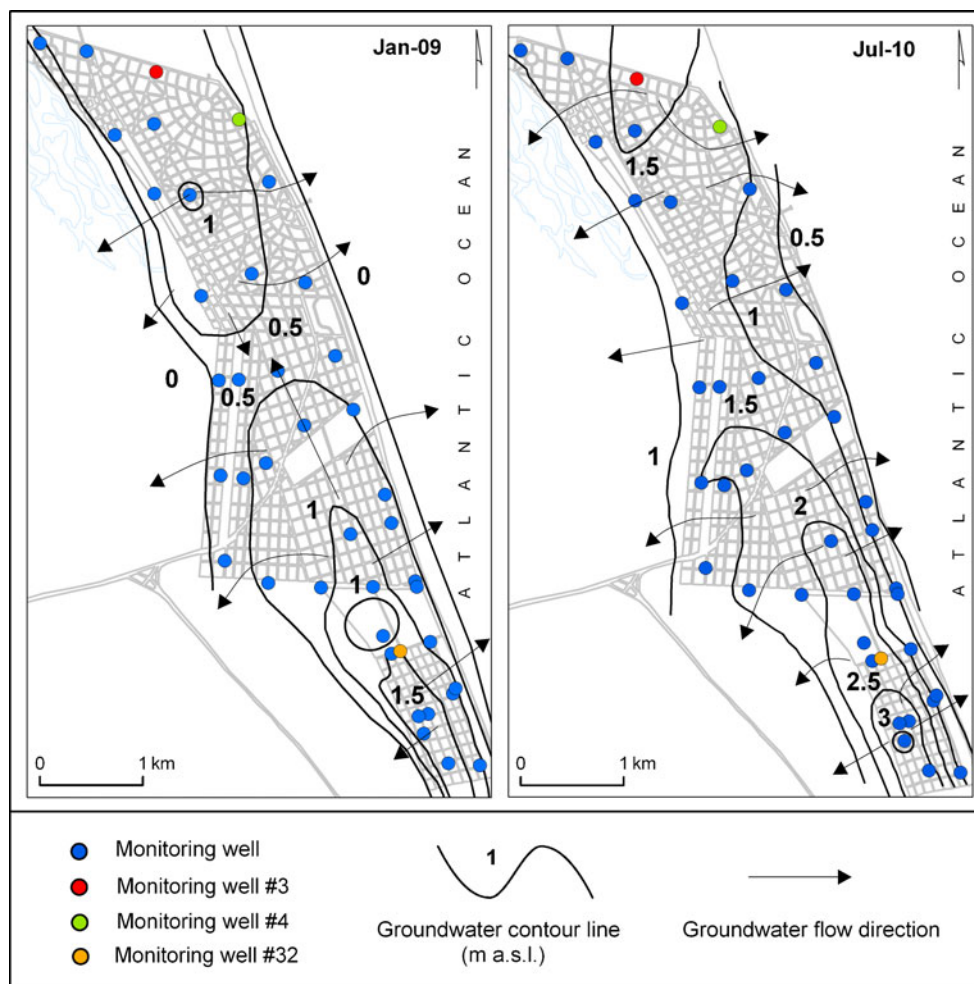


Fig. 3 Monitoring network and isophreatic maps for January 2009 and July 2010. Wells in different colours (wells 3, 4 and 32) were used for plotting hydrographs in Fig. 6

to the fact that low permeability units predominate with some sand intercalations with high-salinity water. In the shallow system, the freshwater phreatic aquifer develops in the sand-dune barrier with a thickness ranging from 4 to 10 m. From a geological viewpoint, this system coincides with Holocene shelly sand and sand (Violante and Parker 2000), overlying a clayey aquitard/aquiclude with sand lens intercalations containing high-salinity water. The shallow system is limited by two interfaces, freshwater–brackish water towards the continent, and freshwater–saltwater towards the sea (Fig. 4). In the sand-dune barrier, water is mainly a low-salinity Ca–HCO<sub>3</sub> type; whereas in the continental plain, water is Na–Cl type with high saline content (Carretero and Kruse 2009a).

