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A Distributed Simulation System for Irrigation Planning at the Catchment Scale

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Abstract: The paper presents the prototype of a simulation system which reproduces all the hydrological processes relevant in alluvial irrigated plains. It allows the evaluation of the distribution of crop water consumption in space and time, as well as the simulation of the interaction between irrigation and groundwater resources. The simulation package is based on the coupling of two hydrological models - a sub-model of the unsaturated soil layer and a sub-model of the aquifer system - with a Geographical Information System (GIS). The prototype has been applied to a large irrigation district, of approximately 700 km², located in the densely-settled Lombardia plain, in Northern Italy.

Keywords: Hydrological processes; Simulation model; Alluvial plain, Irrigation planning

1. INTRODUCTION

Irrigation in the Lombardia plain is predominantly based on traditional methods (border irrigation and flooding). The large water losses through percolation, typical of these methods, and the equally significant water losses from the extended network of unlined irrigation canals, limit the water use efficiency and increase the transport of nutrients and pesticides to groundwater and rivers. On the other hand, however, the percolation of irrigation water is a vital source of recharge for the underlying aquifer system, which is strongly exploited by civil and industrial uses. This research focuses on the modelling of the hydrological processes that are more important at the regional scale in irrigated alluvial plains.

A simulation system which allows the evaluation of the distribution of crop water consumption in space and time and of the interaction between irrigation and groundwater resources has been implemented. It is based on the coupling of two mathematical models with a Geographical Information System (GIS). The two hydrological models simulate the water flow in the vadose zone and in the groundwater saturated zone, respectively. The vadose zone sub-model is a conceptual-type model and performs the hydrologic balance of the plant-soil-atmosphere system on a daily basis. The space variability of soil and crops, as well as of meteorological irrigation inputs, is accounted for by subdividing the region with a regular mesh and applying the relevant equations to each grid cell. A 1D mathematical representation of the infiltration and deep percolation processes in the soil volume obtained as a vertical projection of each cell on the underlying phreatic surface is adopted. The height of this volume varies in time, due to the seasonal fluctuations of phreatic levels, whose dynamics are simulated by the groundwater sub-model. This model is based on a multilayer representation of the aquifer system. The equations of flow in saturated porous media in 2D horizontal form are applied to each layer. The solution is achieved by applying an implicit finite-difference scheme, based on a regular space discretization grid (MODFLOW algorithm). A GIS manages all the information relevant to the study area. Starting from the information stored in the GIS, input data and model parameters can be prepared and continuously updated. Simulation results are transferred back to the GIS for visualisation and further elaboration.

Results of the application of the system to a large irrigation district in Lombardia (approximately 700 km²) are presented.

2. THE SIMULATION SYSTEM

2.1 Vadose zone model

The model for the vadose zone is a conceptual non-linear capacity storage-type model, applied to volume units with regular square base and variable height, extending from the soil surface to the phreatic surface. Each unit is subdivided into three layers. The first layer (evaporative) represents the upper part of the soil profile in which infiltration, evaporation and percolation to the subsequent...
layer take place. In the second layer (transpirative), extending through the root zone, the processes considered are transpiration and percolation to the third layer. In the last layer (percolative), reaching the phreatic surface, only deep percolation is taken into account. The layers are modelled as three non-linear reservoirs in cascade.

The equation describing the hydrological balance for the first layer is the following:

\[ f - E - Q_1 + R_2 - R_1 = d_1 \left( \frac{d \theta_1}{dt} \right) \quad (1) \]

where \( f \) (LT\(^{-1}\)) is the infiltration rate; \( E \) (LT\(^{-1}\)) is the evaporation rate; \( Q_1 \) (LT\(^{-1}\)) is the outflow to the second layer; \( R_1 \) (LT\(^{-1}\)) is the overflow from the first layer to the soil surface; \( R_2 \) (LT\(^{-1}\)) is the overflow from the second layer; \( d_1 \) (L) is the depth of the layer; \( \theta_1 \) is the water content (-).

A similar equation holds for the second layer:

\[ Q_1 - T - Q_2 + R_3 - R_2 = d_2 \left( \frac{d \theta_2}{dt} \right) \quad (2) \]

where \( T \) (LT\(^{-1}\)) is the transpiration rate; \( Q_2 \) (LT\(^{-1}\)) is the outflow to the third layer; \( R_3 \) (LT\(^{-1}\)) is the overflow from the third layer; \( d_2 \) (L) is the depth of the layer; \( \theta_2 \) is the water content (-).

