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# ASSESSMENT OF HYDROLOGIC IMPACTS OF IRRIGATION PROJECTS IN A FLATLAND AREA, SANTA FE, ARGENTINA

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*An analysis of the effects of a hypothetical intensive irrigation in the Ludueña Basin, Santa Fe, Argentina, is presented. The vertical flux of water and vapor is modeled for an extended period of time to assess long-term effects. Synthetic precipitation and evapotranspiration series were constructed with similar statistical properties to those observed in the study region. Daily values of evapotranspiration (7300 values) and hourly hyetographs were generated, including 1293 rain events over a twenty year period. Different simulation scenarios were used: a) the current scenario with extensive agriculture and no irrigation was taken as the reference and b) hypothetical intensive irrigation scenarios. These were divided into three variants: irrigation for maintenance of 60 percent, 75 percent and 90 percent of field capacity. The maximum irrigation scenario causes important changes. There is an increase of 7 percent for evapotranspiration, an increase in direct runoff, and a significant increase in recharge to the phreatic aquifer, which is shown to be the main impact of intensive irrigation. From a statistical point of view, the maximum runoff does not show big changes, but there is a very remarkable increase in the frequencies of high moisture and percolation processes in the soil profile.*

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## INTRODUCTION

From a general point of view, the knowledge of a hydrological system is the key to understanding environmental changes at a global, regional or local scale, and to assess long-term effects. Irrigation, which is often proposed to improve crop yield, can cause significant changes in hydrological processes in very vulnerable systems such as those in the extended flatland areas of Argentina. For example, increases in the frequency of floods can be expected because of incremental increases in soil moisture. To mitigate the undesirable effects of irrigation, it is necessary to quantify its potential impacts on hydrological behavior in the long term.

In a previous work (Zimmermann, 1998b), a water budget model was proposed (called SHPLAN2) that considers soil water distribution in the unsaturated zone and vertical exchange fluxes with the saturated zone and atmosphere. Surface processes such as runoff and infiltration caused by rainfall or irrigation activities were included. The model was applied in the Ludueña Basin, Santa Fe province, Argentina (Figure 1). The Basin has a drainage area of 700 km$^2$. The model was calibrated with streamflow data and has shown a satisfactory performance. It is used here to quantify the potential modifications in the hydrological processes due to irrigation.

## THE SHPLAN2 MODEL

### Submodel of subsurface flows

The submodel is based on the Richard's equation (expressed in terms of volumetric moisture content, $\theta$) to estimate moisture distribution in the non-saturated zone (NSZ), and water exchanges