### Groundwater flow

Geomorphologic features have a direct influence on groundwater dynamics and chemistry. The maximum height areas in the phreatic morphology coincide with the maximum heights in the sand dunes. Groundwater flows in two opposing directions, towards the east and the west. In general, the phreatic aquifer has a transmissivity on the order of 100 m<sup>2</sup>/day (Carretero 2011), a specific yield of 0.10 and an average hydraulic conductivity of 20 m/day (Sala et al. 1976).

In the monthly groundwater flow maps made between February 2008 and September 2010, two extreme situations were identified: one corresponding to one of the highest positions of the water table (July 2010) and the other to the deepest one (January 2009; Fig. 3). In the case of the highest water-table position, a dome in the phreatic morphology can be recognised in the southern sector, with a groundwater contour line varying between 2 and 3 m asl. Besides, an elevated area with a curve of 1.5 m asl occurs in the northern

sector. Prior to this situation (July 2010), surpluses in the water budget occurred between March and July, with values varying between 13 and 154 mm/month (Fig. 5a), associated to low temperatures and, consequently, to low potential evapotranspiration (Fig. 5b).

In the deepest position (January 2009), the water-table curves composing the dome are reduced to values between 1 and 1.5 m asl in the southern sector, whereas the 1.5 m asl curve disappears in the northern sector. The October 2008–January 2009 period is characterised by little to no surpluses (Fig. 5a), together with elevated temperatures and potential evapotranspiration (Fig. 5b).

On the basis of the monthly groundwater maps, the average hydraulic gradient was estimated as being 0.0023 towards the east and 0.0032 towards the west, with an estimated average effective velocity of 0.046 m/day towards the east and 0.064 m/day towards the west. The average depth of the water table usually fluctuates between 0.5 and 1.5 m. As regards the extreme situations mentioned, in the case of the elevated water table (July 2010), the greater depths are located in the central area of the sand-dune barrier, with depth values between 0.5 and 1 m; whereas in the case of the shallower depths, which are located towards the discharge area to the east and west, the values are less than 0.5 m. In January 2009, a further deepening of the water table was recorded. In the centre of the sand-dune barrier, the depths may be over 2 m, whereas towards the east they are less than 1.5 m, and less than 1 m towards the west.

### Relationship between water-table fluctuations and precipitation

The water-table fluctuations measured with a periodicity of approximately 30 days appear in Table 1. The average