Finally the balance equation for the third layer is the following:

\[ Q_3 - Q_2 - R_3 = d_3 \left( \frac{d \theta_3}{dt} \right) \quad (3) \]

where \( Q_3 \) (LT\(^{-1}\)) is the outflow from the third layer (aquifer recharge); \( d_3 \) (L) is the depth of the layer and \( \theta_3 \) is the water content (-). The layer depth varies during the simulation as a result of the groundwater level fluctuations computed by the aquifer model.

The water reaching the soil surface, that is available for infiltration, is the sum of net rainfall (i.e. rainfall minus interception) \( P_e \) (LT\(^{-1}\)) and irrigation amount \( I \) (LT\(^{-1}\)). The canopy interception is evaluated by the Braden formula [Braden, 1985], as a function of the leaf area index, the cover fraction and the volume capacity per unit foliage area. All these parameters vary according to the crop type and the growing stage.

The infiltration rate \( f \) in equation (1) is evaluated considering the potential infiltration rate \( f_p \) (LT\(^{-1}\)), estimated by Green-Ampt equation [Green and Ampt, 1911], and the water amount reaching the soil surface:

\[ f = MIN(P_e + I; f_p) \quad (4) \]

Water exceeding the infiltration capacity is assumed to be removed by the drainage network. The evaporative rate \( E \) and the transpirative rate \( T \), in equations (5a) and (5b) respectively, are computed using the FAO-56 dual crop coefficient method [Allen et al., 1998]. The reference crop evapotraspiration \( ET_0 \) is computed with the FAO-Penman-Monteith equation; the traspiration rate is then obtained by multiplying \( ET_0 \) by a basal coefficient \( K_{cb} \), which accounts for the differences in ground cover, canopy properties and aerodynamic resistance from the reference crop and by the water stress coefficient \( K_c \), which introduces the effect of limited soil water availability. The evaporation rate is determined by multiplying \( ET_0 \) by the evaporative coefficient \( K_e \).

Summarising:

\[ T = K_e K_{cb} ET_0 \quad (5a) \]

\[ E = K_e ET_0 \quad (5b) \]

where \( K_{cb}, K_e \) and \( K_c \) are derived from crop and soil characteristics, meteorological data and soil water content through appropriate equations [Allen et al., 1998].

Drainage discharges \( Q_1, Q_2 \) and \( Q_3 \), are determined using a simplified scheme, similar to those used in other models [see e.g. ANSWERS2000, Bouraoui et al., 1997; EPIC, Williams et al., 1984], which considers a Darcian-type gravity flow in the unsaturated soil, for water content exceeding field capacity. The relation between the unsaturated hydraulic conductivity and the water content is modelled using the Brooks and Corey equation [1964]:

\[ k(\theta) = k_s \left( \frac{\theta - \theta_r}{\phi - \theta_r} \right)^n \quad (6) \]

where \( \theta_r \) is the residual water content, \( \phi \) the soil porosity and \( n \) (-) a parameter depending on the pore-size index.

The calculation of the input and output fluxes as well as the value of the final water content in the three layers is carried out by an implicit iterative procedure. The water percolating out of the last layer is one of the inputs to the underlying groundwater cell.

### 2.2 The aquifer model

Aquifer systems at the regional scale can be often satisfactorily represented by a quasi-three-dimensional multilayer scheme: the flow-field is simulated as two-dimensional horizontal in each layer with exchange through the aquitards, where the flow is assumed to be one-dimensional.
vertical. The flow equations, for a two layers scheme, are:

\[ \nabla \left( (k_1 D_1) \nabla h_1 \right) - s_1 \frac{\partial h_1}{\partial t} = P_1 - Q_3 + \sigma (h_2 - h_1) \]  

(7a)

\[ \nabla \left( (k_2 D_2) \nabla h_2 \right) - s_2 \frac{\partial h_2}{\partial t} = P_2 + \sigma (h_1 - h_2) \]  

(7b)

where \( h_1 \) \([\text{L}]\) and \( h_2 \) \([\text{L}]\) are the piezometric heads of the two aquifers, \( k_i \) \([\text{LT}^{-1}]\), \( D_i \) \([\text{L}]\), and \( s_i \) \([-\text{]}\) are, respectively, the conductivity, the thickness and the effective porosity of the phreatic aquifer, \( T_2 \) \([\text{L}^2\text{T}^{-1}]\) and \( s_2 \) \([-\text{]}\) are, respectively, the transmissivity and the storage coefficient of the semiconfined aquifer, \( P_1 \) \([\text{LT}^{-1}]\) and \( P_2 \) \([\text{LT}^{-1}]\) are unit surface pumping well flow rates, and \( \sigma \) \([\text{T}^{-1}]\) is the leakage coefficient of the aquitard. The groundwater model needs the distributed recharge \( Q_3 \) as input and it provides distributed updated values of the piezometric head \( h_1 \) to the vadose zone sub-model at the end of each stress period.

