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Groundwater Dynamics and Recharge Assessment in an Unconfined Aeolian Sand Aquifer

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***Abstract*- In the sandy plain of the South of Córdoba province, Argentina) the unconfined aquifer is used mainly for agricultural activities. The objective of this work is to show the estimation of the recharge (R) rate in the unconfined aquifer, using the water table fluctuation method (WTF). Furthermore, considerations in relation to monthly recharge and discharge (D) rhythms were performed. The studied unconfined aquifer consists mainly of sandy aeolian sediments with values of hydraulic conductivity in the order of 1.5 m/d. The water table is slightly undulating and hydraulic gradients and flow velocities are low, controlled by lithology and the regional plain topography. The relationship between groundwater and surface water bodies is variable, but in general, the aquifer provides water to the river and to the lagoons. The parabolic dunes of this sandy plain environment show a typical behavior of preferential recharge areas. That is, an important and quick answer of water table to the arrival of precipitations and then the discharge to the base level, the neighboring lagoon in the parabolic dune. Using monthly estimation, an annual average recharge value of 12% of total precipitation was obtained. When the relationship between P and R was analyzed, the 91 % of recharge episodes were clearly dependent on the rainfall behavior. Winter shows very low recharge but a great effectiveness because the recharge arrives to the aquifer from delayed wetting fronts, although almost there were not rainfalls. Nevertheless, the major amount of recharge has occurred in the end of spring, summer, and early autumn. The ratio R/D for the whole series was positive which means that the aquifer recharge predominated, a fact that is coherent with the higher position of the water table at the end of the studied series. These results assure the existence of annual water replacement to the aquifer, a very important feature for a region that depends on groundwater resources.**

***Index Terms*- Unconfined Aeolian aquifer, recharge, water table fluctuation.**

I. INTRODUCTION

Knowledge about groundwater is essential in many places of the world because it is the most used resource for human activities. The study of aquifers is very useful not only for the groundwater consumption but due to its influence in different ecosystems behavior. The analysis and quantification of the aquifer groundwater flow mechanisms and recharge processes is a vital requirement for an efficient management of water resources [1, 2], particularly in semi-arid regions and areas where there is overexploitation i.e., the water extraction from the aquifer is higher than its natural replenishment [3].

Recharge and discharge processes are regularly spatially limited to a small portion of an aquifer. The most common recharge areas are hills, outcrops or erosional exposures of confined aquifers, alluvial fans along mountain fronts and ephemral stream bottoms in dry regions. However, in unconfined aquifers, the entire land surface may allow the infiltration of precipitation, with different rythms, depending on factors such as lithology, relief, etc. Common natural discharge areas include perennial stream valleys in humid regions, swamps, springs, lakes and the oceans. Climatic factors are the key influences on groundwater recharge, because only a small percentage of rainfall results in recharge in arid and semiarid climates. Human activities have a great influence upon recharge, discharge and groundwater flow (artificial recharge, pumping, etc.). Groundwater may also return to the atmosphere directly by evaporation within the soil or by transporation through vegetation but these processes are not formally considered as discharge.

Moreover, taking into account that human activities have a great influence upon recharge, discharge and groundwater flow (artificial recharge, pumping, etc.) the knowing of the groundwater flow network and seasonal variations is critical for the rational planning, management, and use of such resources and in maintaining the sustainability of groundwater-dependent ecosystems.

The complexity of flow within aquifers may require extensive data and detailed modeling to answer development questions. However, relatively simple data, such as specific water levels in a carefully designed network of monitoring wells, can be combined with estimates of rainfall input to provide key indications of groundwater dynamics and recharge.

In the sandy eolian plain of the South of Córdoba province (Argentina), groundwater studies were carried out due to the importance of the unconfined aquifer especially for rural water supply. The area selected for this study (1,000 km^2) is located near Laguna Oscura and Washington towns (Fig. 1).

The objective of this work is to show the groundwater flow characteristics and the estimation of the recharge rate in an unconfined eolian sand aquifer. Several considerations in relation to the aquifer discharge were also included in this paper.