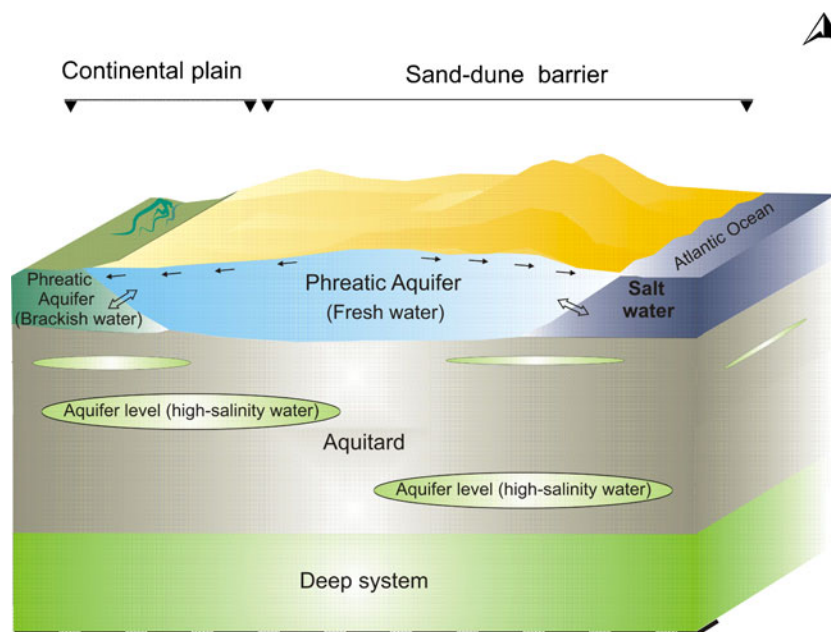
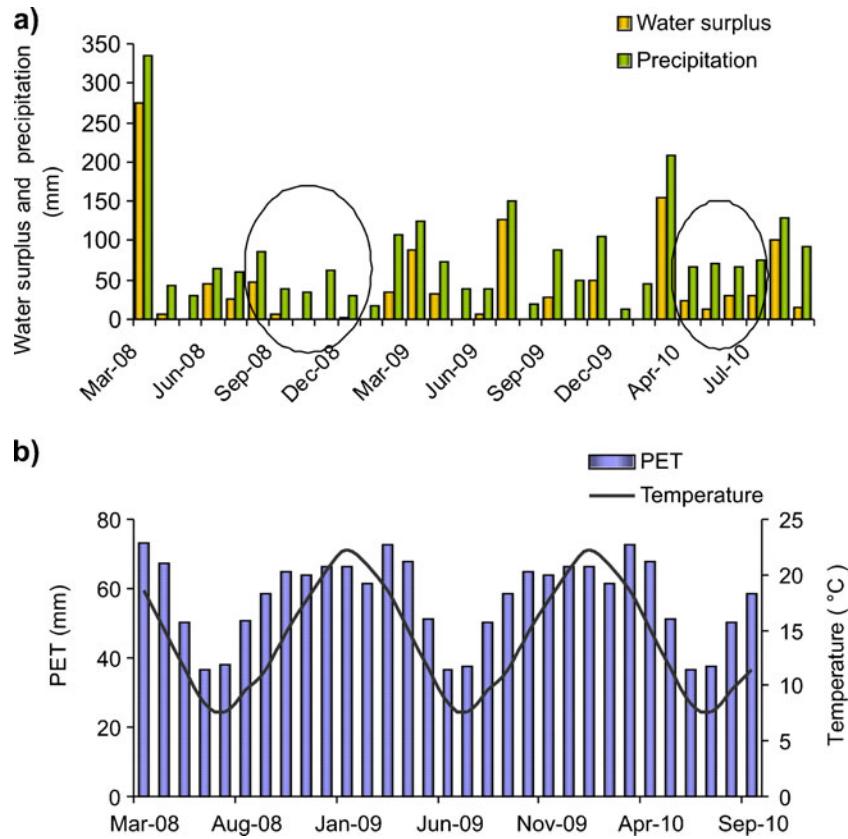


Fig. 4 Schematic of the hydrogeologic system of the study site



**Fig. 5** a Water surplus and precipitation for the monitoring period. The months before January 2009 and July 2010 can be observed in the circles. b Average monthly temperature and potential evapotranspiration (*PET*) for the monitoring period

values of the water-table fluctuations varied between a monthly deepening of 0.25 m (March–April 2008) and a rise of 0.53 m (February–March 2008). The latter value is associated to a precipitation of 336 mm/month, including an extreme rainfall event (180 mm/day) which is the highest value recorded in the 1990–2010 period (Carretero and Kruse 2009b). The normal precipitation values show variable effects on the water-table fluctuations. In the rainy season, in 64 % of the cases a deepening of the water table between 0.07 and 0.25 m was recorded. In the dry season, 63 % of the months show a rise in the water table between 0.06 and 0.49 m.

