SIMULATION SUPPORTED SCENARIO ANALYSIS FOR WATER RESOURCES PLANNING: A CASE STUDY IN NORTHERN ITALY

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ABSTRACT
The work presents the results of a comprehensive modelling study of surface and groundwater resources in the Muzza-Bassa Lodigiana irrigation district, in the Southern part of the densely-settled Lombardia Plain (Northern Italy). The activity focused on the assessment of the impact of changes in land use and irrigation water availability on the distribution of crop water consumption in space and time, as well as on the groundwater resources in the area. In order to carry out the research, a distributed, integrated surface water-groundwater simulation system was implemented and applied to the study area. The system is based on the coupling of a conceptual vadose zone model with the groundwater model MODFLOW. In order to assess the impact of land use and irrigation water availability on water deficit for crops as well as on groundwater system in the area, a number of management scenarios were identified and compared with a base scenario, reflecting the present conditions. Results show that changes in land use may alter significantly both total crop water requirement and aquifer recharge. Water supply is sufficient to meet demand under present conditions and, from the crop water use viewpoint, a reduction of water availabity has a positive effect on the overall irrigation system efficiency; however, evapotranspiration deficit increases and is concentrated in July and August, when it may be critical for maize crops.

KEYWORDS: Water resources planning, Scenario analysis, MODFLOW, Integrated surface-ground water model.

INTRODUCTION
The integrated planning and management of water resources involves several aspects, among which the joint consideration of surface water and groundwater resources is of paramount importance in extensively irrigated alluvial plains. In the Lombardia Plain, in the northern Italy, intensive exploitation of groundwater for civil and industrial supply coexists with massive diversions from surface water bodies, providing abundant irrigation to one of the most productive agricultural districts in Europe. In the last decades no substantial changes have occurred in the irrigation water uses in the Lombardia region, in spite of the fact that the economical and social importance of agriculture has strongly diminished. Irrigation, which is still the main water use, is now confronted with a set of problems among which the management costs of the irrigation and drainage network and the competition with civil, industrial and environmental water uses.
The aim of the research is the evaluation of the effects of changes in land use and water resources allocation in a portion of the Lombardia plain. In order to do this a distributed, integrated surface water-groundwater simulation system was developed and applied to a number of realistic management scenarios which were set up considering both trends of the Common Agricultural Policy (CAP) and possible changes in water resource allocations.

THE MUZZA BASSA LODIGIANA IRRIGATION DISTRICT
The study area (approximately 700 km^2) is located South-East from Milan, in Northern Italy, and is representative of agricultural and irrigation practices in a wide portion of the plain of Lombardia. The hydrogeological borders are quite well defined, being represented by the Adda, Po, and Lambro rivers (respectively East, South and West) and by the Muzza canal (North).
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 soil textures range from coarse to moderately coarse in the northern part of the area and from medium to moderately fine in the south. 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. Traditional and low efficient irrigation methods (border irrigation and flooding) are predominantly applied in the area. Water delivery at the farm level is fixed rotational with constant flow, i.e. each farmer receives his share of water by turn (approximately every 10-15 days). The Muzza canal, originating from the Adda river, is by far the main source of irrigation water in the district with a flow at full capacity of 110 m^3/s. It delivers water to the whole district through an extended network of unlined channels. The total volume of water diverted over the area during the irrigation season (from middle of May to middle of September) is about 9.68 x 10^8 m^3.
The groundwater system is characterised by a two-layer structure, consisting of a phreatic aquifer and an underlying semi-confined aquifer. Both aquifers are exploited by civil and industrial abstractions. There is a close relationship between irrigation, groundwater resources and river flows in the area. Groundwater dynamics is strongly conditioned by the large recharge fluxes, due to the percolation of irrigation water both from fields and the channel network (water losses from the primary network are estimated to be approximately 20% of the amount diverted). On the other hand, the percolation of irrigation water is a vital source of recharge for the underlying aquifer system and provides a significant return flow through drainage to the boundary rivers.

