Weekly and Monthly Groundwater Recharge Estimation in A Rural Piedmont Environment using the Water Table Fluctuation Method

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Abstract— *La Colacha basin (Córdoba province, Argentina) is a typical piedmont rural area where the unconfined aquifer is used 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 and weekly recharge rhythms and to the aquifer discharge (D) were performed. The aquifer shows a typical behavior of groundwater recharge areas with an important and quick answer of water table to the arrival of precipitations (P). After that, a recession curve is observed, representing the groundwater discharge to the local base level (the main stream of the basin). The monthly estimation resulted in an annual average R value of 14.3 % of total P. Although the major amounts of recharge occur in full summer, according to the major total amounts of P, the correlation between monthly R and P was low (r^2 < 0.2) as a result of the high quantities of rainfall water that are converted into runoff. The regression coefficient is higher (r^2 = 0.6) for the end of summer and autumn when rainfalls diminish and have low intensities. This situation provides less water to the aquifer, but the recharge process is more efficient. The ratio R/D for the 3 year series was positive, which means that the aquifer recharge was dominant. In the weekly recharge analysis, the annual average R is slightly lower than in the monthly one, that is, 12.4 % of the total P. Thus, it may be concluded that, in this case, the change from monthly to a weekly time step, did not much improve the final value. However, the information obtained with the weekly estimation is much more useful to interpret the aquifer detailed behavior.*

Keywords— recharge, time step, unconfined aquifer

I. INTRODUCTION

Although groundwater is the most used resource worldwide it is not only involved in the water abstraction for several uses, but also in numerous ecosystems behavior. The analysis and quantification of the aquifer dynamics and recharge is a vital requirement for an efficient management of groundwater resources [1, 2, 3, 4], 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 [5, 6]. Thus, the identification and the definition of a conceptual model of groundwater flow and recharge processes are of major significance. 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. Thus, geological and groundwater data are essential to elaborate numerical models to test and improve the conceptual model and the aquifer management.

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 greatly desirable, uncertainty in estimates generated by current methods remains as well as the difficulty in assessing the uncertainty associated with any given estimate [2]. Recharge is defined as the downward flow of water reaching the water table, adding to groundwater storage [2]. Groundwater recharge occurs through diffuse and focused mechanisms as can be seen in Figure 1.

Specifically, recharge processes in unconfined aquifers of the Argentinian Pampean plain must be described and quantified to evaluate the groundwater resources to be used and the replenishment from rainfalls. Furthermore, the evaluation is required because groundwater is susceptible to the arrival of contaminants, which are able to reach the water table justly through recharge water [7].

In La Colacha basin (Córdoba province, Argentina), a typical piedmont rural area (Fig. 1) groundwater studies were carried out due to the importance of the unconfined aquifer for human consumption and, especially, for rural water supply (mainly cattle). 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 of La Colacha basin, using the water table fluctuation method (WTF). Several considerations in relation to monthly and weekly recharge rhythms and to the aquifer discharge were also included in this paper.

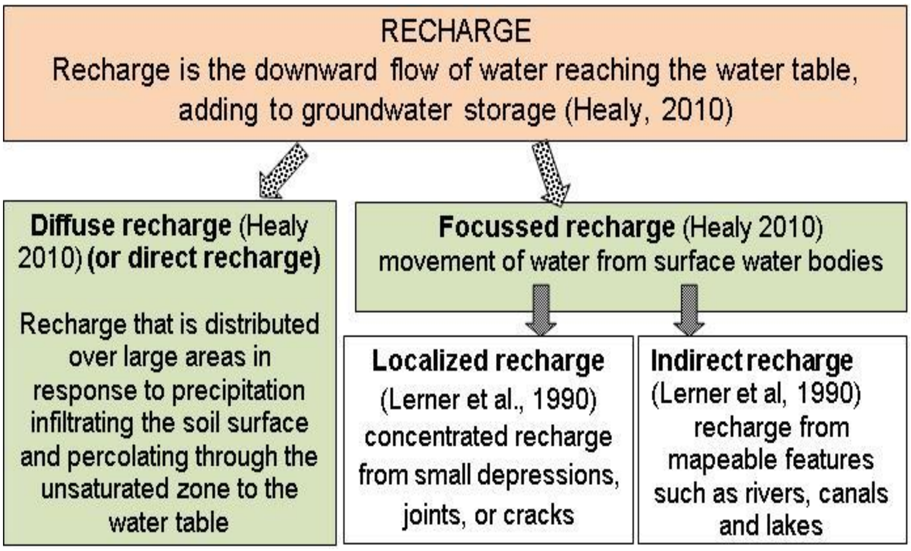

FIG. 1 TYPES OF AQUIFER RECHARGE [5]