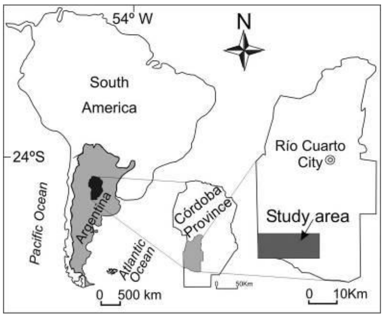

Fig. 1. Location of study area

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II. MATERIALS AND METHODS

Background information (geological, geomorphological, climatic, etc.) of the study area was collected and analyzed. The research was carried out at 1:50,000 scale, based on the analysis and compilation of satellite images (Google Earth, Landsat ETM) and topographic sheets from National Geographic Institute (NGI). Climate characterization of the area was made through the processing and interpretation of the available information (especially precipitations) from the Ea. Laguna Oscura (1911-2013) series (Fig. 2). The regional geological and hydrogeological features were identified at field. The geological and geomorphological study was conducted through the description of the relief and the outcropping lithological profiles. Also, a perforation was made to install the monitoring water table level instrument. Both in the outcrops and during the drilling processes, sediment samples for further textural analysis (ASTM sieves, Udden- Wendworth scale) were taken. The hydrogeological survey consisted in the sampling of 22 wells, which were 10 - 20 m deep. In addition, the water table depth was measured with a piezometric sensor (Solinst) and then hydraulic heads were calculated for the elaboration of the equipotential aquifer map. Some pump tests were made to know hydraulic aquifer parameters such as K (hydraulic conductivity), T (transmissivity) and S (storage coefficient).

Water table fluctuations are being registered with a pressure sensor that was installed in the mentioned monitoring well located in a parabolic dune, near Laguna Oscura lagoon (Fig. 3). For the recharge and discharge estimation presented in this paper, the period of 12 months between 18/12/2014 and 18/12/2015 is used. The period was selected only as an example for this investigation, but the calculus may be applied to series as long as available to answer the requesting of farmers who develop agricultural practices, to link contamination processes with recharge rates, to contribute to regulatory aspects, etc. The aquifer recharge was estimated using the known WTF method, following [1] suggestions. The Liqko 1.0 software developed by [4] was used as a recharge calculation and graphic tool. The software communicates with a MySQL database, makes the calculations and then generates the output charts which can be saved in different formats (JPG, JPEG, BMP, PNG and GIF). More specific aspects of the recharge quantification are given in the following paragraphs.

III. RESULTS AND DISCUSSION

A. *Climatic and geomorphological characterization*

The climate of the area is dry sub-humid, with an annual mean precipitation (P) of 750 mm (Fig. 2a), most of which (about 75 - 80%) is concentrated during spring and summer (Fig. 2b). In the average water balance, the calculated annual mean potential evapotranspiration (PET) is 850 mm whereas the actual evapotranspiration (AET) is 750 mm. The AET results match with the total rainfall, generating a deficit of 100 mm, especially in winter. However, a sequential monthly water balance, linking one month to another during the 103 years, allowed better interpretations about water behavior. Thus, alternating water excess and deficit periods were observed. In humid periods the water excess or surplus is distributed in surface runoff and groundwater recharge [5]. Important aspects related to aquifer recharge will be discussed in the following section.

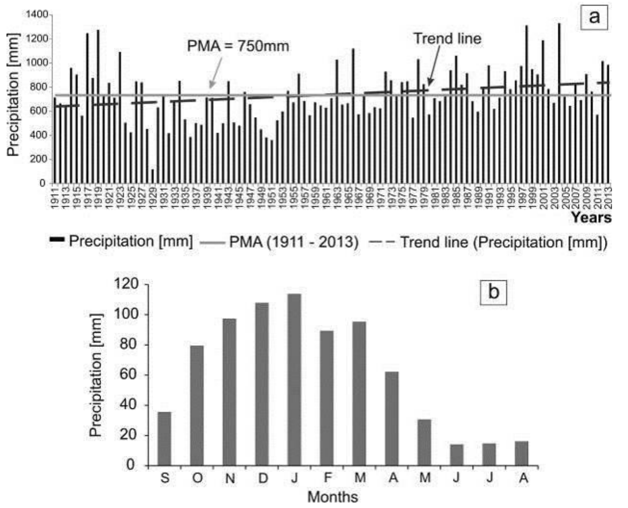


Fig. 2. a)- Annual precipitation chronological curve. b)- Distribution of precipitations

Loess and aeolian sand are common surficial deposits on the Argentina Pampean plain. These extensive eolian deposits are principally related to uplift and enhanced glaciation of the Andes since the Miocene, augmented in the Quaternary with volcanic ash input. The extensive flood plains of the rivers that come from the Andes Mountains are the main source of Pleistocene eolian sediments [6, 7]. Concomitant with loess deposition at least in the past ca. 70 ka there was episodic deposition of aeolian sand with the development of multiple ergs across the Pampas and is referred to as the “Pampean Sand Sea” [8, 7]. In this landscape type, is situated the area selected for this work.

