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ASSESSMENT OF GROUNDWATER RECHARGE AND DISCHARGE PROCESSES IN A LOESSICAL AQUIFER USING A NEW COMPUTER CODE

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Rio Cuarto city and its rural surrounding area (400 km^2) shows two major geological environments, formed by eolian and fluvial sediments. The main source of groundwater recharge is precipitation (P), with an annual mean rainfall of 799 mm; 75-80% concentrated in spring and summer. The aim of this paper is to show the water table behavior in the unconfined eolian aquifer (very fine sands and silts) taking into consideration recharge (R) and discharge (D) events. R was calculated using the water table fluctuation method for a selected period (2002-2009) with a new computer code Likqo 1.0. The recharge was estimated for both the hydrologic and calendar year. The first result was better according to the higher R-P regression coefficient obtained. It is important to highlight the recharge delay (days or weeks) in relation to rain storms; a fact that can be linked to water table depth. The average R value for the entire series was 12% of P, the largest recharge occurring in the hydrologic periods 2002-2003 and 2007-2008 (14% P) and the lowest in 2004-2005 (10 % P). The best correlation P-R occurs in summer (r 0.9) and autumn (r 0.8). There is a similar behavior of R between seasons, with slight decrease in winter, when precipitation is scarce. However, low rates of actual evapotranspiration appear to be able to maintain the recharge process efficiency, which results in a water table rise during winter as was observed in 70% of the analyzed years. This effect can be related to delayed wetting fronts. The greatest value of groundwater discharge occurred in the 2005-2006 cycle (110 mm, 13.7% P). The ratio R/D was maximum and negative in 2005-2006, coinciding with the lowest recorded levels. The ratio R/D for the total series was slightly negative, which means that aquifer discharge was dominant, coinciding with the lowest position of the water table.

INTRODUCTION AND OBJECTIVES

Knowledge about aquifer recharge processes is basic in the development of management and protection strategies for groundwater, since they are involved in the water abstraction for several uses and in ecosystems behavior (Vrba and Verhagen, 2011). Specifically, recharge processes in large unconfined loessical aquifers of the Pampean plain must be described and quantified, not only to evaluate groundwater resources to be used but also because groundwater is susceptible to contamination, which is able to reach the water table through recharge water (Giuliano Albo y Blarasin, 2014).

In Río Cuarto city (Córdoba province) and its surrounding rural area (Figure 1) ground water studies are carried out periodically due to the importance of the unconfined aquifer for urban and rural water supply. Some results of these studies are presented in this paper whose main objective is to show the estimation of the recharge rate in the unconfined aquifer located in the eolian environment of the study area. The method employed was the water table fluctuation (WTF) method which was used with a new computer software. Several considerations in relation to the aquifer discharge were also included in this paper.

MATERIALS AND METHODS

This research is based on regional hydrogeological data collected by the Geohydrology research team of the Department of Geology at the National University of Río Cuarto (Blarasin et al, 2011, Blarasin et al 2014). Rainfall data and water table levels were collected and analyzed. Water table fluctuations are being registered with a pressure sensor that was installed in a monitoring well by the end of 2001 (Figure 2). For this paper, an 8-year period (2002-2009) was selected in which an important dry cycle occurred. The aquifer recharge was estimated using the known WTF method following the Healy (2010) suggestions. New software was developed (*Liqko 1.0,* Alincastro and Algozino, 2010) as a calculation and graphic tool. This software was used for the analysis related to water table fluctuations, rainfall and recharge estimation. 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.

GEOLOGY, HYDROGEOLOGY AND CLIMATE

Two major environments of different genesis, relief and lithology were identified: eolian and fluvial. The first is a gentle to undulating plain, whose regional slope is of 1% to 2%, characterized by loessical sediments (very fine sands and silts) (Figure 1). The second environment includes the area where the Rio Cuarto river and the Santa Catalina stream flow. The typical fluvial geoforms of this environment are associated to the different hydrodynamic stages of both streams (terraces, meanders and so on) while the typical sediments are silts, sand and gravels.

There are also two major hydrogeological environments: one in which the unconfined aquifer is highly heterogeneous with medium-high hydraulic conductivity (modern fluvial area of the Río Cuarto river, Unit 2.a, Figure 1) and the other in which the aquifer is homogeneous with low hydraulic conductivity (aeolian plain, Unit 1.a). There are also other transition sectors such as 1.b (eolian with paleo-channels) and 2.b (fine fluvial sediments and aeolian intercalations). The hydraulic parameters of the aquifer were defined according to the textural characteristics of the sediments and *in situ* aquifer tests (Blarasin, 2003). In relation to the eolian environment, where water table fluctuation is evaluated in this paper, the average value of transmisivity (T) is 50 m^2/day, the hydraulic conductivity (K) is 0,5-1 m/day and the storage coefficient (S) is 0,05-0,1. The groundwater flow direction can be observed in Figure 2. From the position where the pressure sensor was placed, which is close to the groundwater divide, groundwater flows towards the Río Cuarto River in a NW-SE direction (Figure 2).

The climate of the area is sub-humid, with an annual mean precipitation (P) of 797 mm, most of which (about 75-80%) is concentrated during spring and summer. In the average water balance, the calculated annual mean potential evapotranspiration (PET) is 822 mm whereas the actual evapotranspiration (AET) is 797 mm. The AET results match with the total rainfall registered, generating a deficit of 25 mm in autumn and winter. However, a sequential monthly water balance, linking one month to another during the 8 years, allowed better interpretations about water behavior. Thus, alternating water excess and deficit periods were observed (Blarasin, 2003). In those periods with water excess or surplus, this is distributed in surface and groundwater recharge. Important aspects related to aquifer recharge will be discussed in the following section.

ESTIMATION OF GROUNDWATER RECHARGE AND DISCHARGE IN THE AEOLIAN AQUIFER ENVIRONMENT

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 (Healy, 2010). Recharge is defined as the downward flow of water reaching the water table, adding to groundwater storage (Healy, 2010). Groundwater recharge occurs through diffuse and focused mechanisms as can be seen in Figure 3.

