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Using performance indicators for the analysis of water use in the Mendoza irrigated area

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Abstract The Province of Mendoza has more than 20% of the total irrigated land in Argentina. As the average annual rainfall is approximately 200 mm, irrigation is critical for agriculture. A storage dam was recently constructed in the Mendoza River to control the fluctuating inflow and to guarantee meeting water demand through the year. The dam will have an impact on the hydrology. The groundwater system will also be influenced and this, in turn, could have a crucial effect on parts of the irrigation area where groundwater levels are already high and salinization occurs. For the evaluation of these changes and possible mitigation measures, there is a need for performance indicators at a river basin scale that take into consideration groundwater and surface water use efficiency. The SIMGRO model was used for this assessment as it simulates water flow in the saturated zone, in the unsaturated zones and in surface water in an integrated manner. The objective was to use the SIMGRO model as a tool to evaluate the effect of hydrological changes in the irrigated area due to the construction of the storage dam. Scenarios are presented for estimated irrigation water losses and for their effect on agricultural production, by using a set of performance indicators for surface and groundwater.

Key words evapotranspiration; groundwater; hydrological model; indicators; irrigation; salinization

INTRODUCTION

The Province of Mendoza has more than 20% of the total irrigated land in Argentina. As the average annual rainfall is approximately 200 mm, irrigation is critical for agriculture. The rivers that collect snowmelt water from the Andes Mountains are the most important water resource. One of these rivers is the Mendoza River and nearly all its water is used for irrigation.

In the Province of Mendoza, irrigation water is allocated on the basis of the area for which the farmers have water rights. Studies indicate that the actual cultivated area is much smaller than the area with water rights. This leads to over-irrigation and often to gradually rising water tables in wet years. Frequently, the result is soil salinization, which reduces productivity and causes environmental degradation. In principle, there should be no need to use supplementary groundwater in areas with surface water irrigation but, because of surface water misallocation, groundwater has to be used. In the last decade these factors have contributed to the degradation of groundwater quality, which has brought about serious salinity problems in some regions.

During the last 10 years, indicators were developed to quantify and qualify the irrigation and drainage performance. Performance indicators include water delivery, water use efficiency, maintenance, irrigation sustainability, environmental aspects, socio-economics and management. A set of indicators has been described by Bos (1997). In general, it is not recommended to use all of the above-mentioned indicators under all circumstances. The number of indicators depends on the users of the information that will be generated (e.g. researchers, managers, decision-makers), and on the disciplines under consideration (water balance, economics, environment, management). In order to compare the performance of the system with others, however, it is recommended to select some of them.

The objective of this project was to calibrate the SIMGRO model in the area irrigated by the Mendoza River. After calibration, scenarios were analysed because the construction of the Potrerillos storage dam will have a great impact on irrigation scheduling and, hence, on the hydrology and salt balance of the area. The SIMGRO model will be used to calculate several performance indicators in order to qualify the changes in the irrigation district.

DESCRIPTION OF THE SIMGRO MODEL

The SIMGRO model is physically-based and simulates water flow in the saturated zone, the unsaturated zone and in surface water (Fig. 1). It takes into account the effects of irrigation, drainage and groundwater use as well as their impact on crop evapotranspiration. It also includes current irrigation practices used in the region. Because SIMGRO is physically-based, it can be used in situations with changing hydrological conditions. For a more detailed description of the model, see Querner (1988, 1997) and Kupper *et al*. (2002). SIMGRO describes groundwater flow in a multi-layered aquifer system. Saturated groundwater flow is modelled by means of the