The area is characterized by a flat to gently undulated relief with old longitudinal dunes elongated in NW-SE direction. These dunes were reworked during the present climate by NE winds, generating a landscape of parabolic dunes (NE-SW) whose main body was remobilized by lateral winds, forming barjanoides chains in the body of the dunes. In the main depression of the parabolic dunes temporary or permanent lagoons of different size are installed [5]. This aeolian plain is crossed by the Rio Quinto River. The paleochannels linked to fluvial activity of the Rio Quinto River are interlayered and juxtaposed with the dunes systems, so that the sector under study is a real palimpsest [5]. The most relevant geomorphological units can be observed in Figure 3.

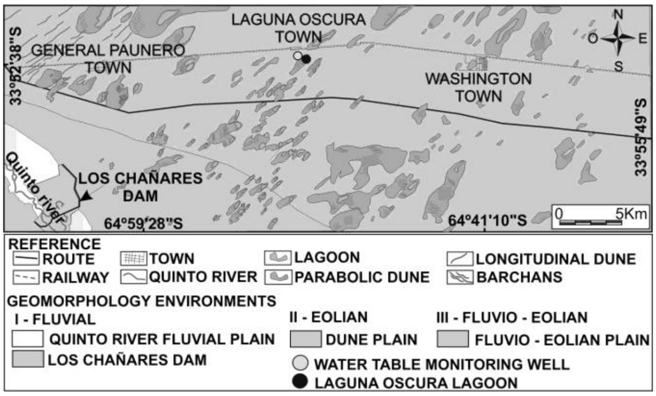


Fig. 3. Geomorphological map in the sand plain of the Paunero - Laguna Oscura - Washington region.

B. *Aquifer and groundwater flow characterization*

The unconfined aquifer, approximately 50 m thick, is formed by sandy-silt brown sediments with dispersed calcareous nodules or layers (calcretes). The dunes sediments are dominantly very fine sands (up to 49 %). Locally, anisotropies linked to the mentioned fluvial system may be found, appearing coarse and medium sands (17 % -30 %) and gravels in minor proportion (Fig. 4).

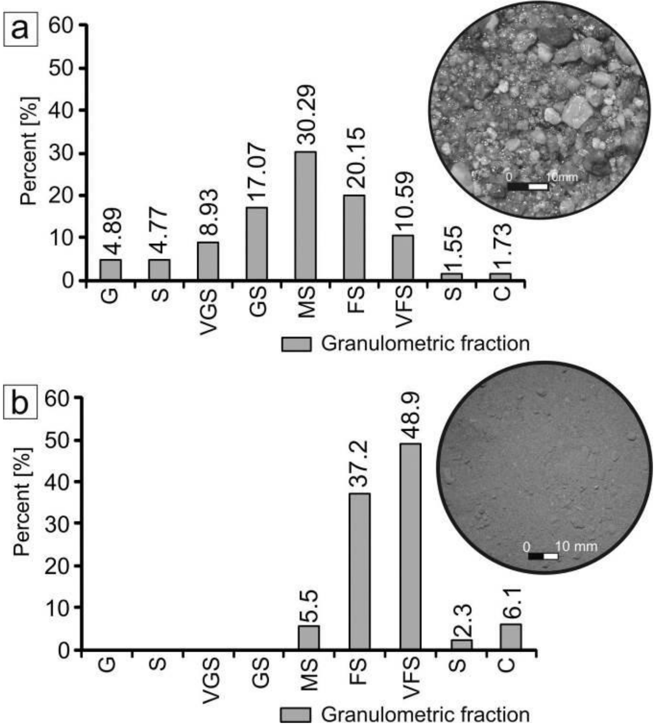


Fig. 4. Textural analysis. b)- Sediments of Rio Quinto River paleochannels. b)Sediments of the dune plain.

