The water and salt budget of an irrigated plot in an oasis in southern Tunisia

BRAHIM ASKRI, RACHIDA BOUHLILA
Laboratoire d'Hydraulique, Ecole Nation d'Ingénieurs de Tunis, BP 37 le Belvédère, 1002 Tunis, Tunisia
e-mail: brahim.askri@enit.rnu.tn

JEAN OLIVIER JOB
Centre Régional de l'Eau et de l'Environnement, ESIB, Université St Joseph, BP 1514, Beyrouth, Liban

Abstract This study focuses on the water flow of a 1.5-ha irrigated plot in the Segdoud oasis, southern Tunisia, with the aim of analysing the processes causing salinization of soil and water. The flow processes, including infiltration, capillary rise, artificial drainage, underground flow and evapo-transpiration, are simulated using the conceptual and distributed model MAPIRA. Model predictions were compared with detailed measurements of piezometric levels made during a 134-day period following different successive irrigations. Calibration results show that the model is able to reproduce the observed response of the groundwater, which corresponds to the water table. However, a difference between measurements and calculations can be explained by uncertainties in the estimation of irrigation water quantity. For validation, calculated and measured water table depths are compared, i.e. for approximately two months. Results show that the model is unable to take into account a rapid piezometric variation due to over-irrigation of the plots situated at a higher altitude.

Key words calibration; model; oasis; salinization; Tunisia; validation

INTRODUCTION

In southern Tunisia, irrigated agriculture has seen an important development through the creation of ten oases during the last two decades; an irrigated area of 3000 ha has been developed. In these new oases, the excess of the irrigation water and the deficiency of the external drainage have caused a groundwater level increase. As a result, the capillary rise has induced the accumulation of salts in the root zone. Subsequently, the processes of evaporation and transpiration have caused salt concentration. Without leaching, the osmotic pressure of the soil solution becomes excessive causing a decline in crop production. A better understanding of the nature of water movement and salt leaching in these sandy soils is critical to maintaining and improving soil quality and thus ensuring efficient crop production by optimizing irrigation applications to maximize water use efficiency as well as salt leaching. This paper presents an application of the MAPIRA model to the cultivated soils of the Segdoud oasis situated in southwest Tunisia. Model performance was tested by comparing simulations to detailed measurements of the water table for a 4-month period. The water and salt budget of an irrigated plot of the Segdoud oasis are calculated for the 4 months covering the irrigation period.
THE STUDY SITE AND FIELD EXPERIMENT

Site details

The 1.5-ha experimental irrigation plot considered in this study was located in the 160-ha Segdoud oasis, which is situated in the catchment of chott El Gharesa. This oasis was created in 1989 by the public authorities with the aim of fixing the local population around the phosphate mines. It has been divided into 107 plots. Each plot covers an area of 1.5-ha composed of 150 basins planted with palm trees. These basins receive, by surface irrigation, an amount of water chosen by each farmer.

The experimental site is located at an edge of the oasis and at the highest elevation in order to reduce the influence of neighbouring plots on the underground flows. This plot included all three culture classes found in the Segdoud oasis. The first class is the densest, which contains palm trees. Fruit trees, forming the second class, are planted in dug channels, which serve to bring the irrigation water to the basins. Seasonal plants that constitute the third class, are cultivated on the side of the experimental plot where irrigation water is applied. A drainage system was installed in 1994; three 100 m long pipes are located at an average depth of 1.5 m and at 50 m spacing. These pipes discharge the drainage water into an open channel perpendicular to the drains (Fig. 1).