II. 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 [8, 9]. 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 2006 (Fig. 2). For this paper, the period of 36 months between 01/09/2006 and 01/09/2009 is used, taking into account the hydrological year criterion, that is, the annual period that does not disrupt the seasonal cycle of rain, which is different from the calendar year. 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 contribute to regulatory aspects, etc. The aquifer recharge was estimated using the known WTF method following Healy [2] suggestions. The *Liqko 1.0* software developed by Alincastro and Algozino [9] 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.

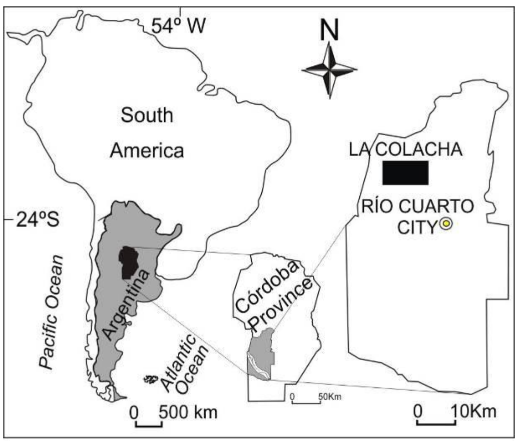

FIG. 2 LOCATION OF STUDY AREA

III. RESULT AND DISCUSSION

3.1 Geology, hidrogeology and climate

The Colacha stream basin is mostly located in the Sierras Pampeanas piedmont area. The upper basin is developed in the mountain, where metamorphic rocks outcrop (Fig. 3). The rest of the area is covered by Holocene and Upper Pleistocene sediments. Most of the basin area is covered by silty-sandy aeolian sediments of loessical type, while sandy-gravel fluvial deposits are restricted to the streams surroundings. Colluvial deposits may be found near the mountains. The basin has an undulating relief, with a regional slope in the order of 2 %.