In the Laguna Oscura area, the results of sediment textural analysis show fine sands as the dominant fraction, up to 44 m depth. A pump test was made in this region using 2 observation wells (Jacob method). The results are shown in the Table I, Figure 5.

Table I. Pumping test in wells in Laguna Oscura region

Data	
Flow (Q) m^3/h	2.05
Water table. Static [m]	4.04
Pump depth [m]	7.0
Intubation diameter (inch)	4.0
Distance (1) m	5.0
Distance (r^2) m	20.0
Drawdown (S1) m	0.19
Drawdown (S2) m	0.027
Pumping time (t) h	14.0
Effective radius (Ro) m	25.0
Q m^3/d	43.0
T (m^2/d)	68.0
K (m/d)	1.50
S	0.12

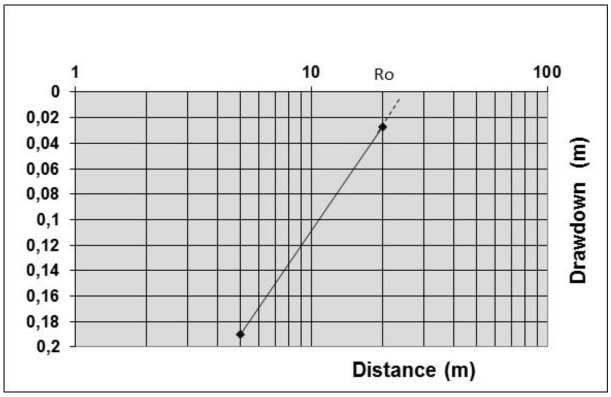


Fig. 5. Pumping test

Water table morphology is almost plane or slightly undulated. Groundwater flow is in WNW-ESE direction (Fig. 6). The aquifer is recharged from precipitations in the entire studied area, but the dunes, with loose sediments, are preferential recharge zones [5]. The hydraulic gradients are in the order of 0.1 % to 0.4 %. Groundwater flow velocity is in the order of 0.04 to 0.07 m/d although in dunes may be higher (0.25 m/d). The aquifer supplies groundwater to the dunes lagoons mainly by the NW margin (Fig. 6).

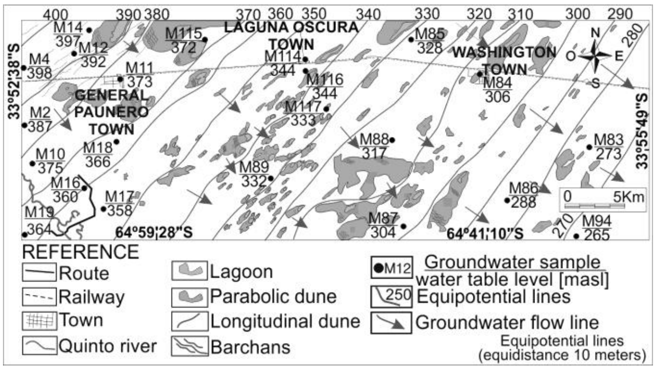


Fig. 6. Equipotential map of the unconfined aquifer.

Water table depth is variable, from 9 m to 0 m (water outcropping areas), according to the control that mostly the topography exerts (Fig. 7). Water table fluctuation in the last 3 years was in the order of 1 meter [5].

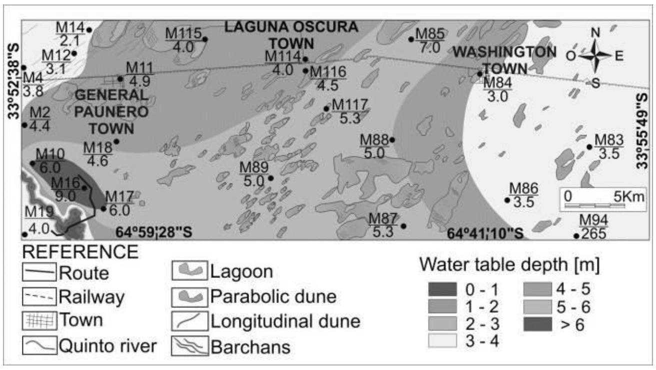
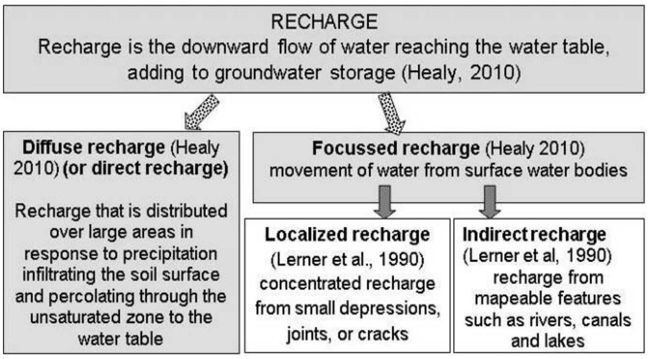


