GROUNDBASE RECHARGE ESTIMATIONS FROM STUDIES OF THE UNSATURATED ZONE

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Abstract: This paper presents two independent methodological approaches for estimating groundwater recharge from data collected in an experimental plot located in a plain region in Argentina. The first method is a direct application of Darcy equation at a flow plane 120 cm deep, whereas the second method took into account a water balance based on groundwater level data using the Visual Balan program. A time period of 711 days was used, after which both methods yielded a recharge of 11 % (expressed as percentage of the rainfall in the same period). The first method concentrated the recharge events in autumn, whereas the Visual Balan was able to reproduce smaller recharge events probably related to the existence of preferential flow paths.

Resumen: En este trabajo se comparan los resultados obtenidos mediante la aplicación de dos metodologías independientes para la obtención de la recarga a partir de datos obtenidos en una parcela experimental ubicada en una zona de llanura. Por un lado se aplicó la ecuación de Darcy en la zona no saturada en un plano de flujo a 120 cm, y por otra parte se apeló a un balance hídrico basado en datos del nivel de agua subterránea, mediante aplicación del programa Visual Balan, para la obtención de la recarga. Las recargas obtenidas con ambos métodos fueron comparadas para un periodo de 711 días, obteniéndose una recarga algo superior al 11 %. Los flujos al acuífero a través del plano de 120 cm se concentraron en los meses de otoño, en cambio el modelo reprodujo otras recargas posiblemente vinculadas a flujos preferenciales.

Keywords: recharge (recarga), unsaturated flow (flujo no saturado), Azul River basin (cuenca del arroyo del Azul).

INTRODUCTION

Supplementary irrigation that relies almost entirely on groundwater resources has steadily grown in many regions of the Argentine humid pampas in the last years. Although no reliable records of number of wells drilled or the individual discharges exist, it becomes evident that there has been an increase in the use of groundwater resources. For instance, in the study area, located in the center of Buenos Aires Province, Argentina, individual wells may yield more than 120 m³h⁻¹; yet, their operation is not ruled by the provincial authorities. Given such a situation, appropriate knowledge of the recharge to the regional aquifers is needed in order to help shape future policies regarding water resources management.

LOCATION

The study area is located in the Azul River basin, Buenos Aires Province, Argentina. It corresponds to a large, flat-land scenario, with regional surface slopes in the order de 0,5 to 0,8 %. According to the Thornthwaite classification, the climate is sub-humid to humid, medium range of temperatures, with scarce or null deficit of water. The mean annual precipitation is around 900 mm, being the maximum values recorded in March and the minimum in August. The mean annual temperature is 14 ºC, with a mean maximum of 21,5 ºC in January and a mean minimum of 7,2 ºC in July.
The upper basin consists of a low hilly area and the lower basin is a large plain. The hilly area is physiographically connected to the plains by pediments (middle basin), where three experimental plots were set up (Figure 1) to assess the characteristics of the unsaturated zone. It should be mentioned that Varni et al. (1999) have found that such an area contributes most of the groundwater recharge due to the properties of the existing soil types.

Data from one of the experimental plots (P1 in Figure 1) were used to estimate groundwater recharge by means of different methodologies. Preliminary analyses indicate that such a comparison is successful at any of the plots, and the reason for selecting P1 is because its larger data sequence. Argic soils (notably Argiudolls) cover the study area. At P1, such a soil is about 1 m thick, with an upper portion made up of clay loam, two clay horizons (Bt1 and Bt2) between depths of 18 to 66 cm, whereas the deepest horizon (Ck) is silt loam. Discontinuous caliche layers are common. Roots are abundant in the upper 20 cm, and penetrate as far down as 70 cm depth.

These soils are primarily used for agriculture, with remarkable harvest yields, and often pastures are grown for cattle grazing.

Groundwater levels are shallow, in general no deeper than 3 m, and rise to less than 1 m below the surface when the rainfall events are important.

**METHODOLOGY**

Two independent methods were employed for calculating the recharge and comparing their results. First, Darcy equation for unsaturated conditions was applied (Weinzettel and Usunoff, 2001), by assuming that the recharge is represented by all water fluxes that cross a plane arbitrarily set at 120 cm depth (far down from the influence of roots). Secondly, a water balance for the unsaturated and saturated zones was carried...
out by considering the Visual Balan program (Samper et al., 1999), that took into account the unsaturated zone parameters measured at P1.

Both methods were applied and compared for a 711-day period, starting October 21, 1998, and ending in September 30, 2000.