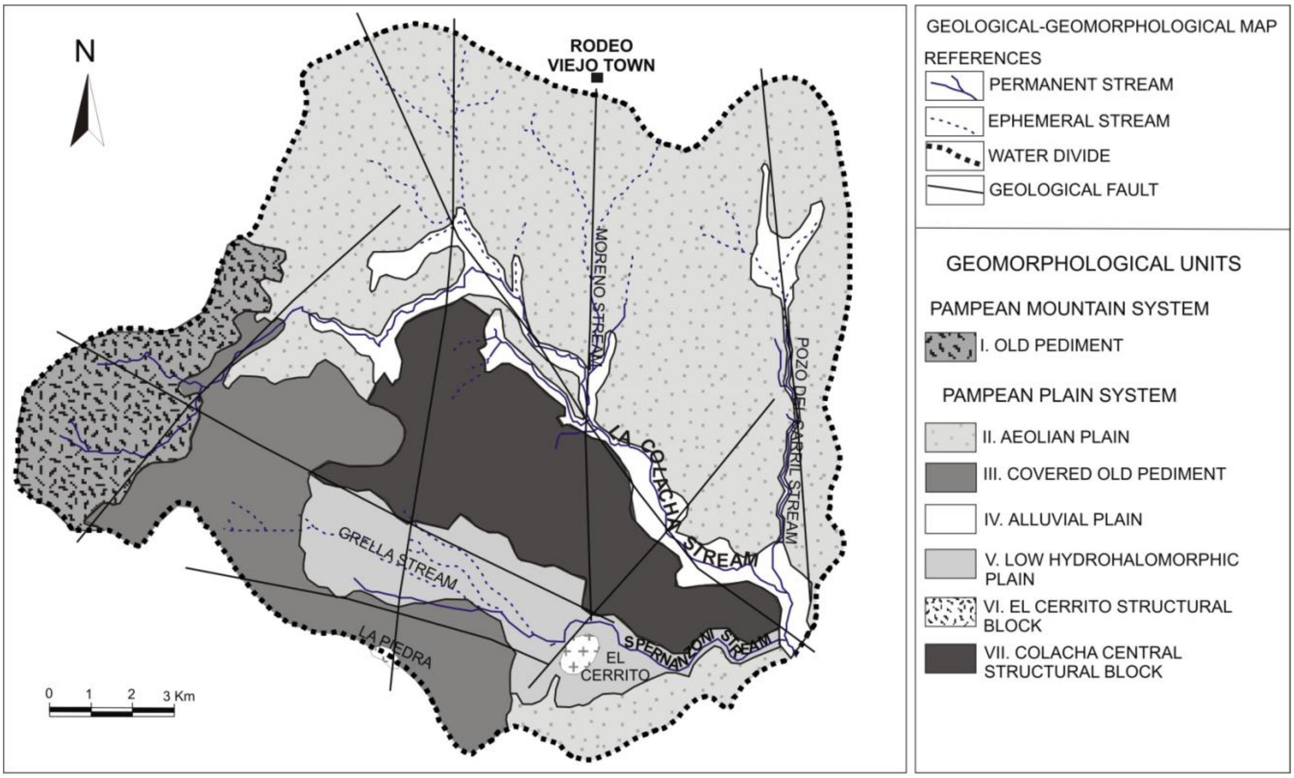

FIG. 3 GEOMORPHOLOGICAL UNITS OF LA COLACHA BASIN (CORDOBA ARGENTINA)

The hydraulic parameters of the aquifer were defined according to the textural characteristics of the sediments and *in situ* aquifer tests [10]. In relation to the aeolian environment, where water table fluctuation is evaluated in this paper, the average value of transmisivity (T) is 80-400 m^2/day, the hydraulic conductivity (K) is 1-5 m/day and the average storage coefficient (S) is in the order of 0.15. The groundwater flow direction can be observed in Figure 4. From the location where the pressure sensor was placed, groundwater flows towards the main stream of La Colacha system in a NW-SE direction (Fig. 4).

The regional climate is sub-humid-dry, with an annual mean precipitation (P) of 780 mm for a series of 30 years. Most of the precipitation, about 75-80%, is concentrated during the end of spring, summer and early autumn. In the average water balance, the calculated annual mean potential evapotranspiration (PET) is 820 mm whereas the actual evapotranspiration (AET) is 780 mm. A sequential monthly water balance, linking one month to another, allowed better interpretations about water behavior. Thus, alternating water deficit and water excess periods were observed [9, 10], especially depending on the annual precipitation. The water excess or surplus is distributed in surface and groundwater recharge. The most important aspects related to aquifer recharge will be discussed in the following section. The selected period for the recharge calculation shows an annual mean precipitation of 633 mm, that is, it may be characterized as a general dominant dry cycle although it also includes a humid period (09/2006 - 09/2007).