Fig. 7. Water table depth

C. *Estimation of groundwater recharge and discharge.*

The estimation of aquifer recharge is difficult since it varies in time and space and its rhythms are difficult to measure in a direct way. Even though accurate estimations of the recharge are highly desirable, uncertainty in estimates generated by current methods remains as well as the difficulty in assessing the uncertainty associated with any given estimate and the extent to which estimations are accurate [1]. Recharge is defined as the downward flow of water reaching the water table, adding to groundwater storage [1]. Groundwater recharge occurs through diffuse and focused mechanisms as can be seen in Figure 8. In the studied area diffuse recharge was estimated to be dominant.

It is important to mention that recharge was estimated with data recorded in the mentioned monitoring well (punctual site) where the water level is being measured every 15 minutes. These data were re-calculated on a daily time step (an average of the measures taken daily) in order to use the same time step that is available for rainfalls.



RECHARGE
Recharge is the downward flow of water reaching the water table, adding to groundwater storage (Healy, 2010)

Diffuse recharge (Healy 2010) **(or direct recharge)**
Recharge that is distributed over large areas in response to precipitation infiltrating the soil surface and percolating through the unsaturated zone to the water table

Focussed recharge (Healy 2010)
movement of water from surface water bodies

Localized recharge (Lerner et al., 1990)
concentrated recharge from small depressions, joints, or cracks

Indirect recharge (Lerner et al, 1990)
recharge from mapeable features such as rivers, canals and lakes

Fig. 8. Types of aquifer recharge [2]

As was mentioned, the applied method was the WTF which is only applicable to unconfined aquifers. In these cases, it is not only necessary the continuous monitoring of groundwater level, but also to have effective porosity values (equivalent to S in this type of aquifer) at the level fluctuation area. It is important to check that the fluctuation levels are not affected by pumping or other causes when calculation is being done.

A water balance for the aquifer can be defined as follows: [1], Figure 9:

$$\Delta S^{gw} = R - Q^{bf} - ET^{gw} - Q_{off}^{gw} + Q_{on}^{gw} \qquad (1)$$

where:
ΔSgw is change in saturated-zone storage (it includes all the changes that can occur at depths that are higher than the zero-flux plane),
R is aquifer recharge rate,
Qbf is base flux,
ETgw is evapotranspiration from the aquifer and
Qgwoff and Qgwon are water flow on to and off the aquifer, including pumping.

WTF is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table. If it is assumed that the amount of water available in a column of unitary base is as many times as S multiplied by the height of the water column, recharge can be calculated as:

$$\Delta S^{gw} = R = Sy\, {}^{dh}\!/_{dt} = Sy\, {}^{\Delta h}\!/_{\Delta t} \qquad (2)$$

where:
R: recharge,
Sy: specific yield,
h: water-table height and
t: time

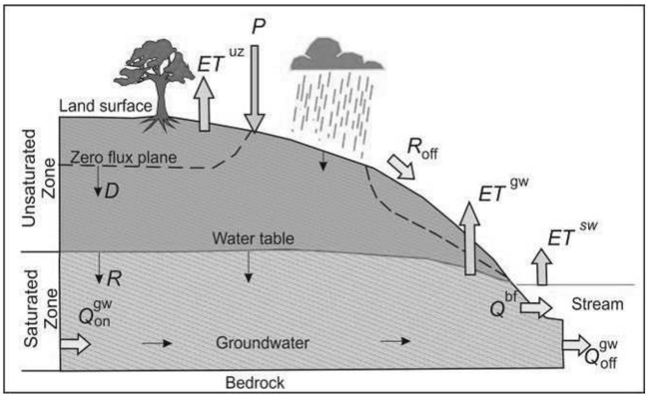


Fig. 9. Diagram through a watershed showing water budget components and directions of water movement [1].