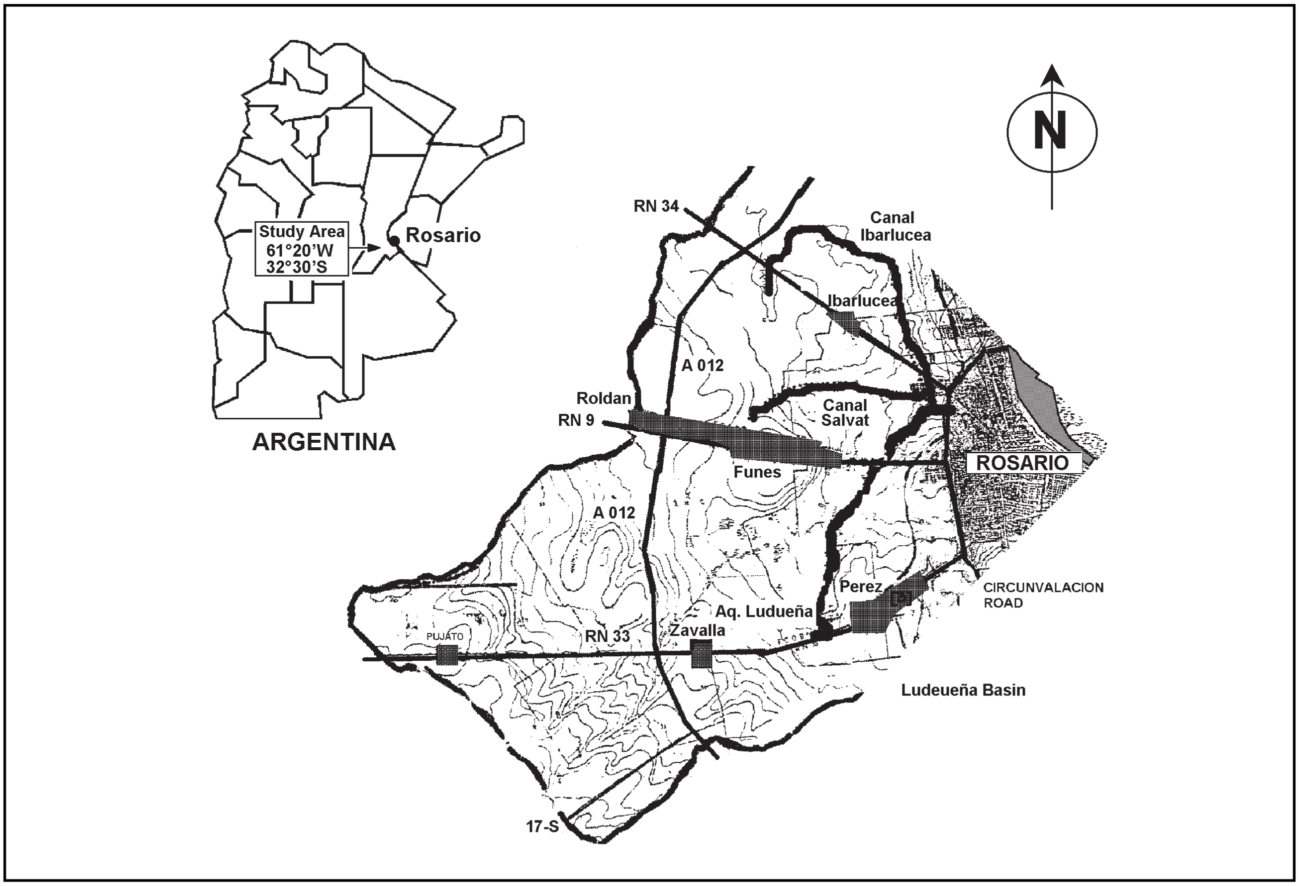

Figure 1. Study Area.

with the atmosphere and the aquifer. For vertical flows, the following equation was used:

$$q = -D(\theta)\frac{\partial \theta}{\partial z} - \lambda k \tag{1}$$

where $q$ is the Darcy velocity, $\theta$ is the volumetric moisture content, $z$ is the vertical coordinate, $k$ is the non-saturated hydraulic conductivity, and $D(\theta)$ is the moisture diffusivity equal to $k\, d\theta/d\Psi$, where $\Psi$ is the capillary potential . The continuity equation used was:

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q}{\partial z} \tag{2}$$

Differential equations (1) and (2) are solved using a space centered, explicit scheme of finite differences (Zimmermann, 1998a). Infiltration without drying at the upper border (surface) and saturated cells in the lower border (aquifer) were established as boundary conditions. The sink model of Feddes et al. (1978) is used to assess evapotranspiration. Brooks and Corey relationships are used to define soil retention curves.

### Submodel of interception and surface storage

The volumes intercepted by crops are simulated by the following equation:

$$Int = minimum[CC(ap+b), MaxInt] \tag{3}$$

where $Int$ is the interception volume, $CC$ is a cover coefficient of crops as a function of growth, $a$ and $b$ are constants as a function of crop types, $P$ is the precipitation and $MaxInt$ is the maximum capacity of interception storage.

Surface storage is considered as the maximum capacity to supply, once interception storage is satisfied, as follows:

$$SS = minimum[MaxSS, P\text{-}int] \tag{4}$$

where $SS$ is the surface storage and $MaxSS$ is the basin storage capacity.

## THE SHPLAN2 APPLICATION

The application of the SHPLAN2 model in the Ludueña hydrological system was carried out under two different scenarios, *a*) the current scenario with extensive agriculture and without intensive use of irrigation and *b)* the future scenario with extensive agriculture and intensive irrigation. A good source of water for irrigation is the Puelche aquifer. This aquifer has good water quality and high transmissivities. The Puelche aquifer is 45 m deep and is separated from the surface phreatic aquifer by semi-confining silts which limit the movement of groundwater between the Puelche and the surface phreatic aquifer. There is no rapid recharge to the Puelche aquifer.

In both scenarios the behavior of the Ludueña hydrologic system was analyzed for a twenty year period. Then, synthetic series of hourly storms and daily evapotranspiration were specifically designed.