It should be noted that, in accordance with Sophocleus (1991), this paper refers to recharge as effective recharge, that is, water that percolates into the lower limits of the vadose zone, reaches the water table, and causes a measurable water-table rise.

Determination of hydrodynamic characteristics of the unsaturated zone at P1 was based on five digital tensiometers installed at various depths (15, 30, 60, 90, and 150 cm), access tube for a TDR probe, class-A evaporation tank, pluviometer, and phreatimeter. Daily readings were taken, except for soil moisture whose values were determined weekly. The plot is covered by short natural grass, like the surrounding prairies.

FLOW IN THE UNSATURATED ZONE

Darcian flow in the unsaturated zone was estimated at a plane located 120 cm below the surface, where the effect of evapotranspiration can be disregarded.

Darcy equation for unsaturated conditions may be written as follows:

\[ q = - K(\theta) \cdot \nabla H \]  

where \( q \) is the flux that crosses the 120-cm deep plane, \( K(\theta) \) is the hydraulic conductivity as a function of soil moisture at 120 cm depth, and \( \nabla H \) is the hydraulic gradient according to the daily readings of the 90 and 150 cm deep tensiometers. It has been assumed that those tensiometers are located in a position that avoids the influence of the root zone and the capillary fringe (see Weinzettel and Usunoff, 2001, for greater details). The method has been applied in many studies on arid, semiarid and humid conditions (Scanlon et al., 2002).

In equation (1), \( K(\theta) \) is of fundamental importance for calculating the unsaturated flow. In this case, the \( K(\theta) \) function came from an internal drainage test (Hillel et al., 1972; Villagra, 1992). Such a test implied complete saturation of the soil profile, and covering the experimental plot with a plastic liner to eliminate evapotranspiration during the 30-day test. Several readings of tension and water content were taken, which allowed the assessment of the \( K(\theta) \) function for a depth of 120 cm (equation 2 and Figure 2). The saturated hydraulic conductivity, for the maximum water content measured during the test, was 66.2 mm day\(^{-1}\). Notice the rather low values of the local hydraulic conductivity in view of the restricted range of variation of the soil water content for the time span of the test. Values of hydraulic conductivity are sensitive to small changes in water content. Nielsen et al (1973) pointed out that characteristically, the hydraulic conductivity value decreases by orders of magnitude for only a small decrease in water content.

\[ K(\theta) = 9 \times 10^{-25} \exp(141.81 \cdot \theta) \]  

Figure 2. Relationship between the soil water content and the hydraulic conductivity at a depth of 120 cm.
The water content at a depth of 120 cm was measured every 7 to 10 days. An average value of θ between successive readings was assumed valid for the period and used to estimate K(θ) according to equation 2. The integration of all fluxes calculated by means of equation (1) gave the recharge for the period (Figure 3). It has to be mentioned that hydraulic gradients indicated that in some cases flow at 120 cm depth had to be upwards, although in practice it is deemed that this was not the case due to low soil water contents.

![Figure 3. Recharge to the aquifer according to flows at 120 cm depth (Weinzettel and Usunoff, 2001)](image-url)

**SOIL WATER AND GROUNDWATER BALANCE MODEL**

In order to obtain estimates of recharge to the aquifer that may be compared to the method above, the Visual Balan program (Samper et al., 1999) was employed. Such a program calculates the water flows in the unsaturated and saturated zones, based on measured groundwater level fluctuations, and computes aquifer recharge. To do so, it carries out water balances in the upper zone of the profile (root zone), the vadose zone, and the upper portion of the aquifer. Although the program is able to perform automatic calibration of parameters, this option was not used because many reliable parameters were available. Thus, the calibration...
was done manually, particularly on those parameters of empirical nature. The code was set up to compute the water balance for a working area unit of 100 by 100 m. Measured groundwater levels were used to fit some of the parameters of the model.

The following sections describe the sources of the input data.

**Evapotranspiration**

Potential evapotranspiration data were fed to the program using estimates coming from the A evaporation tank installed on the plot. Notwithstanding the difference between pan-evaporation and the evapotranspiration of cropped surfaces, the use of pans to predict ETo for periods of 10 days or longer may be warranted (Allen et al., 1998; Jensen 1973).

Estimates of evapotranspiration from pan evaporation make use of a coefficient that was obtained, following Doorenboss and Pruitt (1976), on the basis of wind speed, relative humidity, and distance to relevant vegetation masses. According to the daily climatic conditions in the region, such coefficient ranged between 0,65 and 0,75. Given those values, potential evapotranspiration for the period turned out to be 1.900 mm.