In the study area (eolian plain), diffuse recharge was estimated to be dominant. However it is important to mention that its estimation where done with data recorded in a monitoring well (punctual

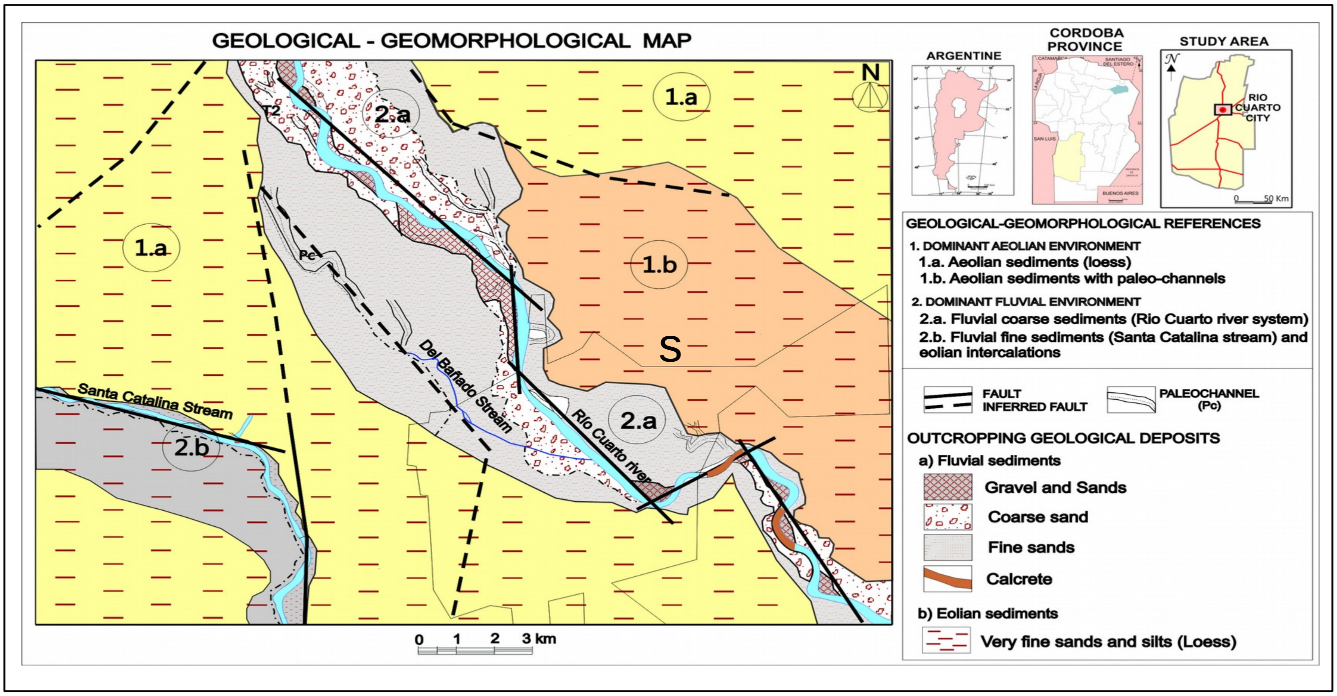


Figure 1. Location of study area and geological-geomorphological map

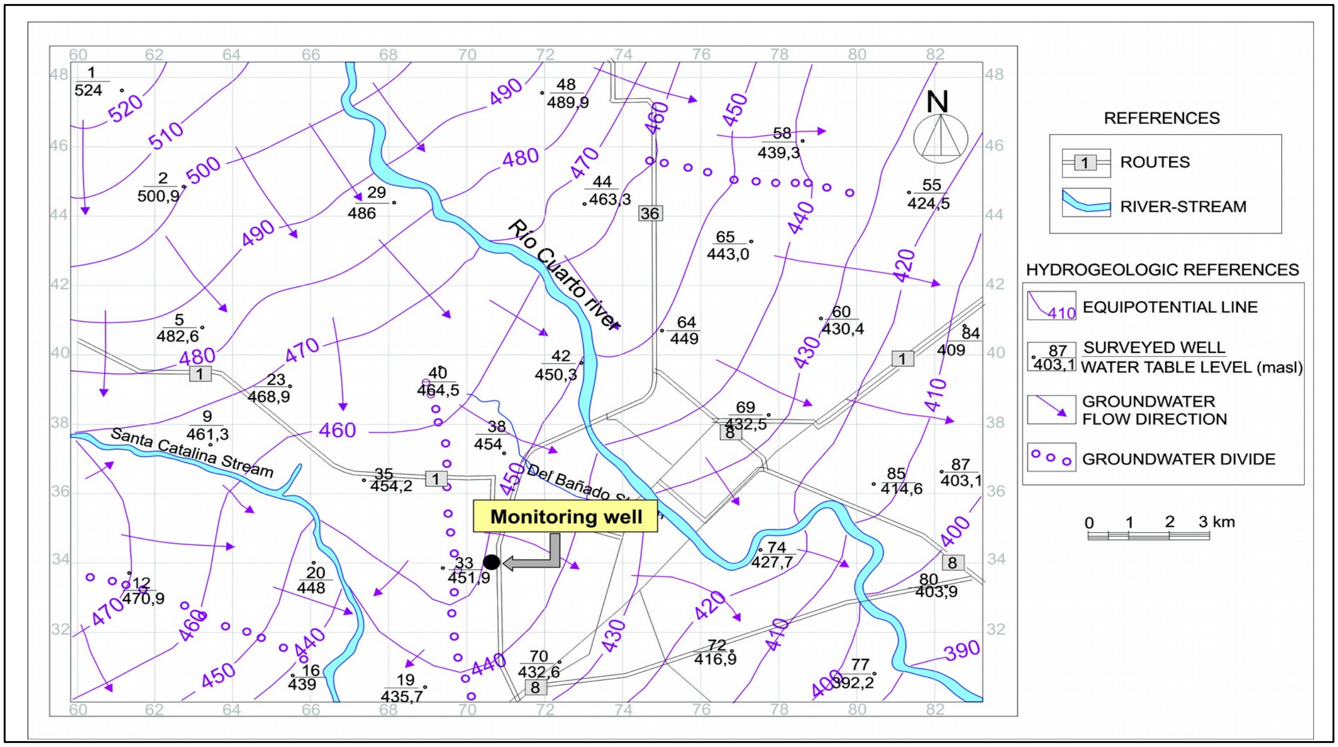
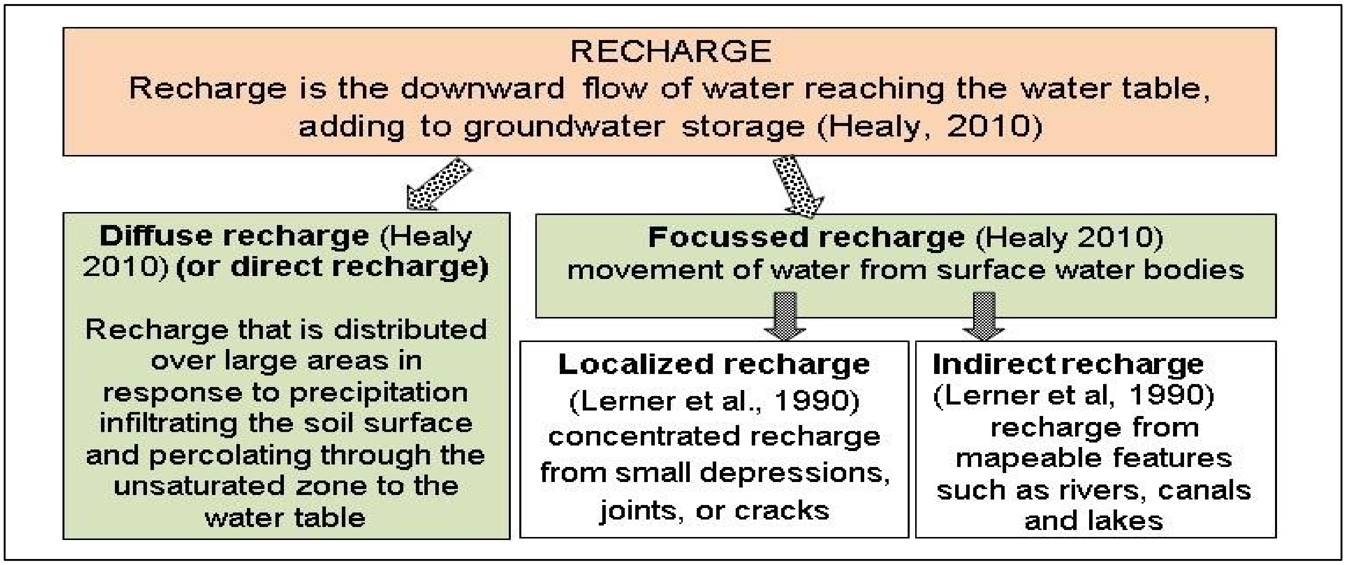


Figure 2. Potentiometric map of the study area (unconfined aquifer).



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

Figure 3. Types of aquifer recharge**.**

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. As was mentioned, the method applied was the WTF which is only applicable to unconfined aquifers. In these cases, it is not only necessary the constant monitoring of groundwater level, but also effective porosity (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: (Healy, 2010, Figure 4):