According to [1] and for (2) to be correct, it is assumed that the water that reaches the water table becomes part of the groundwater storage; and that evapotranspiration from the groundwater level, the contribution to the base flux or to the groundwater regional flux and other outputs or inputs to the groundwater system are all zero.

If the WTF method is applied to every individual water-level rise, an estimation of the total or “gross” recharge can be made, where Δh is equal to the difference between the peak of the rise and the lowest point in the curves of the extrapolated antecedent recession curve at the time of the peak (Δh total or Δht) (Fig. 10). The recession curve is the trace that the hydrograph would have followed in the absence of a rise-producing precipitation. According to [3] the effect of regional groundwater discharge is taken into account by this extrapolation. For the WTF method to produce a value for total or “gross” recharge it requires application of (2) for each individual water-level rise and the corresponding recession curve. Equation (2) can also be applied over longer time intervals (seasonal or annual) to produce an estimate of change in subsurface storage, ΔSgw. This value is sometimes referred to as “net” recharge [9] and is calculated in the same way, but considering the net storage change in the saturated zone for any time interval (days, months, years) and placing the value Δh in (2), which is the difference of the height between the beginning and the end of the interval [1], Figure 10.

In this paper the rises of groundwater levels observed in the water level series were considered and net recharge using Δh was calculated by Likqo 1.0, which make the calculus employing (2).

Regarding to the storage coefficient S (effective porosity of the unconfined aquifer), the available average value of S was used.

On the other hand, according to [1], if additional assumptions are taken into account, the WTF method can be used to estimate any of the parameters involved in (1), (e.g. Qbf, ETgw). Therefore, and taking into consideration the criteria established in [1], [10] and [2] the aquifer discharge (D) was estimated too in this paper. Thus, if there is a water level fall (R=0) and ETR=0 (below zero flux plane) and, if (1) is considered, the registered fall is discharge attributable to Q_{bf}

(Fig. 5) assuming that Q_{gwoff} and Q_{gwon} are equal and have opposite signs).The extended methodology is available at [2].

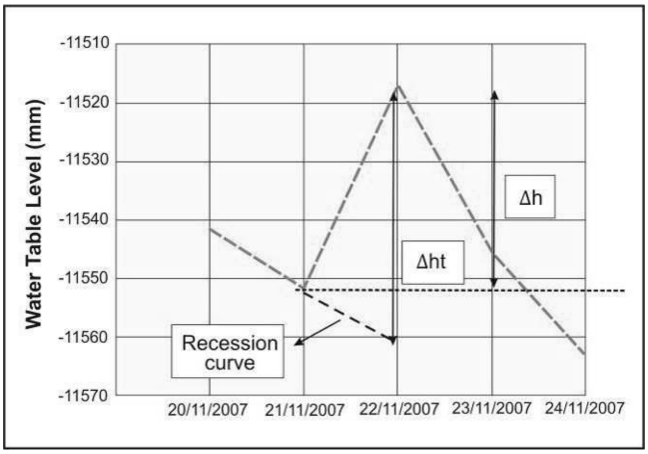


Fig. 10. Measurements to be performed for the recharge estimation

The software Liqko 1.0 makes it possible to calculate R (2), D (2), (with opposite sign for Δh) and balance between R/D for a given period and then to save the information in an Excel spreadsheet.

As it is shown in Figure 11, there are not significant differences in the water level position along the analyzed series but it shows an increasing trend, with a maximum of 3.25 m depth and a minimum of 2.50 m depth, despite there are dry and wet months (Table I). That is, the aquifer was recharged in the analyzed year.