In order to estimate real evapotranspiration, the Penman-Grindley option available in Visual Balan was selected.

**Soil**

Data such as thickness, field capacity, permanent wilting point, and total porosity were taken from the measurements taken in the plot, and assuming an average of the retention curves available for each soil depth (Weinzettel and Usunoff, 1999). Thus, the total porosity is 50%, the field capacity 40%, the permanent wilting point 25%, soil depth of 0,9 m, which gives a water storage of 135 mm.

The total saturated hydraulic conductivity ($K_s$) was obtained as an average of the saturated hydraulic conductivity for each soil horizon weighted by the respective thickness (Jury et al., 1991). The $K_s$ estimated is 25,2 mm day$^{-1}$.

Earlier studies (Weinzettel and Usunoff, 1999) reported the existence of by-pass flow (Beven and Germann, 1982), whose source is macroporosity and/or preferential flow paths, so that water enters the aquifer bypassing the soil matrix. Therefore, a coefficient that activates infiltration through preferential flow paths was applied. This is very convenient to simulate the real situation in those cases that water ponding at the surface induces rapid recharge.

**Aquifer and vadose zone**

Both the aquifer and the unsaturated zone are made up of silty sediments (loess-like). Taking into account the water level response to selected rainfall events a value of 7% was assigned to the effective porosity. That figure is within the range of effective porosities for such sediments. Indeed, as explained by Sophocleous (1991), reliable effective storativity values for each recharge study site can be obtained associating water-table rises with specific precipitation events and combining the recharge estimates from the soilwater balance analysis with consequent water-table rises. For the unsaturated zone and the aquifer, a value of 66 mm day$^{-1}$ was assumed for the vertical hydraulic conductivity. The remaining parameters for the aquifer and the vadose zone were calibrated.

**Model results**

Visual Balan requires that the measured input data (groundwater levels) be given for 365-day periods. Therefore, data for October 21, 1998 and October 20, 2000 were used. In doing so, the simulation covered 20 days more than the first method, which could not be applied because the water level rise at the end of
September 2000 saturated the deeper tensiometers.

Figure 4 depicts the groundwater levels computed by Visual Balan compared to the actual measurements. Overall, the fit is good as far as the shape and the dynamics of the water level rise and decline. The left extreme in Figure 4 shows that the program simulates groundwater levels somewhat higher than the actual ones, whereas the opposite happens during the spring 1999 season. There is an acceptable fit during 2000, with a slight tendency to overestimate the groundwater levels.

The mean square error (measured versus estimated values) turned out to be 0.16 m, which is acceptable at this stage of the research to compare results from the different methods. Figure 5 shows a linear function that relates measured and calculated groundwater levels with respect to the land surface. The largest differences occur when the groundwater levels are relatively deep (2.5 to 3 m below the surface), which may indicate that at such depths the unsaturated zone parameters and/or those of the aquifer are no longer constant.

If a 2-year period is considered (Figure 4), the total precipitation is 2,093.6 mm and Visual Balan estimates 348 mm of recharge. For the same period, the total surface runoff according to Visual Balan was 25.1 mm, or 1.2% (concentrated in a few days of March 1999, and March, May, and October, 2000).
Surface runoff is a small portion of the total input by rainfall, and its eventual occurrence coincides with the heaviest precipitation events that produce aquifer recharge (autumn and spring seasons). Such a water excess, that Visual Balan computes as surface runoff, in reality leads to water ponding. It has not been observed, even during exceptionally intense precipitations, that water leaves the area as surface runoff. In the study area, all excess water (that otherwise would produce surface runoff) ends up being evaporated or infiltrated, which once again confirms that in large plains, the vertical components of the water balance dominate over the horizontal ones.

**DISCUSSION**

The results obtained with the Darcyan approach (details can be found in Weinzettel and Usunoff, 2001) are: groundwater recharge of 216.3 mm for the 711-day period (up to September 30, 1999) for a total precipitation of 1,936.3 mm. For the same period, Visual Balan rendered an estimate of 229.8 mm.

Table 1 summarizes the results of both methods for each hydrological year, as well as for the whole period. For the 711-day period, the recharge (given as a percentage of the rainfall) is similar: 11.8% from Visual Balan, and 11.1% from the Darcy approach. However, some differences emerge when analyzing the monthly totals (Figure 6). During the first year, the flow plane method (Darcy) led to flows greater than those computed by Visual Balan, whereas the opposite occurs from October 1999 on. The greatest differences are found in March and April 1999, and April 2000 (Figure 6).