$$\Delta S^{gw} = R - Q^{bf} - ET^{gw} - Q^{gw}_{off} + Q^{gw}_{on} \tag{1}$$

where:

ΔS^{gw} 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,

Q^{bf} is base flux,

ET^{gw} is evapotranspiration from the aquifer and

$Q^{gw}{}_{off}$ and $Q^{gw}{}_{on}$ are water flow onto 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:

$$\Delta S^{gw} = R = Sy \, {dh}/{dt} = Sy \, {\Delta h}/{\Delta t} \tag{2}$$

where:

R: recharge,

Sy: specific yield,

h: water-table height and

t: time

According to Healy (2010) and in order to equation 2 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 zero.

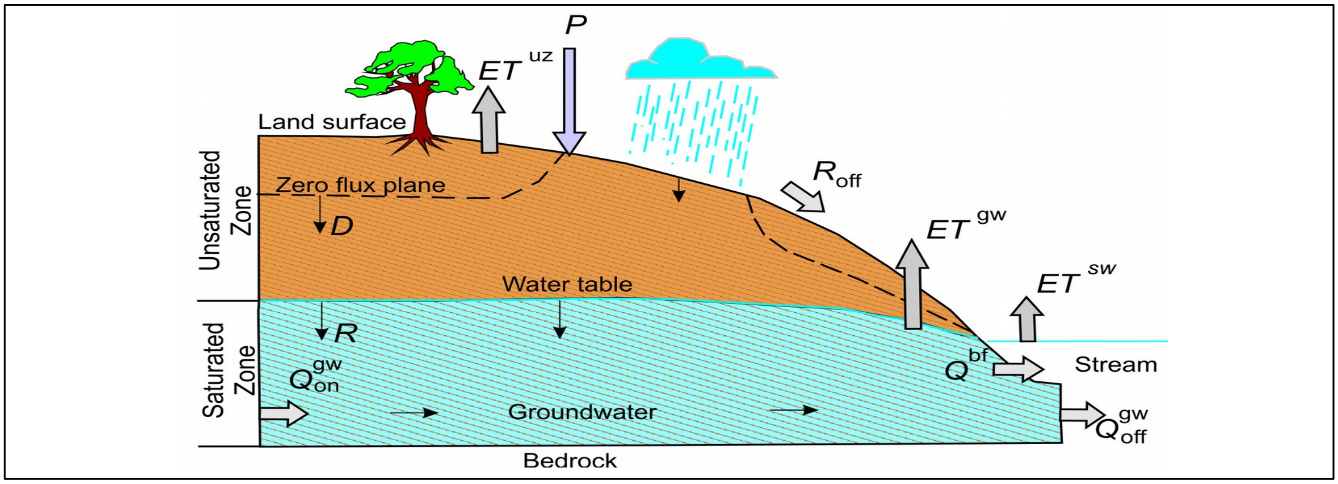


Figure 4. Diagram through a watershed showing water budget components and directions of water movement (Healy, 2010).