The solution of the coupled flow equations (7a) and (7b) is achieved applying an implicit finite-difference scheme, based on a regular space discretization grid, included in the MODFLOW model [McDonald and Harbaugh, 1988].

2.3 Coupling the vadose zone and the aquifer models

One source of difficulty in efficiently coupling and numerically solving vadose zone and groundwater equations is the intrinsic difference in the dynamic behaviour of the two systems. In fact, in order to adequately represent the vadose zone processes, a relatively short time step is needed (i.e. daily or shorter). In contrast, larger time steps can be used for groundwater due to the sluggishness of the dynamics. The approach adopted here is to split the simulation period in a number of stress periods, during which all the inputs and the boundary conditions of the aquifer model are kept constant. Simulation of the vadose zone for each stress period is carried out using a suitable time step, generally much shorter than the stress period, keeping the depth \( d_3 \) of the last layer fixed at its initial value. The average value of the resulting percolation flux \( Q_3 \) is then used in the simulation of the aquifer system for the same stress period. The final value of the phreatic surface level is used to update the depth \( d_3 \) in the simulation for the following stress period.

2.4 The GIS interface

The simulation system is based on the integration of the two coupled hydrological models with a Geographical Information System (GIS), used for the management of model parameters, input layers and simulation results. The GIS represents the interface between (a) data of different types (i.e. cartography, bibliography, remote sensing), (b) numerical simulation algorithms (c) final users, which needs the cartographic representation of simulation results for supporting management, analysis and decision making. The GIS constitutes the digital spatial data base of the area. Data are in a raster format, fully compatible with the simulation models requirements. Starting from the information stored in the GIS, input data and model parameters can be prepared and continuously updated. Simulation results are transferred back to the GIS for visualisation and further elaboration.

3. APPLICATION TO THE MUZZA-BASSA LODIGIANA IRRIGATION DISTRICT

3.1 Description of the study area

The simulation system has been applied to the irrigation district Muzza-Bassa Lodigiana, southeast from Milan, in northern Italy (Figure 1). The Muzza-Bassa Lodigiana district has an area of approximately 700 km² and has been selected for the following main reasons: a) it is representative of agricultural and irrigation practices in a wide portion of the plain of Lombardia; b) it has well defined hydrogeological borders, represented by the Adda, Po, and Lambro rivers (respectively East, South and West) and by the Muzza canal (North). The latter, with a flow at full capacity of 110 m³/s, is the main source of irrigation water in the district.

![Figure 1. The study area - SPOT (3-2-1) Color Composite.](image)

Cereals (particularly maize) are the major crops. Grass, especially permanent, covers a considerable extension of the area. Non agricultural areas cover approximately 15% of the surface. The average annual rainfall over the last 40 years (1960-2000)
is about 900 mm in the northern part of the area and 700 mm in the southern.
The hydrogeological characteristics of the study area can be schematically represented by
i) a top formation, highly pervious, included within the upper fluvioglacial sediments, ii) an underlying formation, with lower hydraulic conductivity. This second formation lies on impervious substrata of Quaternary marine sediments. Clay lentils constitute a more or less continuous semipervious septum separating the two formations. The soil textures in the area range from moderately coarse (loamy sand) to coarse (sand) in the northern part and along the Adda river, from medium (loamy) to moderately coarse in the central area and from moderately fine (sandy clay loam, silty clay loam, silty clay) to medium in the southern part.

3.2 Application of the simulation system

In order to apply the model to the Muzza Bassa-Lodigiana irrigation district, a mesh size of 1 hectare was adopted for the vadose zone model. A coarser mesh size of 36 hectares was used for the aquifer model. Cell dimensions were determined on the basis of the spatial scale of the available data. In order to overpass the difference in spatial scales between the two models in coupling them, the cumulative drainage from the 36-cell cluster of the vadose zone model that overlay each cell of the aquifer model was assigned to $Q_3$ in equation (7a), while the phreatic surface level in such cell was then used to calculate $d_3$ for all 36 corresponding vadose zone cells. Three monthly stress periods were considered in the aquifer model simulation, while a daily time step was used for the vadose zone simulation.