In Fig. 6, the water-table fluctuations in three typical wells are shown, together with the precipitation and the surplus in the water budget. In Fig. 7, the water-table fluctuations and precipitation from Table 1 have been plotted on a graph. If the events corresponding to the dry season are correlated, it can be observed that the regression line has a steeper slope and it intercepts the initial horizontal axis at a lower value (53 mm/month). In the rainy season, in turn, the value is of 97 mm/month. Therefore, in the rainy season more precipitation is necessary to produce a similar effect on the rise of the water table.

In the evaluation of the water-table fluctuations (i.e., changes in water storage in the saturated zone), it is possible to take into consideration the water budget

quoted by Healy (2010) following Schicht and Walton (1961) in Eq. 1:

$$\Delta S^{gw} = R - Q^{bf} - Et^{gw} - Q^{gw}out + Q^{gw}in \quad (1)$$

where  $\Delta S^{gw}$  is the change in storage in the saturated zone;  $R$  is recharge;  $Q^{bf}$  is base flow;  $Et^{gw}$  is evapotranspiration from groundwater;  $Q^{gw}out$  and  $Q^{gw}in$  are groundwater flow from or into the area.

Given the hydrological characteristics of the region, it can be established that  $Q^{bf}=0$  and  $Q^{gw}in=0$ . Therefore, the equation above would be:

$$\Delta S^{gw} = R - Et^{gw} - Q^{gw}out \quad (2)$$

In Table 1 the surplus in the water budget can be observed. The highest water-surplus values were recorded in February–March 2008 at 275 mm, which caused an increase in the water-table fluctuations of 0.53 m; in February–March 2010, 154 mm and an increase of 0.33 m; and in June–July 2009, 126 mm and an increase of 0.49 m.

Even though the greatest water-table deepening values occur when the water surpluses are 0, both in the dry and the rainy season, this deepening also occurs with relatively low water-surplus values. For instance, 32 mm/month in March–April 2009 caused a water-table deepening of 0.07 m, and 7 mm/month in August–September 2009 a

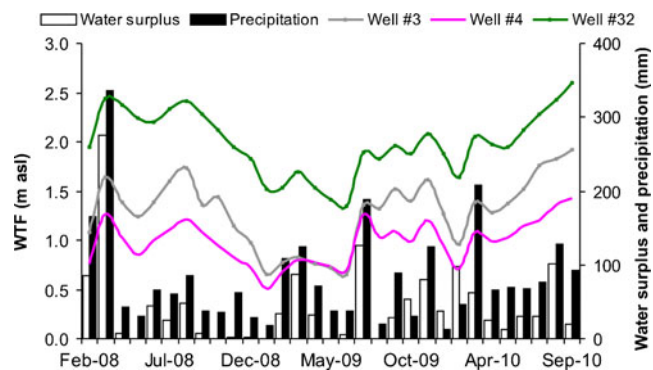
**Table 1** Water-table fluctuation (WTF), precipitation, water surplus and the index for the period February 2008–September 2010