There is a delay between the recharge contribution to the water table and its redistribution to other terms, such as base flux or evapotranspiration. Therefore, if the method is applied during this delay, all the water input will be recorded as recharge. This is valid especially in short lapses of time that range from hours to a few days, although the method has been applied successfully in periods of years and decades (Healy, 2010). In relation to time steps, Morgan and Stolt (2004) found that the recharge estimated using weekly groundwater levels was 33% lower than the one calculated with those levels measured every 30 minutes in the same well and period of time. In general it is recommended to have values with weekly or major frequencies.

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) (Figure 5). The recession curve is the trace that the hydrograph would have followed in the absence of a rise-producing precipitation. According to Scanlon et al. (2003) 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 Equation (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, ΔS^{gw}. This value is sometimes referred to as **"net" recharge** (Healy and Cook, 2002) 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 equation 2, which is the difference of the height between the beginning and the end of the interval (Healy, 2010), Figure 5.

In this paper the rise of groundwater levels observed in the registered water level series (phreatigram) were considered and **net recharge** using Δh was calculated by *Likqo 1.0*, which make the calculus employing Equation (2). This software permits to leave out any level rise that may be due to factors other than the actual recharge. In this case, it was left out any value of change under 3 mm related to fluctuations linked with the equipment itself. This was evaluated in relation to constant water levels tests made in laboratory and checked with the equipment manufacturer.

Regarding to the storage coefficient S (effective porosity of the unconfined aquifer), the use of a uniform value can produce errors in the estimations (Varni, 2002). In spite of this, the available average value of S is used (Blarasin, 2003).

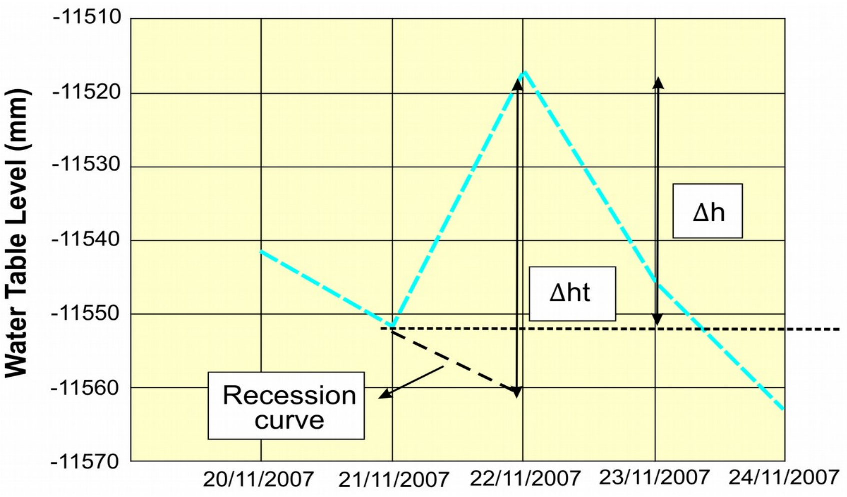


Figure 5. Measurements to be performed for the recharge estimation

The depth of the water table is important in the analysis of the recharge (***R***). Normally, the application of the WTF method for estimating recharge requires identification of the water-level rises that are attributable to precipitation or surface water, which can be a difficult task (Healy, 2010). If the unsaturated zone is of small thickness, the water that percolates into the fractures can rapidly arrive to the water table, and the recharge would thus be *episodic*, in response to rain events. Moreover, shallow depths to the water table are also susceptible to discharge by evapotranspiration. Thick unsaturated zones are less susceptible to having episodic recharge events and thus a stable recharge is expected to occur. This can be explained by the fact that wetting fronts that go down the unsaturated zone tend to move more slowly and several wetting fronts can join and become indistinguishable (Healy, 2010). Bearing in mind all these aspects, and the fact that depth to the water table was average 11.5 m at the place where the measurements were done, it was decided to evaluate all the measurable water-rises that are believed to be caused by the arrival of a wetting front.

On the other hand, according to Healy (2010), if additional assumptions are taken into account, the WTF method can be used to *estimate any of the parameters involved in equation 1* (e.g. Q^{bf}, ET^{gw}). White’s (1932) (Figure 6) and Schilling and Kiniry´s (2007) works are also important since they estimate evapotranspiration ET^{gw} by considering discharge as an effect of this process for shallow water tables (assuming Qb=0 and R=O for these moments) by measuring the level falls in the daytime fluctuations and multiplying them by S. This paper takes these criteria for assessing aquifer discharge (***D***). In this case it is assumed that if the recession line of each peak in the hydrograph is taken, the water table fall would be linked to the discharge but, assuming also that it is below the zero flux plane (Healy, 2010), it is not caused by evapotranspiration from the aquifer because of the depth of the groundwater level (11.5 m). This simplification suggests that if there is a water level fall (R=0) and ETR=0 (below zero flux plane) and, if Equation (1) is considered, the registered fall is *discharge* attributable to Qb (Figure 7), and assuming that Q^{gw}_{off} and Q^{gw}_{on}.are equal and have opposite signs.

The software *Liqko 1.0* makes it possible to calculate R (equation 2), D (equation 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. In the first place and, as shown in Figure 8, it is worth to highlight that there are not significant differences in the water level position along the analyzed series, with a maximum of 12.30 and a minimum of 11.30 m despite there are dry and wet years (Table 1).