Land use was derived from multitemporal Landsat TM images, complemented by direct field surveys. Soil hydraulic parameters, for each layer in which the vadose zone was subdivided, were derived from pedological data by using Rawls & Brakensiek’s pedo-transfer functions [Rawls and Brakensiek, 1989].

Daily meteorological inputs to the vadose zone model were obtained from the existing monitoring network, while spatial and temporal distribution of irrigation was determined on the basis of available data on irrigation supply for the more than one hundred sub-districts included in the area.

The structure as well as the hydrodynamic characteristics of the aquifer model were obtained from a previous study on the groundwater resources system in a wider portion of the Lombardia plain [Giura et al., 1995; Gandolfi et al., 1999].

Civil and industrial pumping rates, as well as the interactions between aquifer and surface channel network were derived from the rather limited information available for the area.

4. SIMULATION RESULTS

Simulation was run for the Muzza-Bassa Lodigiana irrigation district for the years 1999 and 2000. Maps of cumulative evapotranspiration and recharge over the area for the year 2000 are shown respectively in Figures 2 and 3. The mean annual evapotranspiration rate was found to be approximately 500-550 mm for maize and 700-750 mm for grass. The mean value of aquifer recharge due to rainfall and irrigation for the year 2000 was found to be around 600 mm.
The model allows the reproduction of time pattern of the hydrological balance components for each cell within the domain. An example of temporal patterns of the principal input and output variables of the vadose zone sub-model is given in Figure 4. The figure shows the rainfall and irrigation inputs along with the simulated values of recharge and evapotranspiration for a maize cell and a continuous grass cell, located in Mulazzano (in the northern part of the district, see Figure 1).

Figure 4 shows the pattern of the piezometric head of the phreatic aquifer simulated by the model at the beginning of the irrigation season. It can be seen that the predominant flow direction is NW-SE, and that the boundary rivers drain the aquifer. In Figure 6 the rising of piezometric levels from April to September mainly due to the increase in distributed recharge during the irrigation season is shown. Measured seasonal variation in piezometric head at the available points are also reported in Figure 6.

5. CONCLUDING REMARKS

The integrated planning and management of water resources involves several aspects, among which the joint regard of ground and surface water resources is of paramount importance in many irrigated areas. Mathematical simulation models may play a major role as decision support tools, since they improve the understanding of the most important physical processes and may be used to predict the likely effect of selected planning decisions.

The simulation system presented in the paper includes all the most important processes at the scale of large irrigation districts, and explicitly accounts for the spatial and temporal variability of crop cover, management practices and rainfall/irrigation distribution, as well as for the spatial variability of soil types.

The application of the system to a large pilot study area has demonstrated that it can reproduce the global pattern of the variables involved in the hydrological balance (with particular regard to the...
interaction between irrigation and groundwater recharge). Moreover, temporal patterns of the balance terms at a single cell level have proved to be consistent with agro-meteorological conditions, soil and crop types and agricultural practices of the area. Finally, the model reproduced with sufficient accuracy the seasonal fluctuations of the water table levels.

In spite of these favourable results, several limitations in the operational use of the simulation system emerged, mostly deriving from the limited availability of data both for calibration and validation of the models. In fact some of the input variables (especially groundwater abstractions, water losses from the network of unlined irrigation canals and spatial distribution of the actual irrigation amounts) were very poorly known. In addition many of the output variables are intrinsically difficult to measure and even for those that could be monitored (mainly groundwater levels) the availability of data was not sufficient. Finally the problem of accounting for the influence of the high uncertainty in the estimate of some of the models parameters (e.g. the soil hydraulic characteristics derived by the pedo-transfer functions) on the simulation results must still be largely investigated.

The ongoing developments of the research will address these limitations by means of expanding data collection as well as developing stochastic simulation algorithms for the assessment of the uncertainty in simulation results. A significant contribution to data acquisition will be hopefully obtained by applying remote sensing techniques, addressed to the estimation of spatial and temporal patterns of some land attribute relevant for hydrological purposes (i.e. Leaf Area Index, fraction cover, biomass density, etc.) as well as of important water balance terms (i.e. actual evapotranspiration).

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7. REFERENCES