### Synthetic storm series

Synthetic storm series, with similar statistical properties to observed series, were developed by Zimmermann et al. (1996). Data of the Alcorta raingauge (with a 5-year series of data) were analyzed by means of five variables: duration of the rain, time between events, average and maximum intensity of the rain, and storm advance coefficient. The variables were classified as independent (the first three variables) and dependent (the last two variables). Probability distribution functions were fitted for the independent variables. Multiplicative relationships were proposed for dependent variables and their coefficients were adjusted previously. The statistical characteristics of the synthetic series were calculated and compared with the observed data series. A good agreement between calculated and observed series was obtained.

The synthetically generated series consisted of sets of day and hour of storm beginning, duration, maximum and average intensity, and advance coefficient. Triangular hyetographs were adopted since they present a high frequency of occurrence (Zimmermann, 1998c). In the twenty years of simulation, 1293 rain events were included, about 65 storms per year, totalling 952.9 mm of annual precipitation, which is widely representative of the regional statistics.

### Synthetic series of evapotranspiration data

Synthetic generation of potential evapotranspiration data affected by a tank coefficient was carried out. In order to fit the parameters of the generation model, an observed series (1992-1994) of tank “A” data (Zavalla agroexperimental station, 33°S – 61°W) was taken into account. The periodogram of observed data showed a strong component with annual frequency. The partial autocorrelation function indicated that the series could be represented by an autoregressive process of 5th order (AR(5)), or mixed process ARMA(2,2). Since the last model included too many parameters, another simpler model was built, with a deterministic sinusoidal component together with an aleatory component as white noise. It is described by the following equation:

$$ET(t) = ETm + \Delta ET^{*} \cos\frac{2\pi t}{365} + a_t \qquad (5)$$

where *ET(t)* the value of tank evaporation in a day *t*, *ETm* is the average value of the evapotranspiration series, $\Delta ET$ is the amplitude and $a_t$ is a white noise component (with a normal distribution, null average $\mu$ and non-null variance $\sigma$ ). The fitted parameters were *ETm* = 3.45 mm; $\Delta ET$ = 3.0 mm, $\mu$ = 0.002 and $\sigma$ = 2.19 mm with a frequency of repetition of 365 days.

### Simulation scenarios

**Current scenario**. (*Scenario # 0)* The typical crops are soybean, wheat and corn. The cultivated area in the Ludueña Basin occupies between 85 percent and 90 percent of the entire drainage area. The corn parcels occupy about 10-15 percent of the cultivated area while the wheat crop occupies about 15-20 percent, and the soybean crops cover about 65-75 percent of cultivated area. These percentages are dynamic and relate to market prices for export. For the simulations, the following parameters were taken into account: saturated hydraulic conductivity *Ks* = 2.52 mm/h, radicular depth *Za* = 0.45 m; phreatic depth *Zf* = 3.50 m; surface storage *MaxSS* = 4.65 mm, and interception storage *MaxInt* = 5 mm. Soil parameters and characteristic curves were taken from regional studies (INTA, 1991). All parameters were previously fitted with streamflow data (Zimmermann, 1998b).

**Irrigation scenarios**. During the irrigation season the moisture state of the soil profile should be maintained between 60 percent and 90 percent of field capacity, and the irrigation doses (norms) should provide the difference between the actual moisture state and the ideal one.

The operative sequence in the model consisted of the following steps: a) verify if the day of simulation is the day of irrigation, then compute the cover coefficient *CC* corresponding to this day, else there is no irrigation, b) specify the irrigation norm, as the difference (mm) between the antecedent moisture of the soil profile and the optimum moisture, fixed as a percentage of field capacity, c) the irrigation norm, affected by the cover coefficient, is distributed in 24 hrs as precipitation and is simulated by the infiltration routine. The simulations were carried out under three irrigation hypotheses:

*Scenario # 1*: Optimum moisture is 60 percent of the field capacity during irrigation days (it implies permanently maintaining the profile capacity at 306 mm of water).

*Scenario # 2*: Same as above with 75 percent of field capacity (fixing water content at 383 mm).

*Scenario # 3*: Same as above with 90 percent of field capacity (fixing water content at 459 mm).