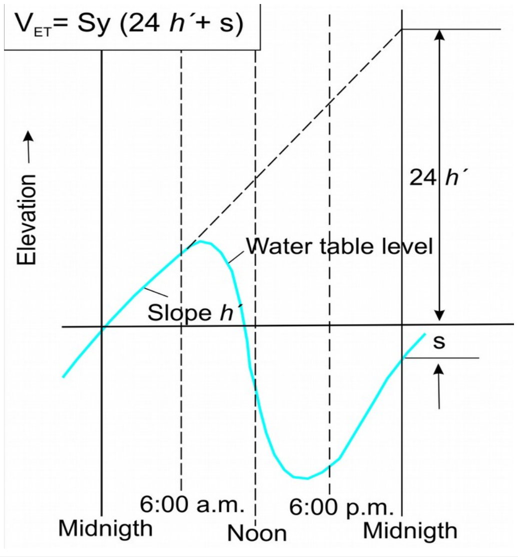


Figure 6. White method (1932) for estimating evapotranspiration (ET) (extracted from Healy, 2010)

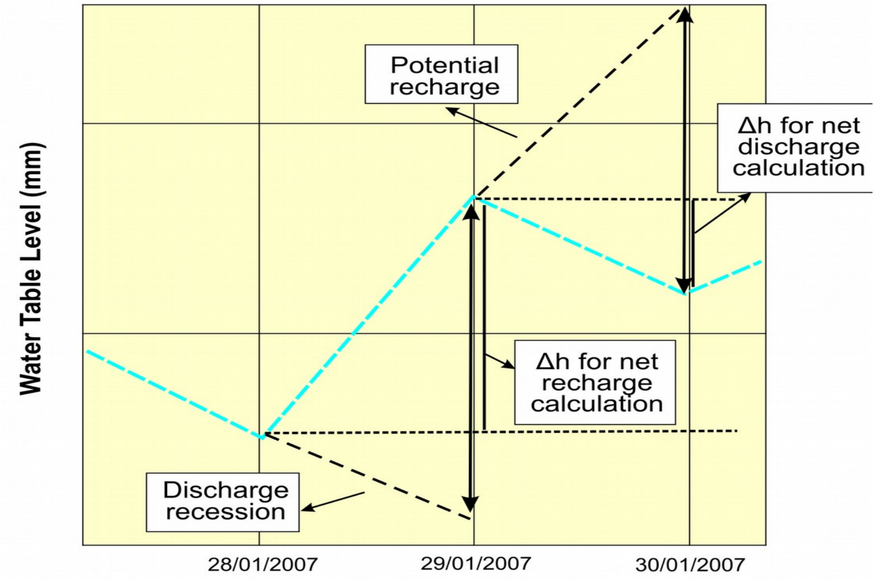


Figure 7. Measurements to be performed for the discharge estimation

Table 1. Annual rainfall, aquifer recharge and discharge.

RECHARGE (R), DISCHARGE (D) AND BALANCE BETWEEN R and D (EOLIAN PLAIN NEAR RIO CUARTO CITY) Hydrological year						
PERIOD	PRECIPITATION (mm)	RECHARGE (mm)	DISCHARGE (mm)	BALANCE (mm)	POROSITY	R as %P
21/09/2002– 20/09/2003	769	109	97	12	0.05	14.2
21/09/2003 – 20/09/2004	891	97	106	-9	0.05	10.9
21/09/2004 – 20/09/2005	897	94	89	5	0.05	10.5
21/09/2005 – 20/09/2006	647	74	110	-35	0.05	11.5
21/09/2006 – 20/09/2007	930	118	92	26	0.05	12.7
21/09/2007 – 20/09/2008	821	114	102	12	0.05	13.9
21/09/2008 – 20/09/2009	639	75	100	-24	0.05	11.8
Average	799	97	99	-1.89		12.2

Next, comparing the daily variation of the water table level with the previous one (Figure 9), the similarities between the variations in the rises and falls are remarkable, with a maximum of 0.58 for the falls and a maximum of 0.52 for the rises. These results would indicate that the aquifer has similar possibilities for recharge and discharge and that it has not inertia for the discharge, a fact that is coherent with the position of the evaluated well: close to the water divide and a high slope oriented towards a discharge area (the Río Cuarto river). In contrast to what can be observed here, the inertia is high in discharge processes in low plain areas and, therefore, water storage and level rises are notorious (Ferreyra y Rodriguez, 2005).