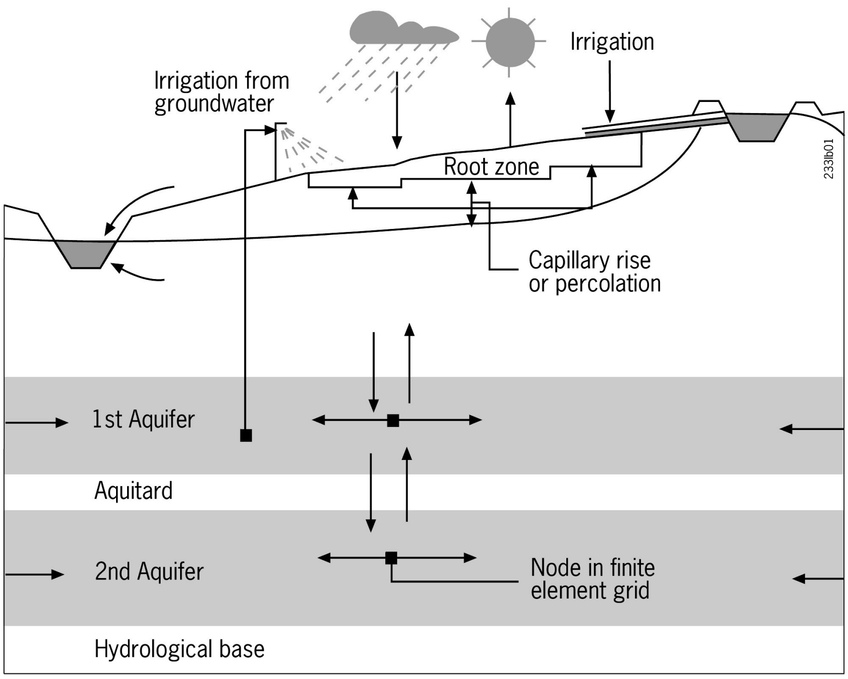

Fig. 1 Schematization of the hydrological system in the SIMGRO model for a subregion with irrigation (adapted from Querner, 1997).

finite element method, for which purpose the region is divided into a network of nodal points. Quasi three-dimensional (3-D) flow is considered, which means horizontal flow in water-bearing layers and vertical flow in the less permeable layers (Fig. 1). Groundwater levels and fluxes are calculated per nodal point.

The surface water system is made up of the irrigation canals on the one hand, and of the drainage network on the other (Querner, 1997). It is important to consider water flow in the irrigation canals, because of leakage from these canals to the groundwater. The schematization of drainage canals accounts for the discharge of surplus water from the region. In the model, four subsystems are used to simulate the interaction between surface water and groundwater, using drainage resistance and the difference in level between groundwater and surface water (Ernst, 1978).

As the groundwater part reacts much more slowly to changes than the surface water part, both parts have their own time step. Groundwater generally uses one-day time steps; in the case of surface water it is 0.1 day (Querner, 1997).

Transport of soluble salts is considered as advective transport of conservative matter. In the model, this has been integrated in each module, based on the water balance calculated for each compartment (Kupper *et al.*, 2002). That balance is expanded with a salt balance, taking into account the amount of water and solutes. The unsaturated zone has been divided into one compartment for the root zone and several compartments for the subsoil below the root zone, each 0.25 m thick up to the water table. In turn, each node of the finite element grid is a compartment for the saturated zone. Surface water, simplified in the model as one reservoir for the subregion, is also one compartment.

DESCRIPTION OF THE MENDOZA RIVER COMMAND AREA AND MODEL APPLICATION

Although only 800 km^2 in area, the Mendoza River basin has more than 800 000 inhabitants and contributes 68% of the provincial GDP, while 25% of its water is used for domestic and industrial purposes. The decentralized and participatory management model—in force for more than 100 years—has proved to be inefficient in terms of water distribution, irrigation and drainage system maintenance and, above all, water use control. Users' participation in management activities—formerly emblematic of the province—has almost ceased, and this situation has led to dissatisfaction, a loss of financial autonomy and to organizational deficiencies in users' organizations. The recent construction of the Potrerillos dam on the Mendoza River will allow river regulation and programmed delivery to users in its six administrative irrigation areas. Given this complex situation, an integrated water quality study of the Mendoza River becomes mandatory in order to devise a proposal to supersede the current management model and the sustainability crisis that is bound to occur in the oasis.