THE SIMULATION SYSTEM

The simulation system is based on the coupling of two mathematical models – a conceptual SVAT (Soil Vegetation Atmosphere Transfer) model and the groundwater model MODFLOW (McDonald & Harbaugh, 1988) - in the framework of a Geographical Information System (GIS) environment. The SVAT model combines the FAO-56 dual crop coefficient approach for evapotranspiration (Allen *et al*., 1998) with a conceptual model of the flow in the vadose zone, running 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 1-D 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. Each soil volume is subdivided into three layers (evaporative, transpirative and percolative), modelled as three non-linear reservoirs in cascade. The calculation of the water content as well as the input and output fluxes in the three layers at the end of each time step is carried out by an implicit iterative procedure. The height of the third layer varies in time, due to the seasonal fluctuations of phreatic levels, simulated by the groundwater model; the water percolating out of this layer is the recharge input for the groundwater model.

Groundwater model considers a multi-layered representation of the aquifer, with a quasi-3D flow scheme. Flow equations are resolved by applying an implicit finite-difference scheme (MODFLOW algorithm), with a regular mesh. An interface performs the explicit coupling in space and time between the two models. A GIS manages all the information relevant to the study area and is used to prepare and continuously update the input data and model parameters. Simulation results are transferred back to the GIS for visualisation and further elaboration (see Gandolfi *et al*. [2002], Facchi *et al*., [2002] for a description of the simulation system).

APPLICATION OF THE SYSTEM TO THE MUZZA IRRIGATION DISTRICT

The simulation system was applied to the Muzza-Bassa Lodigiana irrigation, using a mesh size of 1 hectare for the SVAT model, while a coarser mesh size of 36 hectares was adopted for the groundwater model. Cell dimensions were determined on the basis of the spatial scale of the available data. Groundwater simulations were based on three months stress periods, while a daily time step was adopted for the SVAT simulation. Due to the limited availability of direct measurements, soil hydraulic properties were inferred from the known physical/chemical characteristics by indirect methods, i.e. by using pedo-transfer functions (Rawls & Brakensiek, 1989). Crops and vegetation characteristics were derived from literature data (Allen *et al*., 1998; Huygen *et al*., 1997; Borgarello *et al*., 1993) and verified by field surveys. Daily irrigation supply to each grid cell was estimated from the daily flow diverted by the Muzza channel and delivered to the 147 sub-district in study area. The hydrogeological structure of the aquifer, as well as the hydrodynamic parameters for the groundwater model, were obtained from a previous study on the system (Giura *et al*., 1995; Gandolfi *et al*., 1999). The pumping rates were derived from the available data on groundwater abstractions. Water stage measurements were used for the boundary conditions of the aquifer model (because of the hydraulic connection between groundwater system and boundary rivers). The simulation system performances were verified for the years 1999-2000 using observed water stage in rivers and groundwater level data, as well as available information on evapotranspiration fluxes (see Facchi *et al.* [2002] and Ortuani [2002] for further details).

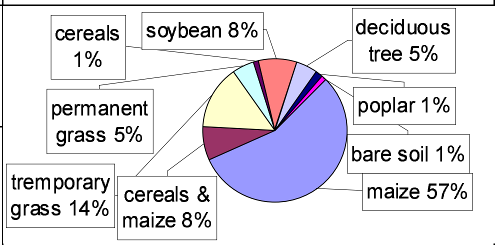
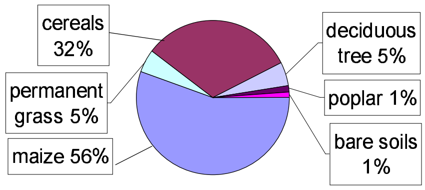
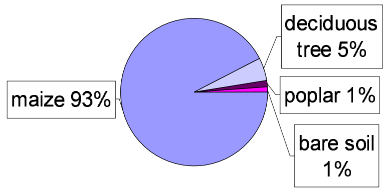
DEFINITION OF SCENARIOS

In order to assess the impact of changes in land use and water resource allocations on crop water consumption and on groundwater resources in the Muzza-Bassa Lodigiana irrigation district, four scenarios were identified. The characteristics of the different scenarios are summarized in Table 1.