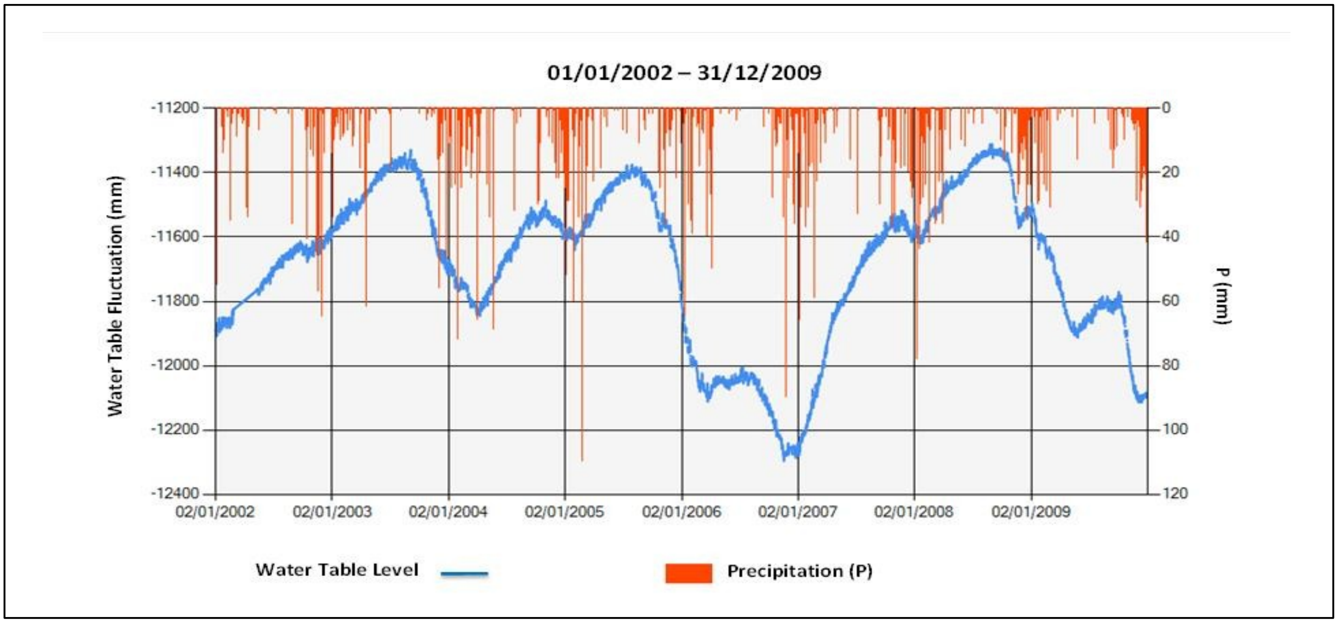


Figure 8. Water Table Fluctuation vs Precipitation

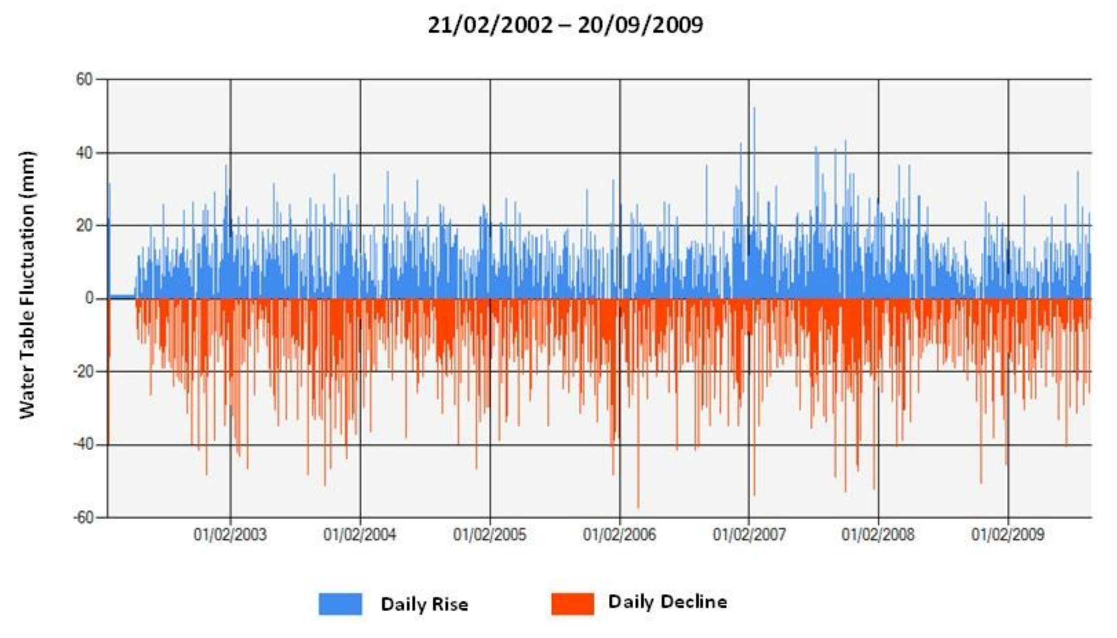


Figure 9. Daily variation of the water table level in relation to the previous day level

The recharge was calculated for each hydrologic and calendar year (Table 1). The calculation by hydrologic year turned out to be more appropriate due to the regression between R and P (r^2=0.6 Figure 10). The moderate recharge value of r^2 -despite being somewhat influenced by seasonality- may be attributed to the fact that if the unsaturated zone is thick, it is less susceptible to having episodic recharge events. Thus, a more stable recharge process could be expected throughout the year that is, less correlated to the storms due to the level depth. The mean R for the whole series was 12% of precipitation and the hydrologic years of greatest recharge were 2002-2003 and 2007-2008 (approximately 14% P) while the years of lowest recharge were 2004-2005 (10%P).