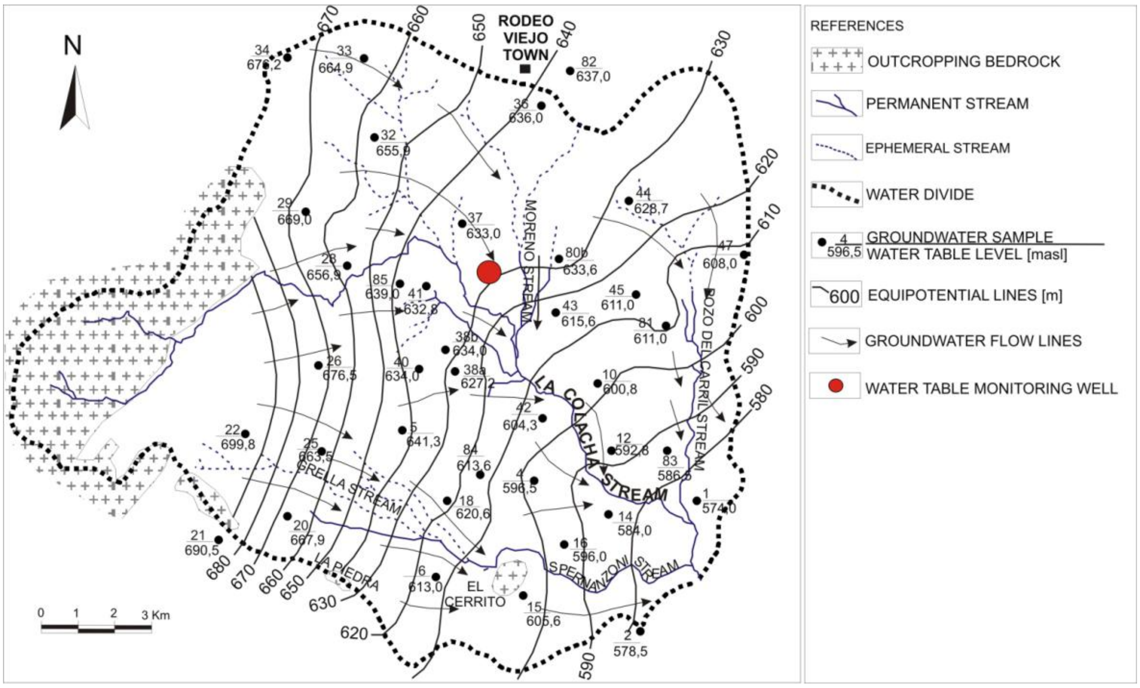

FIG. 4 EQUIPOTENTIAL MAP OF THE UNCONFINED AQUIFER

3.2 Estimation of groundwater recharge and discharge

In the studied area, diffuse recharge was estimated to be dominant, taking into account the hydrogeological features. It is important to mention that the recharge was calculated with data recorded every 15 minutes in a monitoring well. 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 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: ([2], Fig. 5):

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

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 [2] 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. 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 [2]. Different time steps can be used for the recharge calculus, and different results were obtained. In general, it seems that the smaller the time step, the best the recharge estimation. Morgan and Stolt [11] 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.

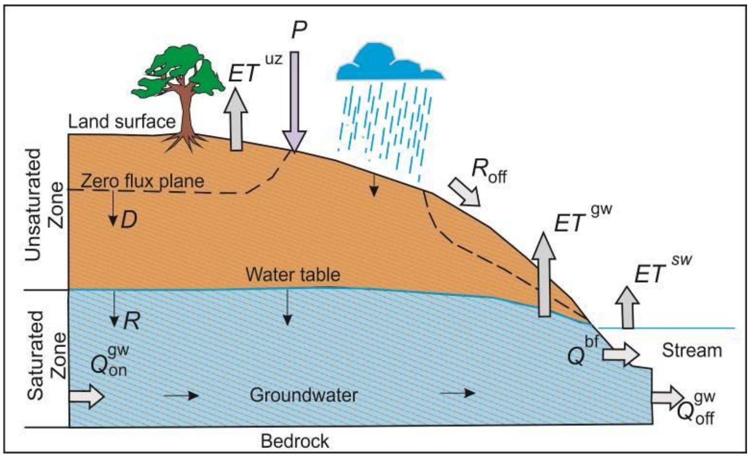

FIG. 5 DIAGRAM THROUGH A WATERSHED SHOWING WATER BUDGET COMPONENTS AND DIRECTIONS OF WATER MOVEMENT [2]

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. 6). 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. [5] 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. The (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** [12] 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 [2], Figure 6.

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). This software allows leaving out any level rise that may be due to factors other than the actual recharge. In this case, any value of change under 3 mm related to fluctuations linked with the equipment itself was left out. 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 available average value of S was used.

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 to accomplish [2]. 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. Instead, thick unsaturated zones are less susceptible to having episodic recharge events and hence a stable recharge is expected. This occurs when wetting fronts that go down the unsaturated zone tend to move more slowly and several wetting fronts can join and become indistinguishable [2]. Taking into account these aspects, and the depth to the water table at the place of measurements (in the order of 9.0 m), it was decided to evaluate all the measurable water rises that are believed to be caused by the arrival of a wetting front.

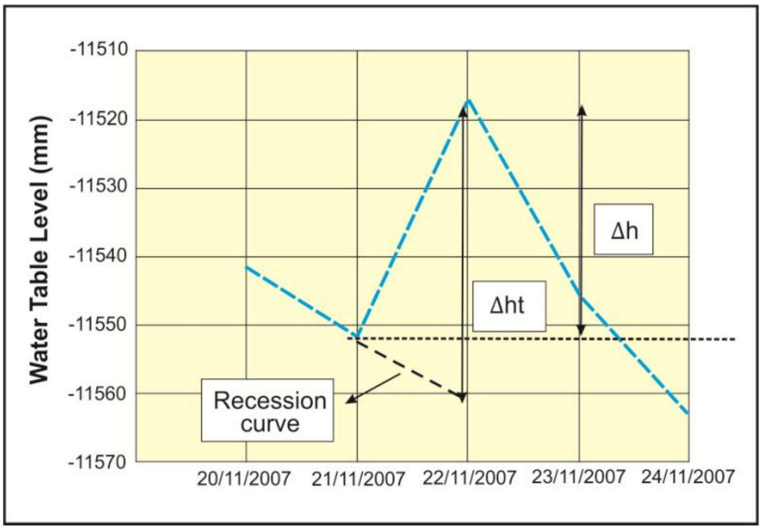

FIG. 6 MEASUREMENTS TO BE PERFORMED FOR THE RECHARGE ESTIMATION

On the other hand, according to Healy [2] 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}). Therefore, and taking into consideration the criteria established in Healy [2], Blarasin et al [5] and Schilling and Kiniry´s [13] the aquifer discharge (**D**) was estimated too in this paper (Fig. 7). 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 [2], it is not caused by evapotranspiration from the aquifer due to the important water table depth (9.2 m). This simplification suggests that 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 $Q^{gw}{}_{off}$ and $Q^{gw}{}_{on}$. are equal and have opposite signs.