| Period <sup>a</sup> | WTF (m) | Precipitation (mm) | Water surplus (mm) | Index |
|---------------------|---------|--------------------|--------------------|-------|
| Feb-08; Mar-08      | 0.53    | 336                | 275                | 1.6   |
| Mar-08; Apr-08      | -0.19   | 43                 | 7                  | -4.4  |
| Abr-08; May-08      | -0.12   | 30                 | 0                  | -4.1  |
| May-08; Jun-08      | 0.06    | 65                 | 45                 | 1.0   |
| Jun-08; Jul-08      | 0.12    | 60                 | 25                 | 2.0   |
| Jul-08; Aug-08      | 0.09    | 86                 | 48                 | 1.0   |
| Aug-08; Sep-08      | -0.15   | 38                 | 7                  | -4.0  |
| Sep-08; Oct-08      | -0.15   | 35                 | 0                  | -4.3  |
| Oct-08; Nov-08      | -0.15   | 62                 | 1                  | -2.5  |
| Nov-08; Dec-08      | -0.11   | 29                 | 1                  | -4.0  |
| Dec-08; Jan-09      | -0.20   | 17                 | 0                  | -11.5 |
| Jan-09; Feb-09      | 0.08    | 108                | 34                 | 0.8   |
| Feb-09; Mar-09      | 0.10    | 125                | 88                 | 0.8   |
| Mar-09; Apr-09      | -0.07   | 72                 | 32                 | -1.0  |
| Apr-09; May-09      | -0.03   | 38                 | 0                  | -0.8  |
| May-09; Jun-09      | -0.02   | 38                 | 6                  | -0.4  |
| Jun-09; Jul-09      | 0.49    | 150                | 126                | 3.3   |
| Jul-09; Aug-09      | -0.11   | 20                 | 0                  | -5.4  |
| Aug-09; Sep-09      | 0.14    | 89                 | 28                 | 1.5   |
| Sep-09; Oct-09      | -0.10   | 50                 | 0                  | -1.9  |
| Oct-09; Nov-09      | 0.17    | 105                | 49                 | 1.6   |
| Nov-09; Dec-09      | -0.25   | 13                 | 0                  | -19.0 |
| Dec-09; Feb-10      | -0.22   | 46                 | 0                  | -4.7  |
| Feb-10; Mar-10      | 0.33    | 208                | 154                | 1.6   |
| Mar-10; Apr-10      | -0.09   | 66                 | 24                 | -1.4  |
| Apr-10; May-10      | 0.06    | 70                 | 13                 | 0.9   |
| May-10; Jun-10      | 0.12    | 67                 | 30                 | 1.8   |
| Jun-10; Jul-10      | 0.15    | 76                 | 30                 | 2.0   |
| Jul-10; Aug-10      | 0.09    | 128                | 101                | 0.7   |
| Aug-10; Sep-10      | 0.13    | 93                 | 16                 | 1.4   |

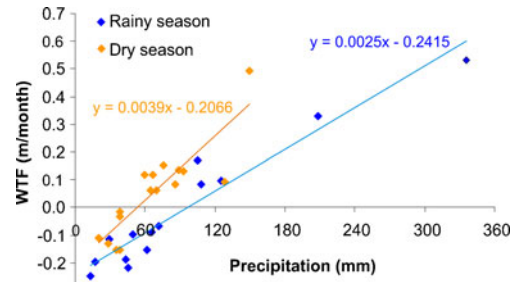
<sup>a</sup> Period: taken from mid-month to mid-next month, e.g. mid-Feb-08; mid-March-08

deepening of 0.15 m. In 47 % of the months studied, it can be observed that the occurring surpluses are not enough to generate a rise in the water table. In the dry season, a water surplus of 13 mm/month was necessary for a rise of 0.06 m to be observed; in the rainy season, with a water surplus of 34 mm/month, there was a rise of 0.08 m (Table 1).

In keeping with the dynamics of the groundwater system, there is a volume of water (water surplus) which



**Fig. 6** Water-table fluctuation (WTF) for three typical wells, precipitation and calculated water surplus for the analysed period. Location for these wells can be observed in Fig. 3



**Fig. 7** Relationship between water-table fluctuation (WTF) and precipitation

reaches the water table, but which is not enough to trigger a rise in the water table, as it leaves the system by groundwater flow ( $Q^{gw}_{out}$ ), causing a deepening of the water table.

The water-table fluctuations are related to recharge as a function of the specific yield (Eq. 3):

$$\Delta S^{gw} = R = S_y \frac{\Delta H}{\Delta t} \quad (3)$$

where  $S_y$  is specific yield and  $\Delta H$  is the change in the water table over a time interval ( $\Delta t$ ).