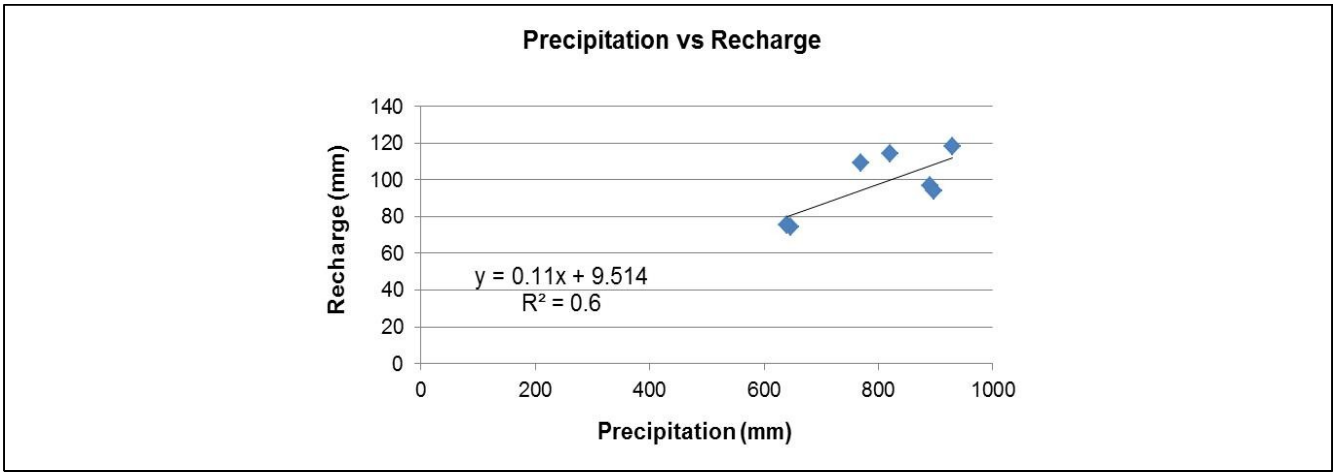


Figure 10. Relationship between rainfall and recharge

Similarities are observed in the behavior of the recharge between seasons (Figure 11) although there is a slight decline in winter when precipitations are scarce. However, efficiency in the recharge is observed and it is interpreted as a result of delayed wetting fronts and the low rates of AET in this season. This may explain the high correlation between the Precipitation and Recharge in winter (Figure 12), which accounts for an increasing water table level in 70% of the years under analysis (Figure 13). In spite of the fact that the seasonal differences of the recharge are not great, the best correlation between the annual *P* (hydrological year) and the aquifer recharge occurs in winter (*r*=0.9) and autumn (*r*= 0.8). This correlation goes down to *r*= 0.6 and 0.5 in spring and winter respectively. It is important to show up the delay of the rises of the water table level (days or months) in relation to some storms, a phenomenon which can be attributable to the water table depth.

As explained earlier, the computer software *Liqko 1.0* makes possible the calculation of the aquifer discharge (*D*). The highest discharge (110 mm) was observed in the period 2005-2006 and the lowest (89 mm) in the period 2004-2005 (Table 1). The relation recharge-discharge (*R/D*) is maximum and negative (-35 mm) in the period 2005-2006 (26 mm), which coincides with the maximum recorded

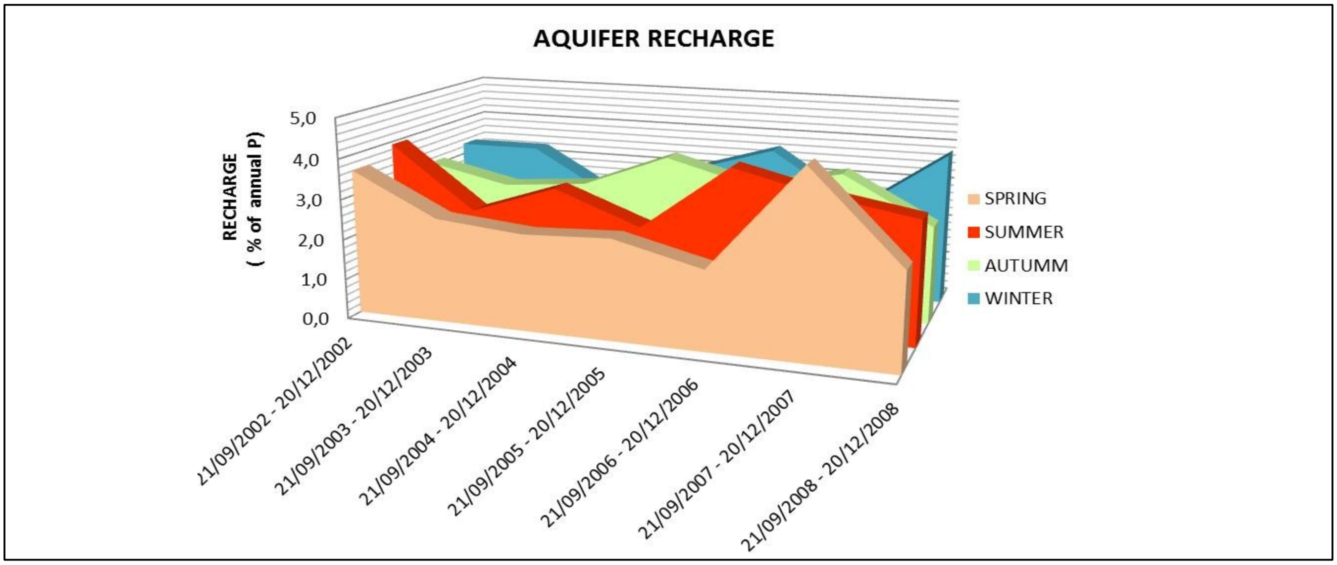


Figure 11. Recharge estimation for each season (hydrological year)

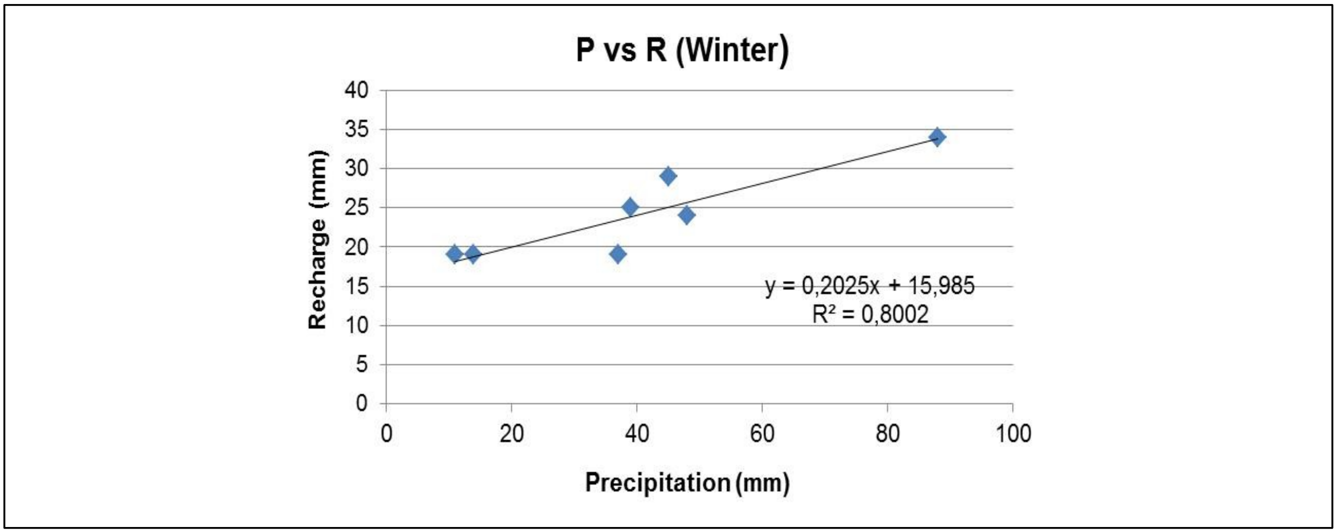


Figure 12. Correlation between the Precipitation and Recharge (winter season).