## RESULTS AND DISCUSSION

Table 1. Statistics for the Simulation Scenarios

| | | *Scenario # 0* | *Scenario # 1* | *Scenario # 2* | *Scenario # 3* |
|---|---|---|---|---|---|
| Mean | P | 952.9 mm | 952.9 mm | 952.9 mm | 952.9 mm |
| Annual | IN | 0 mm | 1.6 mm | 230.5 mm | 1277.2 mm |
| Budget | Q | 173.2 mm | 177.8 mm | 185.1 mm | 229.4 mm |
| | ET | 936.7 mm | 938.5 mm | 948.8 mm | 1000.1 mm |
| | B | 157.2 mm | 161.8 mm | 49.5 mm | -1000.6 mm |
| Frequency | 0 mm < Q < 5 mm | 37% | 36% | 34% | 29% |
| Analysis of | 5 mm < Q < 10 mm | 15% | 15% | 18% | 22% |
| Q | Q > 10 mm | 48% | 49% | 48% | 48% |
| Frequency | B < 0 mm | 47% | 50% | 63% | 78% |
| Analysis of | 0 mm < B < 50 mm | 50% | 49% | 36% | 21% |
| B | B > 50 mm | 3% | 1% | 1% | 1% |
| Frequency | 350 < H < 375 mm | 37% | 35% | 21% | 15% |
| Anaysis of | 375 < H < 400 mm | 58% | 59% | 70% | 48% |
| H | H > 400 mm | 5% | 6% | 9% | 37% |

**Explanation**: P precipitation, IN irrigation norm, Q runoff, ET evapotranspiration, B percolation, H moisture of soil profile to a depth of 120 cm. Negative percolation indicates aquifer recharge.

### Changes in the hydrological budget

The simulation results are summarized in Table 1. The persistent action of evapotranspiration can be observed, so that its demand must be satisfied by discharging the aquifer if there is no other water source. This was also checked in the stages of model calibration.

The simulation under *Scenario # 1* offered a similar scenario to the current one (Scenario # 0). The frequency of storms that cause direct runoff ($Q > 0$) was 12.6 percent of the annual rainy events. Practically, there are no differences in the system behavior between the current situation and *Scenario # 1* since the norm of irrigation is very small. Annual mean budgets are also very similar. It is corroborated that the natural humidity of the profile does not fall below 60 percent of the field capacity.

*Scenario # 2* gave a storm frequency that caused direct runoff of 13.2 percent with respect to annual rain events. Real evapotranspiration grows 1.3 percent and the annual mean runoff shows an increment of 6.7 percent with respect to the situation without irrigation. The most significant change is the reduction of ascending moisture, although without modifying the tendency in the upward direction.

*Scenario # 3* causes significant differences in the hydrological behavior of the system. The supply of water for irrigation is 34 percent greater than the average annual precipitation. Consequently, real evapotranspiration grows by 7 percent, although it is not the more important modification. Another change is the direct runoff increment (a 32 percent increase in annual mean volume, and a 38 percent increase in frequencies of storms that cause runoff). However, the most significant change is in the exchange water fluxes between the unsaturated zone and the aquifer. It is preponderantly in the downward direction, as aquifer recharge, with high volume rates (see Table 1). It is the predominant effect and the main movement of the irrigation volume has, as its destination, the phreatic aquifer. This great increase of recharge will cause a significant increase in phreatic levels.

## Statistical changes in the hydrological response

Hydrologists carry out hydraulic design based on a forecast of catastrophic events (droughts or floods) by means of statistical support. When the hydrological system changes its configuration (climatic changes, man's interventions, etc.), it is evident that the old samples of some variable of interest are not representative of the future. In this work, after the quantification of the general effects caused by irrigation, an assessment of their statistical influence was taken into account. Probability distribution functions were fitted to the runoff, percolation and soil moisture samples. These samples were built taking maximum annual values over the twenty years of simulation, for each variable and scenario. Pearson's law was selected for the comparisons. In Figure 2, the direct runoff for different scenarios as a function of its return period is represented on a logarithmic scale. It can be observed that there are no big changes in the statistical behavior with irrigation. This can also be observed in the frequencies of the largest runoff ($Q > 10$ mm), in Table 1, since they are similar.