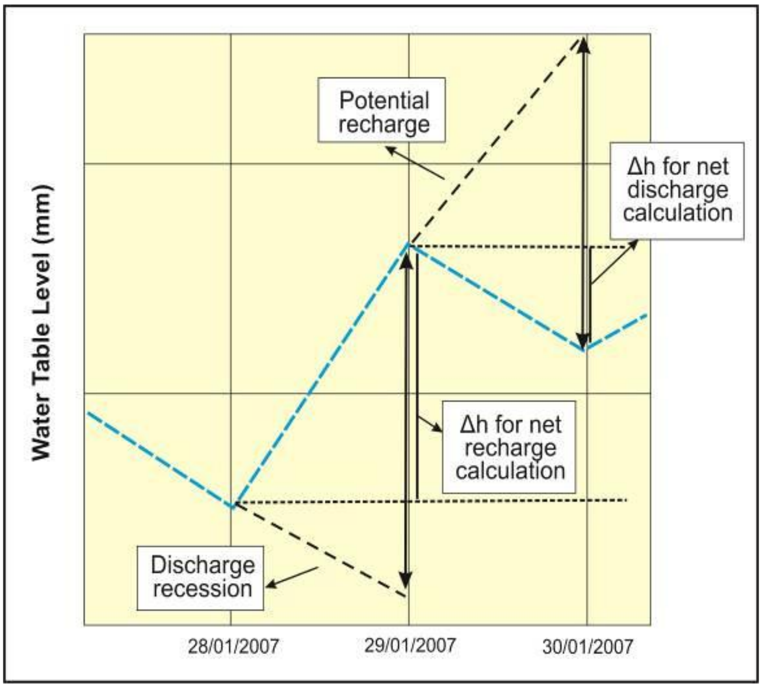

FIG. 7 MEASUREMENTS TO BE PERFORMED FOR THE DISCHARGE ESTIMATION

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. The information is saved in an Excel spreadsheet.

First, as is shown in Figure 8, it is worth to highlight that, although not very significant, there are differences in the water level depth along the analyzed series, with a maximum of 9.75 and a minimum of 8.70 m, following the dry and wet cycles. Next, comparing the daily variation of the water table level with the previous one (Fig. 9), it is notorious that there are very clear level rise cycles, with peaks in summer. After these, the daily level changes decline in a "recession curve" until late autumn and then, the water level decreases in winter and early spring. It is observed that, in relation to the variations in the rises and falls, there was a maximum of 0.15 m for the falls and a maximum of 0.25 for the rises. These results and the general appearance for the curve of Figure 9 would indicate a typical behavior of recharge areas with an important and quick answer to the arrival of precipitations and then the discharge to the base level (the main stream of the basin).

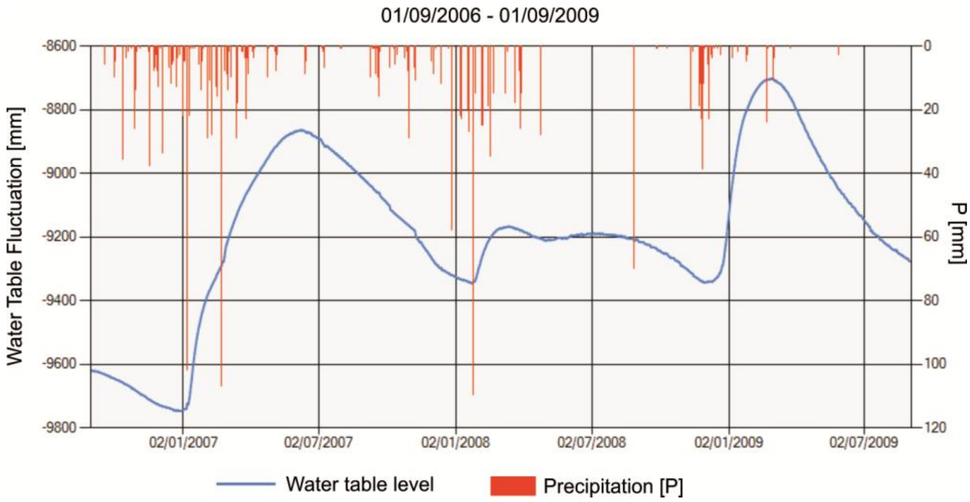

FIG. 8 WATER TABLE DEPTH VS. PRECIPITATION

The monthly recharge was calculated for each month of each hydrologic year (Table 1). The calculation by hydrologic year is considered to be more appropriate due to the higher correlation between R and P, as was demonstrated by other authors [14].