A "base scenario", (a), was defined to allow comparative analysis of the results of the (b), (c) and (d) scenarios, that were identified considering trends deriving from the Common Agricultural Policy (CAP) and possible changes in water resource allocation to agriculture. For scenarios (a), (c) and (d), the water available for irrigation was kept constant to the present value. Scenario (b) maintains the same land use of the base scenario, but includes a 30% reduction of water volume distributed for irrigation compared to the base scenario.

Simulations of all the scenarios were run with the same ten-years (1993-2002) of weather data, as well as with the same initial and boundary conditions for both the unsaturated zone and the groundwater models. The same water delivery policy, irrigation method (border irrigation with a fixed application depth of 250 mm) and irrigation scheduling criterion were also used. Irrigation scheduling considers that water application takes place when the water is available according to the turn and when the soil water deficit exceeds a certain threshold (fixed as the 80% of the readily available soil water). Finally, land use and cropping practices were held constant throughout the simulation period.

Table 1 – Characteristics of the four scenarios

SCENARIO	LAND USE
(a) "base case" scenario: - current land use (from remote sensed images – year 2000), - current cropping practice, - current water availability for irrigation;	
(b) "30% irrigation reduction" scenario: - land use as (a) - current cropping practice, - 30 % less of water applied from irrigation;	
(c) "maize-winter cereals" scenario: - land use obtained by magnifying one of the possible effects of the Agenda2000 in Lombardia (decreasing of maize, and oilseeds, increasing of other cereals), - current cropping practice, - current water availability for irrigation;	
(d) "maize estensive" scenario: - land use obtained by magnifying one of the possible effects of the Agenda2000 in Lombardia (increasing of maize, decreasing of oilseeds and other cereals) - estensive cropping practice (hybrid with a shorter cycle, less productive, with less water requirement) - current water availability for irrigation;	

RESULTS AND DISCUSSION

Scenario results were evaluated by comparison with the "base case" scenario (a). They were grouped and analysed on the basis of the differences in: *i)* crop water requirement, *ii)* irrigation water consumption, *iii)* groundwater recharge, over the entire irrigated area.

Crop Water Requirements

Figure 1 and Table 2 show the evapotranspiration under standard conditions (i.e. crop water consumption with no water limitation on crop growth (Allen et al., 1998)) calculated over the entire irrigation district for the three different land use/cropping practice scenarios (a), (c) and (d). Figure 1.I shows the three-monthly averages over the simulation period (1993-2002), while Figure 1.II shows the pattern of the annual values. The higher evapotranspiration values of the "base case" scenario are mainly due to temporary grass and single and double-crop maize. Inter-annual variability is quite limited, while both scenarios (c) and (d) give a significant reduction of the peak seasonal (July-September) evapotranspiration, which drops from 340 mm in case (a) to approximately 250 mm both in (c) and (d).

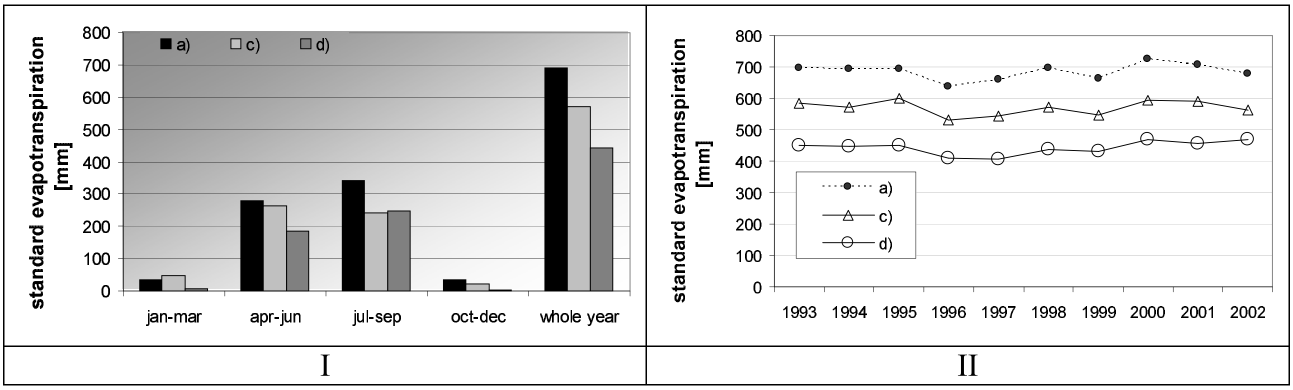


Figure 1 – Standard evapotranspiration for scenarios (a), (c), (d) over the period 1993-2002; I: three-montly average values; II: pattern of annual values