In contrast, percolation changes its statistical behavior with the irrigation scenario. For example,

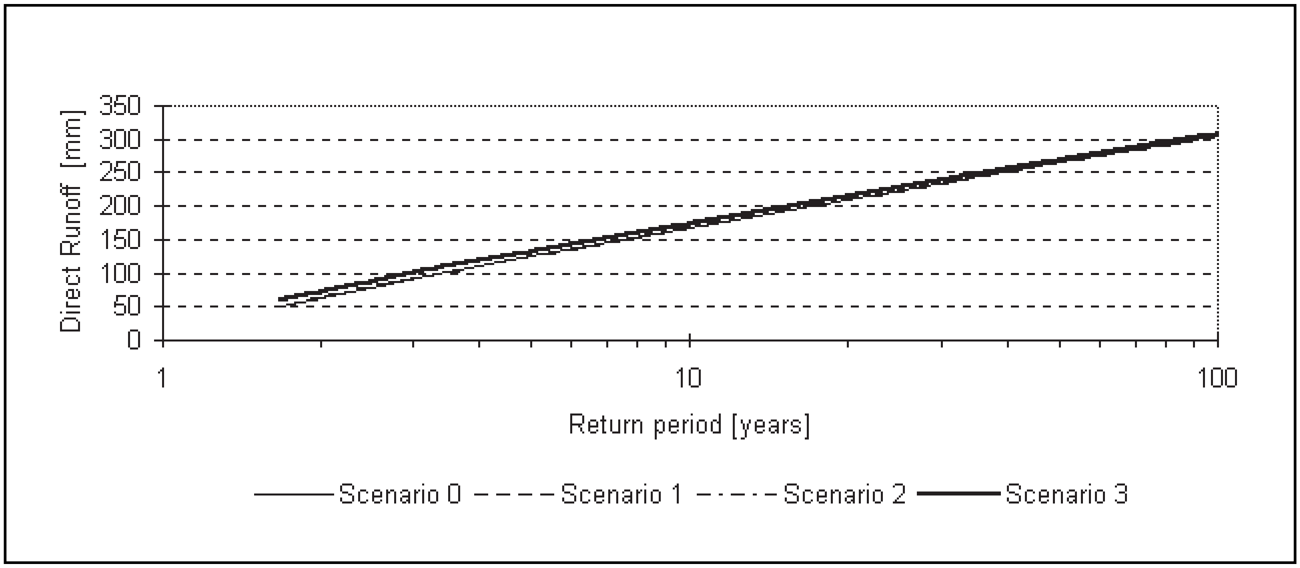

Figure 2. Direct runoff period of return.

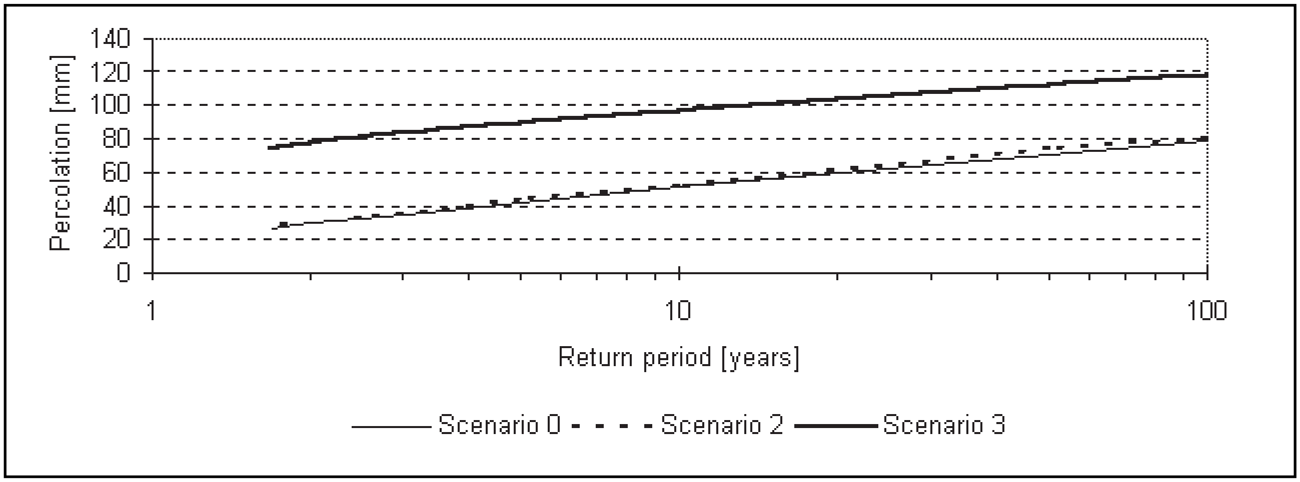

Figure 3. Percolation period of return.