TABLE 1.
MONTHLY ESTIMATION: RECHARGE (R), DISCHARGE (D) AND BALANCE BETWEEN R AND D IN LA COLACHA BASIN

MONTHLY GROUNDWATER RECHARGE ESTIMATION						
HYDROLOGICAL YEAR	PRECIPITATION [mm]	RECHARGE [mm]	DISCHARGE [mm]	BALANCE [mm]	POROSITY	Ras %P
09-2006/08-2007	886	134	46	88	0.15	15.1
09-2007/08-2008	762	41	58	-27	0.15	5.3
09-2008/08-2009	251	96	107	-11	0.15	38.4
TOTAL	1899	271	221	50		14.3

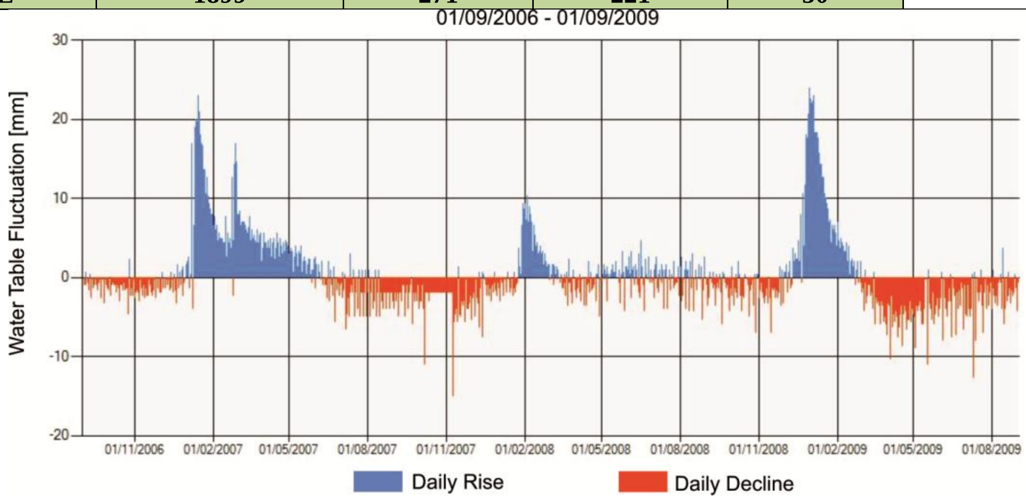

FIG. 9 DAILY VARIATION OF THE WATER TABLE LEVEL IN RELATION TO THE PREVIOUS DAY LEVEL.

However, in La Colacha basin, the regression coefficient is low (R < 0.2). This situation may be explained if the high intensity of rains during spring and full summer is considered. Consequently, a significant part of rainfall water is converted into runoff, a scenario that may be clearly observed at field. In this sense, this piedmont area is one of the most affected by erosional processes (gullies and ravines). The regression coefficient only has a moderate to high value (R = 0.6) when the relationship between R and P is evaluated for the end of summer and autumn (Fig.10). That is, 60 % 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.

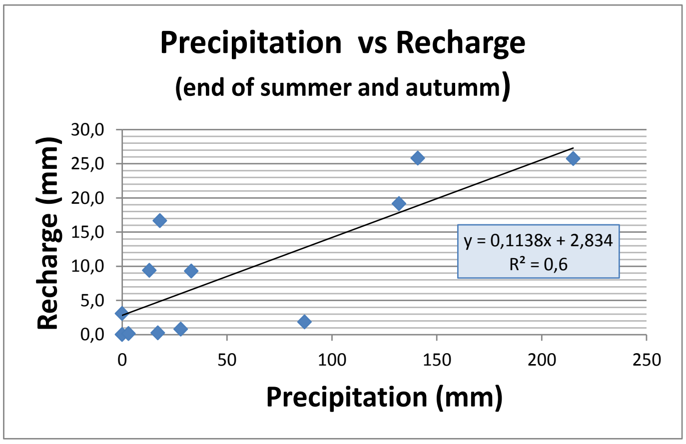

FIG. 10 RELATION BETWEEN P AND R

The mean annual recharge, taking into consideration monthly calculations for the whole series, was 14.3 % of the total precipitation. As is shown in Figure 11 the major amounts of recharge (in the order of 50 mm) occurred in full summer, in January, according to the major total amounts of rainfalls. The 2007-2008 year shows low recharge successive peaks during autumn and winter, which may be the consequence of delayed wetting fronts coming from minor intensity rainfalls.