Field and laboratory measurements

Measurements were made from 19 May to 30 September 1995. The irrigated plot was instrumented in May 1995 with seven piezometers. For each, the soil was sampled at
10 and 60 cm in order to measure the hydraulic conductivity and the moisture characteristics in the laboratory. Vertical saturated hydraulic conductivity was determined using a constant head permeameter method. For soil sampled at 10 cm the values obtained were in the range 4-19 cm h^{-1}; and at 60 cm depth, 5-39 cm h^{-1}. The water content at permanent wilting point is about 0.05. At field capacity and at saturation, the values of water content were in the ranges 0.12-0.20 and 0.41-0.48 respectively. These values were used to calculate the soil profile storage at permanent wilting point, at field capacity and at saturation; the values were 44-66 mm, 126-161 mm and 424-450 mm, respectively. The measurement of the drainage flow and the depth of the groundwater allowed the determination of the storativity of the aquifer. The values obtained were in the range 0.07-0.26. In the experimental plot, there is an impermeable layer at a depth of 5.0 m (Askri et al., 1995).

No rainfall was recorded during the 134-day experimental period. For the same period potential évapotranspiration was estimated using an equation developed by the National Meteorological Institute of Tunisia based on meteorological data from a weather station located 50 km from the plot. The irrigation site was subjected to surface irrigation, and was intensively monitored to obtain time series data on piezometric levels, drain flows, and salinity levels of the groundwater.

**MODEL DESCRIPTION**

In the MAPIRA model, each plot of the oasis is divided into 150 cells (Fig. 1). Each cell is composed of four interconnected blocks: the basin, the irrigated soil, the groundwater, and the area that surrounds the basin. The MAPIRA model simulates the water transfer and the salt transport in each block of the cell. It operates with a sequence of two hydrological phases; initially, there is a rapid infiltration phase and this is followed by a slow evaporation phase. These two phases occur each day, but at vastly different rates. During the wetting phase, the basin receives an amount of irrigation water, $I$, which infiltrates, $F$, into the irrigated soil store, $W$. The infiltration rate into dry soil is initially high but decreases as the storage is filled until it is limited by the deep percolation rate, $p$, into the groundwater storage, $G$. When the groundwater storage is saturated, deep percolation from the saturated storage to the groundwater ceases.

The groundwater storage is depleted by capillary rise ($CR$), drainflow ($D$), and saturated subsurface flow ($Q$). These processes are assumed to vary with the level of the groundwater (Bouraoui et al., 1997). Finally, there is the slow drying phase where evapotranspiration sequentially dries out each storage beginning with the basin, followed by the irrigated soil, the storage of the area, which surrounds the basin, and the groundwater storage, respectively. During the wetting and drying phases the transport of salts is assumed to be convective. The salt concentration was then calculated at each block of the cell according to the principle of mass conservation.

In each plot of the oasis, water flows can be defined by three classes of parameters: (a) topographic parameters which consist of the surface topography, the depth of the drainage pipes, and the depth of the impermeable layer; (b) agro-pedological parameters which consist of the irrigated area, the crop coefficient, the water storage of the soil at permanent wilting point, at field capacity and at saturation;
and (c) hydrological parameters which consist of the maximum rate of infiltration, the coefficient of drainage of the groundwater by the drainage pipes and by the underground flow, the storativity of the aquifer, and the groundwater inflow.

MODEL SIMULATIONS AND EVALUATION

Initial conditions

The initial water storage of each basin of the experimental plot was assumed to be equal to zero. The initial soil water content was set equal to $\theta_{33\%}$ (field capacity). For each piezometer, initial soil salinity was measured on 19 May 1995. The initial depth and salinity of the water table were measured in the field on the same date.

Model calibration

A number of parameters that are obtained from field and laboratory tests are required for calibration. There are three (nonmeasurable) parameters that need to be determined by calibration. These parameters include the maximum infiltration rate ($F_0$), the crop coefficient ($K_c$) and the groundwater inflow ($Q_0$). These parameters had to be determined in such a manner that the difference between the simulated and observed piezometric levels for the period 20 May to 24 July 1995 was minimized. The objective function is to minimize the sum of the squared differences between the measured and predicted piezometric levels. The nonmeasurable parameters were determined by using an iterative Fibonacci search technique which minimizes the objective function for parameter ranges in Table 1 (Varsavas, 1989).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Constraining range</th>
<th>Value</th>
<th>Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_0$ (m day$^{-1}$)</td>
<td>3.0–6.0</td>
<td>5.1</td>
<td>0.002</td>
</tr>
<tr>
<td>$Q_0$ (m day$^{-1}$)</td>
<td>$2.1 \times 10^{-3}$–$7 \times 10^{-3}$</td>
<td>$3.9 \times 10^{-3}$</td>
<td>0.5</td>
</tr>
<tr>
<td>$K_c$</td>
<td>0.32–0.95</td>
<td>0.94</td>
<td>0.166</td>
</tr>
</tbody>
</table>