The altitude of the area varies between 578 and 1200 m above mean sea level. In the higher parts, phreatic levels are relatively deep and in the lower parts they are shallow, resulting in waterlogging and salinization. Infiltration velocities representative of the Mendoza area alluvial soil series are found to be low, with extreme mean basic infiltration values of 1.3 and 7.3 mm h^{-1}. The mean irrigation application efficiency of the area is "poor" (59%). Soil salinity in the rhizosphere of irrigated crops ranges from 1.8 dS m^{-1} (±1 dS m^{-1}) at the highest part to 3.8 dS m^{-1} (±1.9 dS m^{-1}) in the lowest area. Irrigation water has an electric conductivity of less than 0.9 dS m^{-1} at the inlet of the irrigation project; and subsurface drainage water at the tail of the system ranges in conductivity from 3.0 to 5.2 dS m^{-1} (Morábito *et al*., 2004).

Much of the geohydrological data is based on the figures for groundwater abstractions. Using these data, the geohydrology was schematized as a system with three aquifers and two aquitards. Horizontal permeability, vertical resistance of aquitards and specific storage were estimated from pumping tests in the different layers of the river basin. From these data, transmissivity in the area was calculated at 7000 m^2 per day in the phreatic aquifer, at 120–5700 m^2 per day in the first confined aquifer, and at 240 to 7500 m^2 per day in the second confined aquifer. Vertical resistance of the first aquitard is generally 400 days; locally it may be as low as 100 days or as high as 4000 days. The second aquitard is considered to be variable and known to have a vertical resistance of between 100 and 6000 days, the more common value being 700.

The finite element network, comprising of 3685 nodes, spaced some 1000 m apart, covers an area of approx. 327 000 ha. The main crops are grapes, fruit trees, olives, summer and winter vegetables and grass. The total cultivated area under irrigation is about 100 000 ha. The modelling area was subdivided into 124 subregions. The subregions were identified according to the command area of the irrigation canals of the six different administrative units (subregions 100 to 600) with superficial and groundwater irrigation possibilities; irrigation with only groundwater (subregions identified as 700); irrigation with treated sewage water (subregions identified as 800), and non-irrigated areas (subregions identified as 900).

The inflow of irrigation water at some main canal inlets was obtained from a data base for the 1977–1997 period. In order to meet crop water needs, irrigation depths were calculated per subregion and month (Morábito *et al*., 2003). According to our calculations, the total irrigation for all crops varies between 500 and 2100 mm per year (mean value is 740 mm per year). Groundwater for irrigation purposes is extracted from the third and fifth layers (those with the best water quality), and was estimated according to basin balance (Hernandez & Martinis, 2001). Because of the size of the area, meteorological data for the Penman-Monteith equation (Allen *et al*., 1998) were recorded at four meteorological stations (Fuerza Aérea Argentina, 2005). Each subregion was assigned to one of them.

PERFORMANCE INDICATORS USED

Relative evapotranspiration (R_{ET}), defined as the ratio between actual evapotranspiration and potential evapotranspiration, can be used as a performance indicator. It reflects the extent to which the potential evapotranspiration is met and it influences crop yield.

The depleted fraction relates water balance parameters for an irrigated area with each other in such a way that the manager knows the rate of change of groundwater table level. If the water table is close to the surface, the information is useful to avoid plant anoxia and excessive capillary rise (which is undesirable if groundwater is too salty). The depleted fraction (D_F) considers three components of an irrigated area's water balance. It relates actual evapotranspiration to the sum of all precipitation plus the irrigation water from surface and groundwater. It is defined as (Molden, 1997; Bastiaanssen *et al*., 2001):

$$D_F = \frac{ET_{actual}}{P + V_c} \quad (1)$$

ET_{actual}, actual evapotranspiration by irrigated crops; P, precipitation; V_c, volume of irrigation water from surface water and groundwater

At first glance, the depleted fraction looks like the overall consumed ratio, but the latter ratio uses potential evapotranspiration.

Many of the adverse environmental impacts of irrigation are related to the rate of change of the depth to the groundwater table. Because of ineffective drainage or delays in constructing drainage systems, in comparison with the surface water supply infrastructure, the groundwater table often rises into the root zone of the irrigated crop. In (semi-) arid regions this often leads to an increase of capillary rise over seepage, resulting in salinity near the soil surface. If groundwater pumped for irrigation exceeds aquifer recharge, the groundwater table drops. As a result, energy costs for pumping may increase to such a level that water becomes too expensive.