In general, as expected, both methods associate larger recharges to the relevant rainfall events. Visual Balan, however, has detected a larger number of small recharges throughout the year. That might be attributed to the existence of preferential flow paths, whose effect was taken into account in setting up the program. The flow plane method, on the other hand, cannot pick up by-pass flow because it is based solely on matrix flow.

In the long run (the whole period), the overestimations and underestimations from both methods compensate, so that the amount of water recharged is quite similar.

![Figure 6. Comparison between the recharge according to Visual Balan and that obtained from Darcian flow in the unsaturated zone.](image-url)
flows coming from the surrounding areas. It is deemed, however, that such flows are relatively unimportant with respect to the local evapotranspiration and infiltration phenomena.

Inasmuch as the Darcian approach relies heavily on the $K(\theta)$ function, such a relationship has to be carefully validated by new internal drainage tests, by van Genuchten-type models, or other methodologies that may help reduce the inherent uncertainties. Shortening the frequency of field measurements is also recommended, particularly during the seasons of heavy rainfall.

It may also be advisable to apply both methods for longer periods to check whether the differences detected persist and, in that case, how relevant they are in order to come up with acceptable values of groundwater recharge. The Darcian approach has a limitation given by the depth of the reference flow plane and that of the water level, both of which may be subject to the influence of the capillary fringe. As said before, the assumption was made that it could be considered as negligible for the time period selected, although it should be taken into account in those cases where rising groundwater levels approach the lower tensiometers.

<table>
<thead>
<tr>
<th></th>
<th>Visual Balan</th>
<th>Flow plane</th>
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<tr>
<td><strong>Oct 98 - Oct 99</strong></td>
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<td>Precipitation (mm)</td>
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<td>Recharge (mm)</td>
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<td><strong>Oct 99 - Sep 00</strong></td>
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<tr>
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<td>Recharge (mm)</td>
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<td>Recharge (% rain)</td>
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<td><strong>Oct 98 - Sep 00</strong></td>
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<tr>
<td>Precipitation (mm)</td>
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<tr>
<td>Recharge (mm)</td>
<td>229,8</td>
<td>216,5</td>
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<tr>
<td>Recharge (% rain)</td>
<td>11,8</td>
<td>11,1</td>
</tr>
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</table>

Table 1. Groundwater recharge comparison

The methodological comparison here presented reveals that any of them is valid for the study plot as long as the limitations attached to each application are acknowledged. In terms of relative error, the uncertainty related to recharge estimations cannot be below that attributed to the data and variables used along the methodological procedure (Samper, 1998).

Mention should be made of the results of chloride ion mass balance for the period 1994-1999, which indicated a mean recharge of 9.7% of the annual rainfall (IHLLA, unpublished data, 2000). This method assumes that piston flow is the dominant mechanism of recharge. Although the cited figure is close to the recharge values here presented, it should be taken cautiously because on-going studies (Weinzettel and Usunoff, 1999) indicate that local recharge has an important component of preferential flow. As a matter of fact, Weinzettel and Usunoff (1998) obtained samples of the chloride ion traveling through the unsaturated zone of the study area and found that chloride contents increase with depth, but it decreases in samples right above the water table, which was interpreted as the existence of preferential flow paths (Allison, 1994), disregarding the dilution effect of the lateral flow (Sharma and Craig, 1989).
CONCLUSIONS

Two independent methods, that take into account the features of the local soils and the unsaturated zone, were applied and compared in order to estimate the recharge for a 711-day period. The recharge, measured as a percentage of the rainfall during the period, gave comparable results. Likewise, the distribution of recharge during the period followed a similar pattern.

Although those methods have limitations, it would appear that their thoughtful use may render good results. The Darcian approach implies a great deal of uncertainty related to the validity of the K(θ) function, whereas Visual Balan performance is quite sensitive to some input parameters that may not always be available or whose computation is not easily carried out. Nonetheless, their complementary use in the study area gave satisfactory results.

The availability of records for 2 years in the experimental plot was a major point in defining some of the parameters required by Visual Balan, which, in turn, was able to come up with an aquifer recharge function distributed along the simulated period.

The recharge values obtained are comparable to those coming from chloride ion mass balance, taking into account a much larger time period.

REFERENCES