The specific yield may vary with water-table depth and with time (Said et al. 2005). In the first case, a significant decrease in  $S_y$  could occur if the water table or the capillary fringe are close to the surface (Childs 1960; Healy 2010). In the case studied, even though the water table is at an average depth which may vary between 1 and 1.5 m, the limited thickness of the capillary fringe—due to the sandy composition of the medium—minimises this effect. As regards the changes in specific yield with time, the value of the fluctuation is negligible given the time intervals in the measurements and the quick response of the water table.

In Fig. 7, the differences in water-table response depending on the dry or rainy season are shown. In the rainy season, more precipitation is necessary to produce a similar effect on the rise of the water table. In the first approximation, considering the water-budget equation, it is stated that some of the water surpluses that do not trigger a rise in the water table are related to the  $Q^{gw}_{out}$  of the system. The differences in the relationship between water-table fluctuations and precipitation indicate that in the dry season precipitation of 53 mm/month is required to have a positive effect on the water table, whereas in the rainy season precipitation of 97 mm/month is necessary. These values are more significant than those estimated for the  $Q^{gw}_{out}$ , and they can be attributed to the effect in the water budget of the evapotranspiration from groundwater ( $Et^{gw}$ ).

This situation indicates that, in the dry season, the most favourable conditions prevail for less rainfall to trigger a manifestation of higher recharge in the water table. This must be related to the fact that in these months there is less evapotranspiration and consequently the  $Et^{gw}$  is of a smaller magnitude.

The largest rise in the water table and its consequent response in the recharge take place in the dry season, due to the influence of the evapotranspiration. In the months with highest temperatures, the evapotranspiration is higher. Months with lower temperatures and a low evapotranspiration rate create favourable conditions for a larger recharge at the water table, despite the smaller magnitude of the precipitation.

Given the lack of detailed knowledge of the recharge process and the behaviour of the water table, an index ( $I$ ) which would simply associate water-table fluctuations (WTF) and precipitation ( $P$ )—as they are the only data measured (Eq. 4)—may result in a practical procedure of a qualitative kind to assess the hydrological situation, especially regarding the influence on groundwater reserves.

$$I = \frac{WTF[mm]}{P[mm]} \quad (4)$$

This index (Table 1), even though it does not quantify the different factors influencing the behaviour of the water table, makes it possible to observe that values below 0 would represent a decrease in the freshwater reserves and would therefore trigger an alert to water-resource managers. Values between 0 and 1 would indicate a stable hydrological situation, with a slight recovery of the water reserves. Indices between 1 and 3 would express an average recovery of the reserves. Values above 3 would imply an important recovery of the reserves, although it would constitute a warning about the risk of waterlogging in the topographically lower areas, especially in those situated to the west of the sand-dune barrier.

## Conclusions

The average monthly water-table measurements from the monitoring network and the precipitation occurring between measurement periods made it possible to identify a positive response in the water table when the accumulated precipitation is above 53 mm in the dry season and above 97 mm in the rainy season. The climatic conditions indicate a rainy season (warm) and a dry season (cold), with the dry period being more significant regarding the rise in the water table and the consequent response in the recharge. In the rainy period, evapotranspiration from groundwater occurs, given the shallow depth of the water table; whereas the effects of the evapotranspiration cause a decrease in the water surplus which might infiltrate. This behaviour differs from the one generally observed in certain recharge analyses, in which it is established that the more precipitation, the greater the rise in the water table.

The coast of the Buenos Aires province, which extends over 640 km and has characteristics comparable to those of the study area, has experienced a strong demographic growth that has imposed increasing requirements on the

supply of freshwater. However, the data on the hydrodynamic and hydrochemical regime of groundwater is still insufficient. Further knowledge on the relationship between water-table fluctuations and precipitation would constitute a useful tool in the planning of water-resource use and conservation, which in turn could be extrapolated to other regions with similar hydrogeological conditions, but which lack this type of data. The relationship between water-table fluctuations and precipitation could be used as a means to set up a water supply early warning system in case rainfall falls short of the recharge required. In this manner, it would help decision-makers to redefine the supply strategies.

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