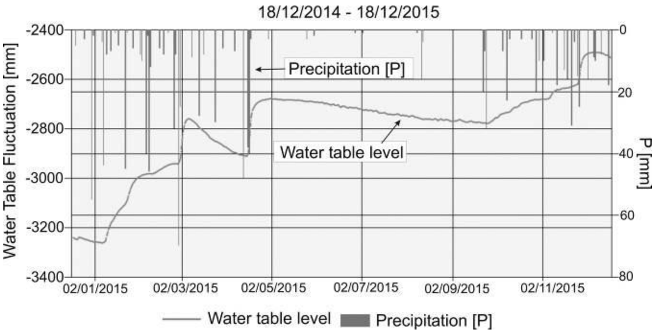


Fig. 11. Water table depth vs precipitations

Comparing the daily variation of the water table level with the previous one (Fig. 12, it is notorious that there are very clear level rise cycles, with peaks related to storms (especially in spring and summer). In relation to the variations in the rises and falls, there was a maximum of 0.012 m for the falls and a maximum of 0.075 m for the rises. These results and the general appearance for the curve of Figure 12 would indicate a typical behavior of preferential recharge areas with an important and quick answer to the arrival of precipitations and then, small discharges into the base level (the neighboring Laguna Oscura lagoon). During the autumn and winter, the aquifer shows similar and very little recharge and discharge episodes.

The regression coefficient beween P and R is low (R^2 <0.4). This situation may be explained if the high intensity of rains during full summer is considered. Consequently, a significant part of rainfall water is converted into runoff.

The regression coefficient only showed a high value (R^2=0.91) when the relationship between R and P was evaluated for the year, but excluding summer (Fig. 13). That is, 91 % of recharge episodes are clearly dependent on the rainfall behavior. Thus, the minor rainfall intensities in the considered months provide less water to the aquifer, but the recharge process is more efficient.

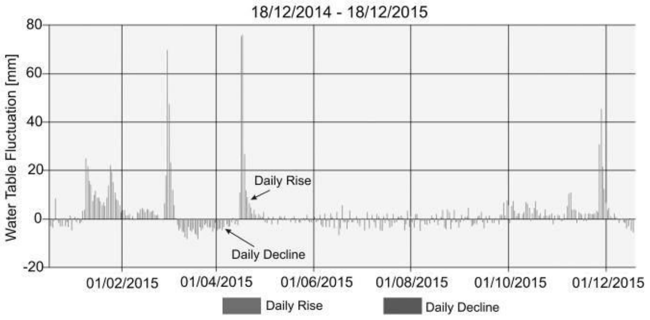


Fig. 12. Daily variation of the water table level in relation to the previous day level.

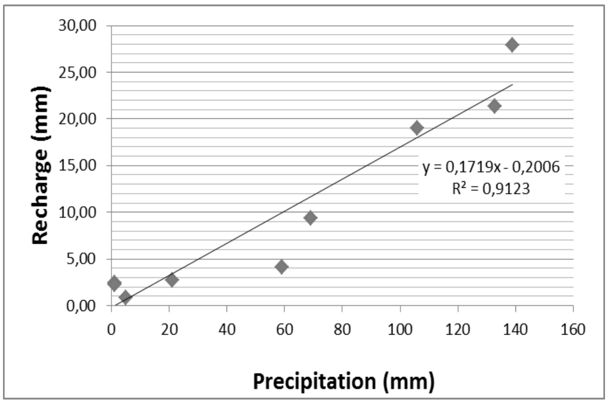


Fig. 13. Relation between P and R when summer was excluded.

As it can be seen in Figure 14, the behavior of recharge is variable between seasons and, in general, is similar to precipitations. Major amounts of recharge are observed in summer (January and March), part of autumn (April) and in spring (especially November).

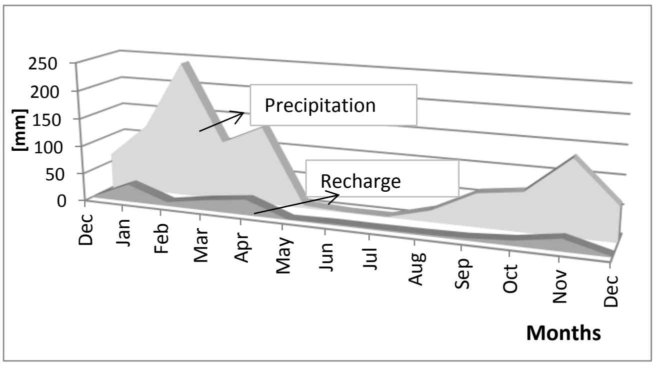


Fig. 14. Evolution of groundwater recharge and precipitation for the 12 months (12/2014-12/2015)

The highest discharge (13.60 mm) was observed in the starting of autumn, and a sustained discharge was observed during winter (Table II). However, small quantities of water through delayed fronts arrive to the aquifer (Fig. 12) in winter. The ration R/D or balance between recharge and discharge for the whole series was positive (Table II), which means that the aquifer recharge was dominant, a fact that is coherent with the higher position of the water table at the end of the analyzed period (Fig. 11).