MODEL CALIBRATION

In order to compare calculated and observed values, the model was run several times using five years of meteorological data, and the results were then compared. The difference between observed and calculated values may have been enhanced by the coarse schematization of the saturated zone (finite element network). The model was calibrated using groundwater levels, evapotranspiration, and water and soil salinity for the 1994/95 growing season. For grapes, the evapotranspiration calculated was compared with observed data based on actual monthly evapotranspiration from grapes grown at the INTA Lujan Experimental Station. The comparison showed that the evapotranspiration calculated by the SIMGRO model was consistent with observed values at the beginning of the growing season (mainly September–December); however, calculated evapotranspiration was about 10–15 mm month^{-1} less than observed. During summer (January–April) the ET difference was about 20 mm lower.

Groundwater levels calculated with SIMGRO were compared with observed groundwater levels. Such a comparison is a good indicator of the model's accuracy in describing the interaction of irrigation and drainage with an aquifer system. The calculated groundwater level shows relatively little difference with the observed values. Differences between measured and calculated groundwater levels in the order of –0.5 to –2 m were found.

The electric conductivity (EC) of the groundwater system was measured at different (7) locations in open subsurface drainage systems during the period 2002–2004 and at layers 3 and 5 (Morábito *et al*., 2003, 2004). The model estimated EC at different locations and layers quite well. Differences between measured and calculated EC of 0.1 to 1.0 dS m^{-1} were noted.

RESULTS OF PERFORMANCE INDICATORS

The total amount of water for irrigation purposes and the ET_{actual} are not entirely independent of each other. As long as there is sufficient irrigation water, the ET_{actual} will be near its potential value. Figure 2 shows "relative ET" (R_{ET}) for agricultural technologies in subregion 104 (upper sector of the Mendoza River command area). The figure shows a mean value of 0.75, but in summer (January–April) RET is very low (<0.6). This indicates water shortage and reduced crop yields because of water misallocations. Subregions identified as 400 have higher R_{ET} values With respect to the depleted fraction for subregions identified as 400 and 500, the water table fluctuates very close to the root zone; and in that case the depleted fraction can be a useful indicator. Figure 3 shows that if the value of the depleted fraction exceeds 0.6, the volume of water stored in the area decreases. Part of this decrease is due to natural drainage and part is due to capillary rise into the root zone of irrigated crops. For most crops, a decrease of ET by about 25% would result in higher yields per cubic metre of water (Bos, 2004). However, yields per hectare (and thus farm income) would decrease. If local boundary conditions are such that the average annual value of the depleted fraction is lower than the critical intersection value, then the groundwater table would rise each year, unless an artificial drainage system is either improved or installed.

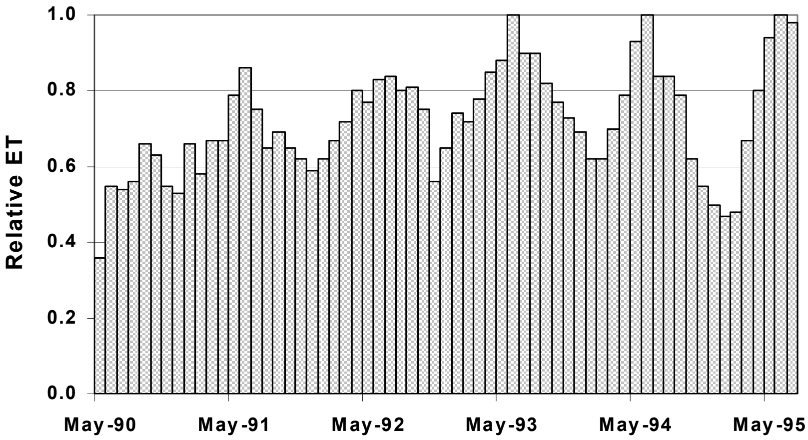

Fig. 2 Relative evapotranspiration of agricultural technologies for subregion 104.