As explained earlier, the computer software *Liqko 1.0* makes the calculation of the aquifer discharge (D) possible. The highest discharge (107 mm) was observed in the period 2008-2009 and the lowest (46 mm) in the period 2006-2007 (Table 1). The ratio Recharge /Discharge for the whole series was positive (Table 1), 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 studied series (Fig.8).

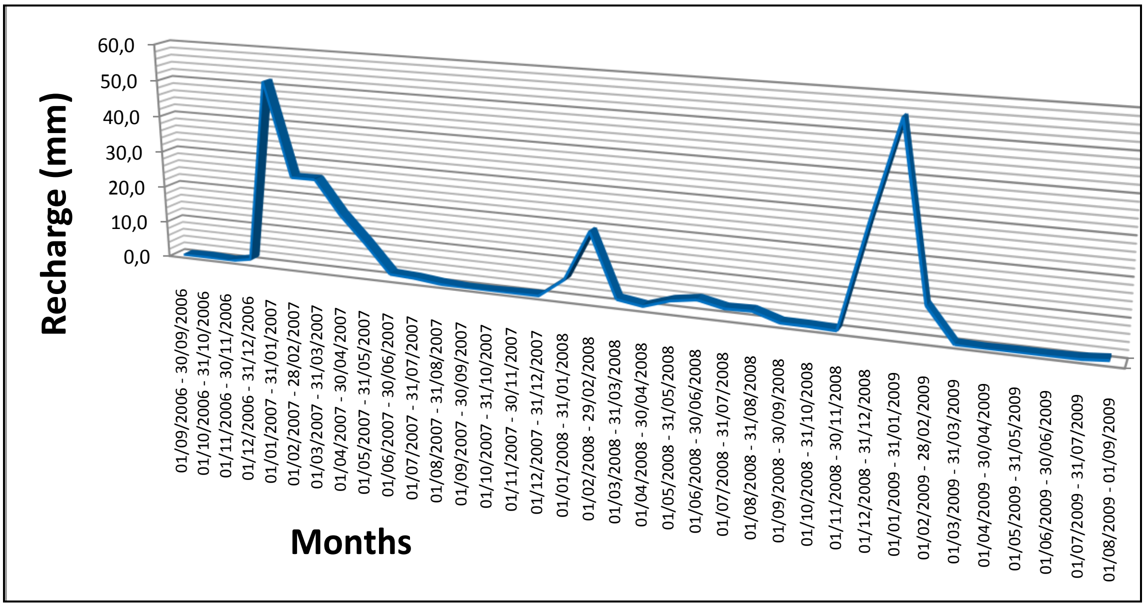

FIG. 11 EVOLUTION OF MONTHLY GROUNDWATER RECHARGE FOR THE 36 MONTHS (09/2006-09/2007)

The weekly recharge analysis was made to compare with the monthly analyses. As it can be seen in Table 2, the aquifer recharge in the 3 years is slightly lower, that is, 191 mm or 12.4 % when is expressed as a percentage of the total precipitation. In this case, the change from monthly to a weekly time step did not improve the general information because the final result was similar and even somewhat lower despite having decreased the time step.

TABLE 2.
WEEKLY ESTIMATION: RECHARGE (R), DISCHARGE (D) AND BALANCE BETWEEN R AND D IN LA COLACHA BASIN

WEEKLY GROUNDWATER RECHARGE ESTIMATION						
HYDROLOGICAL YEAR	PRECIPITATION [mm]	RECHARGE [mm]	DISCHARGE [mm]	BALANCE [mm]	POROSITY	Ras %P
09-2006/08-2007	886	116	39	78	0.15	13.0
09-2007/08-2008	762	34	58	-24	0.15	4.5
09-2008/08-2009	251	85	94	-8	0.15	33.8
TOTAL	1899	235	191	46		12.4

However, the data and the graph obtained with the weekly information (Fig.12), is much more detailed and more useful to interpret the aquifer behavior.