level fall, and it is maximum positive in 2006-2007 (26 mm), which agrees with the maximum rises, when a water table level recovery is observed. The latter can be attributed to the fact that in July 2007 there was an important snowfall (more than 30 cm) that lasted for a week (Figure 13). The ratio *R/D* for the whole series was slightly negative (Table 1), which means that the aquifer discharge was dominant, a fact that is coherent with the lower position of the water table at the end of the series.

Finally, it is important to point out the fact that very similar values were obtained in the same place (the overall *R* value lying between 10-12% of *P*) when calculated with other methods (chlorides and total balance methods) for other similar humid-dry cycles (Blarasin, 2003).

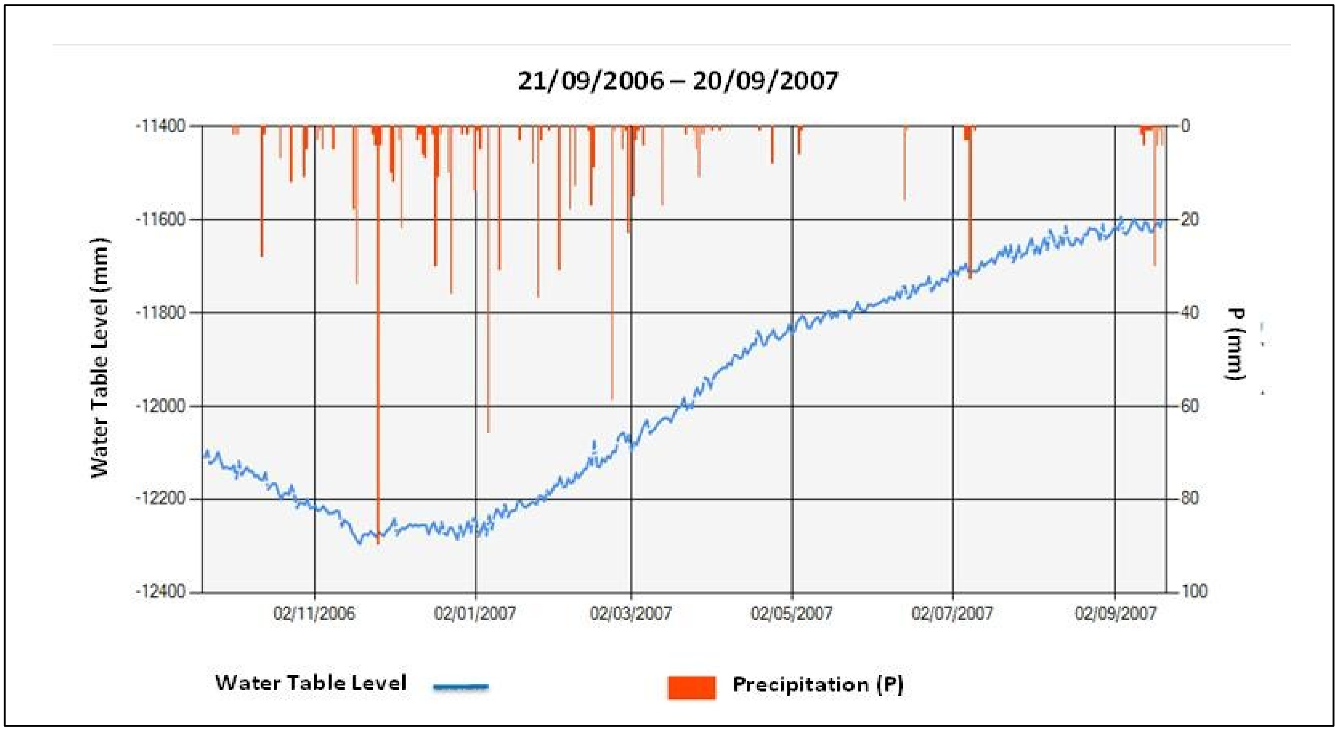


Figure 13. Precipitation vs Recharge during 2006-2007 (hydrological year)

CONCLUSIONS

The average aquifer recharge value for the entire series was 12% of precipitation, the highest recharge occurring in the hydrological periods 2002-2003 and 2007-2008 (14%) and the lowest in 2004-2005 (10 %).

The aquifer recharge was calculated for both the hydrological and calendar year, where the first resulted more appropriate given the higher *R-P* correlation obtained (related to seasonal water table rises). The best correlation of the annual *P-R* (hydrological year) occurs in summer (*r* 0.9) and autumn (*r* 0.8).

There is a similar behavior of *R* between seasons, with slight falls in winter, when *P* are scarce. However, low rates of actual evapotranspiration appear to be able to maintain the recharge process efficiency which results in a water table rise during winter as observed in 70% of the years under analysis. This effect can be related to delayed wetting fronts. It is important to highlight the recharge delay (2-6 days) in relation to what would be expected from storms; a fact that can be related to the depth of the water table.

The new software *Liqko 1.0* made the calculation of the aquifer discharge (*D*) possible. It showed that the greatest value of groundwater discharge occurred in the 2005-2006 cycles, the highest recorded of 110 mm, 13.7% of *P*. The ratio *R/D* was slightly negative, which means that aquifer discharge was dominant, coinciding with the lowest position of the water table at the end of the studied period.

Taking into account the easily management of the computer code, the calculus may be done very quickly for different period of hydrological interest.

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