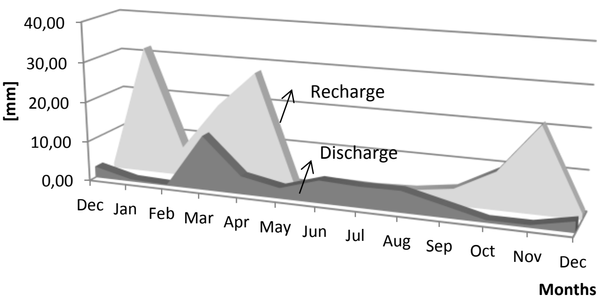


Fig. 15. Evolution of groundwater recharge/discharge for the 12 months (12/2014-12/2015)

Table II. Estimation: recharge (R), discharge (D) and balance between R and D

PERIOD	PRECIPITATION (mm)	RECHARGE [mm]	DISCHARGE [mm]	BALANCE [mm]	R as % P
18/12/2014 - 31/12/2014	63	1.16	2.84	-1.68	1.8
01/01/2015 - 31/01/2015	123	31.96	0.56	31.40	26.0
01/02/2015 - 28/02/2015	243	7.32	0.24	7.08	3.0
01/03/2015 - 31/03/2015	106	19.00	13.60	5.40	17.9
01/04/2015 - 30/04/2015	139	27.92	4.52	23.40	20.1
01/05/2015 - 31/05/2015	5	0.88	2.68	-1.80	17.6
01/06/2015 - 30/06/2015	1	2.44	5.64	-3.20	244.0
01/07/2015 - 31/07/2015	1	2.28	5.20	-2.92	228.0
01/08/2015 - 31/08/2015	21	2.68	5.32	-2.64	12.8
01/09/2015 - 30/09/2015	59	4.12	3.00	1.12	7.0
01/10/2015 - 31/10/2015	69	9.36	0.64	8.72	13.6
01/11/2015 - 30/11/2015	133	21.32	0.68	20.64	16.0
01/12/2015 - 18/12/2015	61	1.52	2.74	-1.22	2.5
TOTAL	1024	131.96	47.66	84.30	12.9

S (Storage coefficient) used for the calculus: 0.12

IV. CONCLUSION

The studied unconfined aquifer consists mainly of sandy aeolian sediments with values of hydraulic conductivity typical for this kind of aquifers, in the order of 1.5 m/d. The water table is slightly undulating and hydraulic gradients and flow velocities are low, controlled by lithology and the regional plain topography. The relationship between groundwater and surface water bodies is variable, but in general, the aquifer supplies water to the river and to the lagoons installed in the parabolic dunes.

The parabolic dunes of this sandy plain environment show a typical behavior of preferential recharge areas with an important and quick answer of water table to the arrival of precipitations and then the discharge to the base level, the neighboring lagoon in the parabolic dune. The correlation between monthly R and P for the entire year was low (R^2 <0.4), a situation that is considered to be related to the high quantities of rainfall water that are converted into runoff and do not arrive to the aquifer. Nevertheless, the regression coefficient has a high value ($R^2 = 0.91$) when the relationship between R and P is evaluated excluding summer. That is, 91 % of recharge episodes are clearly dependent on the rainfall behavior. Thus, the minor rainfall intensities in this period provide less water to the aquifer, but the recharge process is more efficient

Using monthly estimation, an annual average recharge value of 12% of total precipitation was obtained. If the relationship between P and R is analyzed, the winter show a great effectiveness because the recharge arrives to the aquifer from delayed wetting fronts, although there were not almost rainfalls. Nevertheless, the major amount of recharge has occurred in the end of spring, summer, and early autumn. The ratio Recharge/Discharge for the whole series was positive which means that the aquifer recharge was predominant, a fact that is coherent with the higher position of the water table at the end of the studied series. These results assure the existence of annual water replacement to the aquifer, a very important feature for a region that depends on groundwater resources.

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