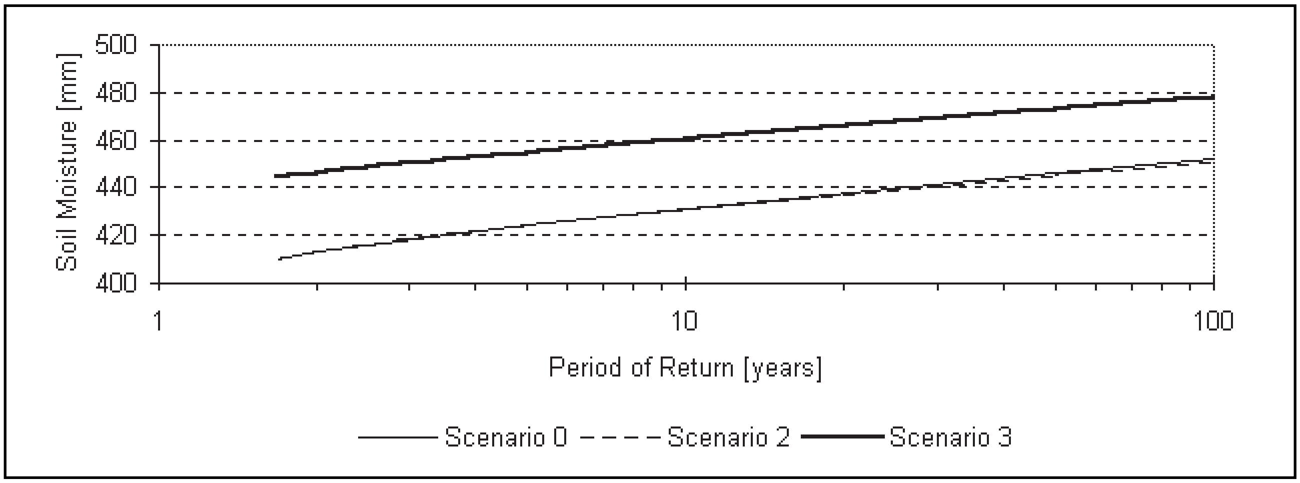

Figure 4. Soil moisture period of return (120 cm).

a percolation value of 80 mm would happen with a frequency of once every 100 years in the current scenario while, in*Scenario # 3,* the same event will occur once every 2.5 years (Figure 3). This is the most negative impact of irrigation without control, since these modifications in the moisture flux distribution could result in significant changes of the phreatic levels, mainly in the areas of aquifer discharge. However, *Scenarios # 1* and *# 2* do not show statistical changes in the hydrological variables. This fact demonstrates that if the irrigation doses are controlled, the changes of hydrological response can be minimized. A similar phenomenon is seen in the soil moisture return period (Figure 4).

## CONCLUSIONS

The results provided by the SHPLAN2 model quantifying hydrological changes in flatland areas due to irrigation are satisfactory. The most important interactions are taken into account such as changes in the vertical moisture profile in the unsaturated zone, exchange water fluxes with the saturated zone, and the same with the surface by means of infiltration or evapotranspiration processes, together with interception and surface storage processes.

Four simulation scenarios are taken into account, the current scenario without irrigation and three hypothetical scenarios with different degrees of irrigation supply.

The scenario that maintains the soil moisture permanently at 90 percent of the field capacity is the most conflicting. The main change it causes is an increase of percolation rates with a corresponding increase in phreatic levels, which is the expected result. The frequencies of runoff also increase, although the increase is not of great magnitude. The frequency of high moisture of the soil profile also increases.

The maximum annual runoff volumes do not show big changes in a statistical sense as might be expected. However, the change of the statistical behavior of percolation is notable, mainly for the last irrigation scenario. This can be the most negative impact of irrigation without control, showing that vertical water fluxes predominate in a flatland area.

Suggested recommendations are that it is necessary to control irrigation, managing the doses in order that alterations in the natural hydrological budget are minimized. The recommended limit during irrigation cycles is 75 percent of the field capacity. These results show that the phreatic aquifer could also be used as a water source, effectively recirculating irrigation water, as long as the chemical quality of water remains satisfactory.

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