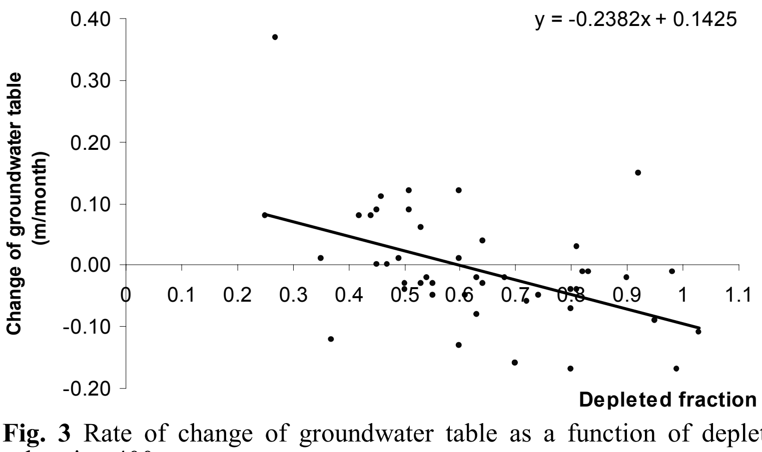

Fig. 3 Rate of change of groundwater table as a function of depleted fraction for subregion 400.

SCENARIO ANALYSIS

Water distributed along the irrigation system of the Mendoza River contains a quantity of suspended sediments (lime and clay), depending on river discharge, which contributes to the imperviousness of irrigation canals and diminishes irrigation water losses. This situation is considered as the reference situation (scenario 0 = S0). Because of the construction of the Potrerillos storage dam, a large portion of the sediments will remain in the reservoir. The water in the irrigation canals contains less suspended matter and, therefore, infiltration into the river bed and irrigation canals will increase (20 and 17%, respectively). Phreatic levels will rise causing other secondary effects, such as changes in irrigation efficiency, capillary rise, actual evapotranspiration, etc. The dam is considered as scenario 1 (S1). Using SIMGRO, we modelled this new situation. The effects of erosion, which can occur in the irrigation canals as a consequence of erosive forces of clear water, were not considered.

In order to evaluate the results of the new scenario (S1), results were compared with the reference scenario (Fig. 4). In S1 there is an important reduction of ET_{actual} and higher root zone EC; both of these consequences will reduce potential crop yield in the zone.

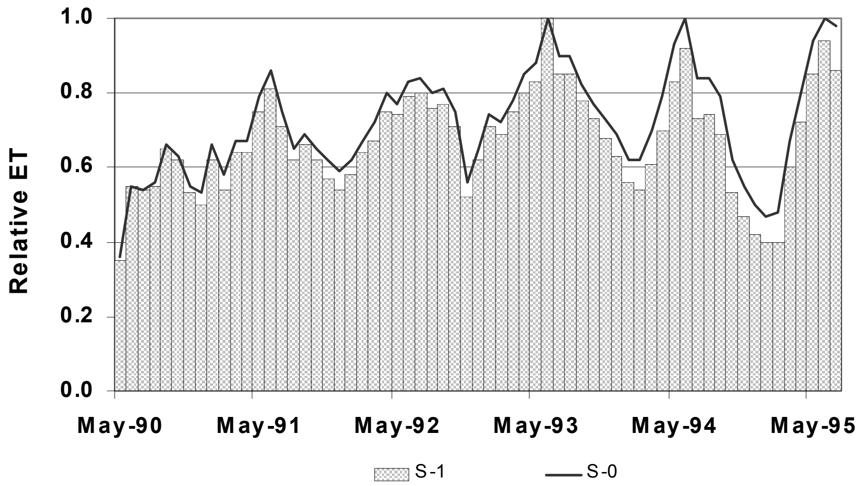

Fig. 4 Relative evapotranspiration of agricultural technologies for subregion 104. S0, present situation and S1, new scenario

CONCLUSIONS AND RECOMMENDATIONS

The advantage of a physically-based model, such as SIMGRO, as a tool to evaluate measures, is that it can be used in situations where changing conditions affect the hydrological system. Irrigation practices can be simulated for a number of years with changing meteorological conditions and irrigation depths.

On the basis of our study, we are confident that an increment of infiltration losses in the riverbed and canals will result in a smaller amount of surface irrigation water with an elevation of the groundwater table. According to our model results, in the lower part of the basin, a significant increment in salinity will be observed in the root zone and in the phreatic aquifer. Future action must assess the effect of a better water distribution by the irrigation network and of more groundwater extraction to avoid water shortages.

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