Model testing and evaluation

To test the ability of the model to predict system response, the simulated piezometric levels were compared with the measured piezometric levels for the period 25 July to 30 September 1995. Initial water content and salinity of the soil were obtained from the calibration simulation. The salinity and the depth of the water table were measured in the field on 24 July 1995. The water storage of the basin was assumed to be equal to zero.
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Fig. 2 Observed (dots) and simulated (line) groundwater levels from the 20 May to 24 July 1995.

Fig. 3 Observed (dots) and simulated (line) groundwater levels from the 24 July to 30 September 1995.
Results and discussion

Figure 2 shows a typical example of the measured vs predicted daily piezometric levels for the calibration period at the piezometers PZ1 and PZ3 (Fig. 1). Similar graphs were made for individual piezometers but are not shown here. Model simulation was generally consistent with observed data. The model was able to react to successive irrigation events and evapotranspiration. However, a difference between measurements and calculations can be explained by uncertainties in the amount of the irrigation water that each basin received. The reason for these uncertainties is the water losses in the open channels through which the irrigation water is distributed. This quantity is far from being uniform as assumed in the model.

For validation, calculated and measured levels of the water table were compared (Fig. 3). The model was able to predict the general trend over the observation period (25 July to 30 September 1995). However, it was unable to take into account a rapid piezometric variation that occurred during the period 7–14 September 1995 due to the fact that the groundwater inflow was assumed to be constant in the model. This may be true if the same quantity of irrigation water per unit of surface is delivered to each user. But this is not the case in the Segdoud oasis where free access to irrigation water is the general rule. Over irrigation in the plots situated at higher elevation can induce a rapid variation of the piezometric levels in the experimental plot.

RELATIVE FLOW CONTRIBUTIONS

The water and salt budgets in the irrigated plot calculated for the period of 20 May to 30 September 1995 are summarized in Figs 4(a) and 4(b) respectively. This plot received a total of 3650 m$^3$ water, of which 64% came from irrigation. The rest was provided by underground flows. The volume of water leaving the plot is about 3170 m$^3$, of which approximately 55% is evapotranspiration, and the rest drainage (14%) and underground flow (31%).

![Fig. 4 Water (a), and salt (b), budgets for the irrigation site over the entire modelling period.](image)

The mass of salt accumulated in the experimental plot is of the order of 18.4 t. The contribution of the irrigation is about 50%. The rest comes from plots situated at
higher elevation, and is transported to the experimental plot by the underground flow. The quantity of salts leaving the experimental plot is about 10.1 t. The contribution of the underground flow is about 69%; the rest is evacuated by the drainage pipes. Thus, the quantity of salt accumulation within the soil during the simulation period was calculated as 4.6 kg m\(^{-2}\) of the irrigated area.

**CONCLUSION**

A conceptual and distributed model was developed to calculate water and salt budgets in an irrigated plot of an oasis. The physical parameters of this model can be defined by laboratory and field measurements. The non-measurable parameters can be determined automatically by minimizing the difference between measured and simulated piezometric levels. The calibration quality depends on the precision of estimating the irrigation water quantity. The validation of the model can be done by simple measurements applied during a short period. If one wishes to simulate the process causing salinization of the oasis, it is important to manage this system with piezometers and to quantify the amount of the irrigation water that is applied. Thus, one would be able to evaluate the water flow and the salt concentration of the soil. It would then be possible to correct case by case the excesses of irrigation water that are the main causes of the soil salinization.

**REFERENCES**