Finally, it is important to point out the fact that similar values were obtained in the region, that is, the overall R value lying between 10 – 12 % of precipitation when is calculated with other methods (chlorides and total balance methods) for similar humid-dry cycles [15].

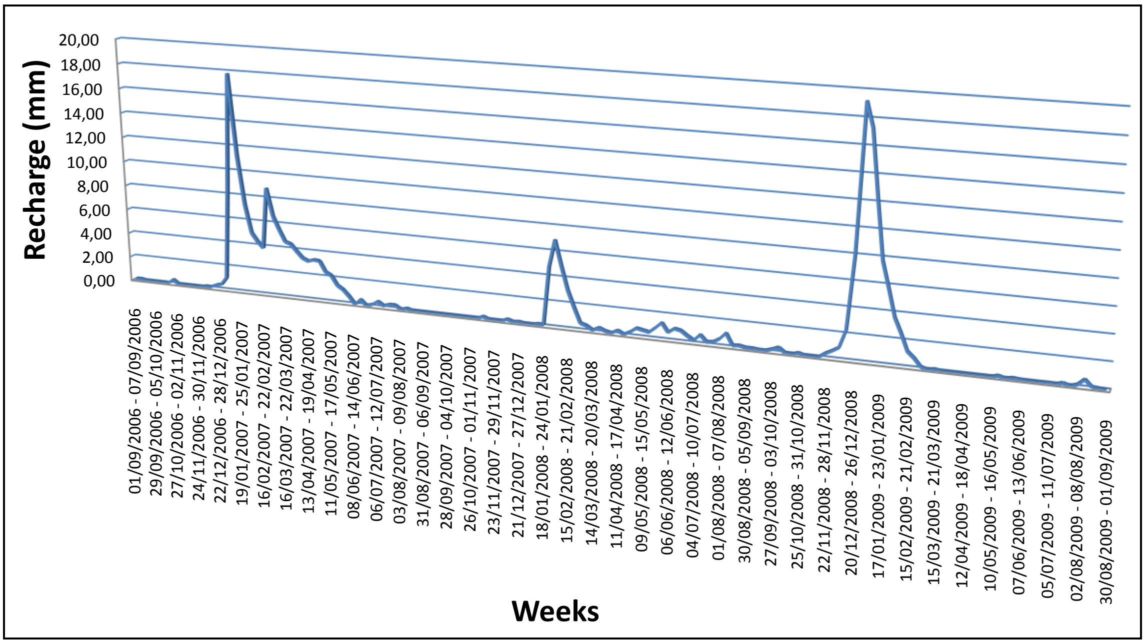

FIG. 12 EVOLUTION OF WEEKLY GROUNDWATER RECHARGE FOR 156 WEEKS (09/2006-09/2007)

IV. CONCLUSION

The evaluated unconfined aquifer in the piedmont environment shows a typical behavior of 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 main stream of the basin. A delay of the rises of the water table level (days) was observed in relation to the main storms, a phenomenon attributable to the water table depth.

Using monthly estimation, an annual average recharge value of 14.3 % of total precipitation was obtained. The correlation between monthly R and P was low ($r^2 < 0.2$), a situation that may be related to the high quantities of rainfall water that are converted into runoff and do not arrive to the aquifer. Nevertheless, the major amounts of recharge (in the order of 50 mm) occurred in full summer, according to the major total amounts of rainfalls. The regression coefficient is higher ($r^2 = 0.6$) for the end of the summer and autumn as a consequence of minor rainfall quantities and intensities. Thus, less water is provided to the aquifer, but the recharge process is more efficient and clearly linked to rainfalls. The 2007-2008 hydrological year shows low recharge successive peaks during autumn and winter which may be the consequence of delayed wetting fronts coming from minor intensity rainfalls.

The ratio Recharge/Discharge for the whole series was positive 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 studied series.

In the weekly recharge analysis, the aquifer recharge in the 3 years is slightly lower than the monthly estimation, that is, 12.4 % of the total precipitation. It may be concluded that, in this case, the change from monthly to a weekly time step, did not improve the general information. Thus, the final result was similar and even a little lower, despite having made the calculations with a laborious weekly time step. However, the information obtained with the weekly estimation is much more useful to interpret the aquifer detailed behavior.

Taking into account the easy management of the computer code, the calculus may be done for different periods of hydrological interest, including daily time steps. Nevertheless, and even though it is recommended to have values with weekly or major frequencies, the monthly time step can be very useful to analyze long periods to have a first approach to the aquifer behavior.

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