Irrigation Water Use

All scenarios were analysed in terms of the quantity of water actually applied to the fields during the irrigation season. Figure 2.I shows the annual volumes (Mm^3) for the different scenarios, and Figure 2.II the ten-days average flows obtained for scenario (a) in the two years (1996 and 1997) in which the annual volume was highest and lowest, respectively. The latter figure shows that the irrigation flow is highly variable during the irrigation season, usually peaking up to approximately 60 m^3/s in July, when maize water requirement is higher. The role of rainfall inputs may be significant in reducing irrigation flow and volume, as it is demonstrated by the simulated patterns of year 1997, when heavy rainfalls occurred in the irrigation season. It must be observed, however, that the peak flow does not generally diminish in wet years.

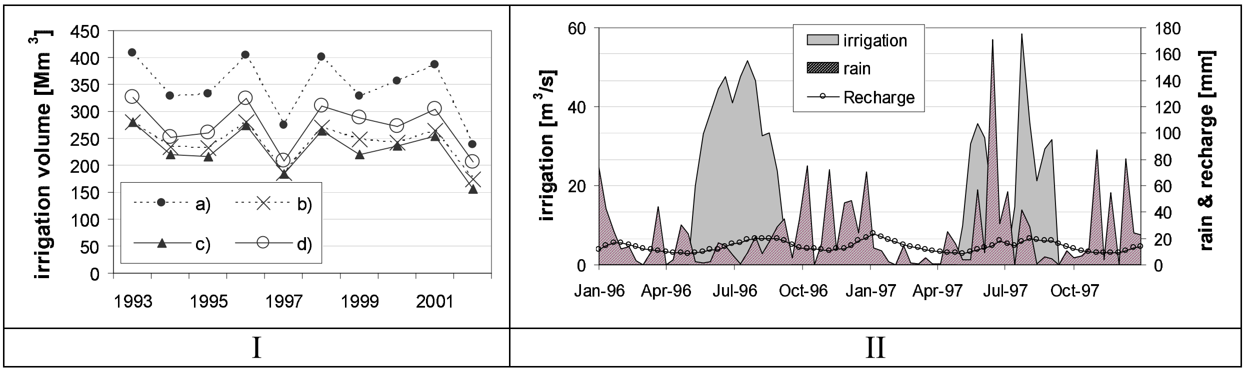


Figure 2–I: annual volumes of irrigation over the study area – II: Ten-days average flows applied to the fields over the study area in years 1996-1997 compared with ten-days cumulative rain and recharge - scenario (a).

Scenario (c) has the smallest irrigation volumes, mostly due to the reduction of the irrigated area (winter cereal water requirement is satisfied by the rainfall before the irrigation season). The decrease in irrigation volumes of scenario (d), compared to the base scenario, is due to the shorter vegetative period of maize. Results also show that the present water supply is sufficient to satisfy the crop water requirement of scenario (a), with practically no significant failure over the whole simulation period (i.e. standard and actual evapotranspiration are always very close), while it exceeds the crop water requirements of scenarios (c) and (d) (see Table 2). Finally, the effect of the 30% reduction of irrigation volume in scenario (b) can be seen in the difference between standard and actual transpiration: actual transpiration of irrigated crops over the irrigation season amounts to 419 mm, while the standard value is 478 mm. Therefore the transpiration deficit is 13% only, though it must be underlined that it is mostly concentrated in July and August, when it may be critical for maize crops.

Groundwater Recharge

Figure 3 shows the patterns of total groundwater recharge for the four scenarios. Figure 3.I shows the three-monthly average recharge for the period 1993-2002 is shown. In Figure 3.II the pattern of the annual value during the simulation period is illustrated.

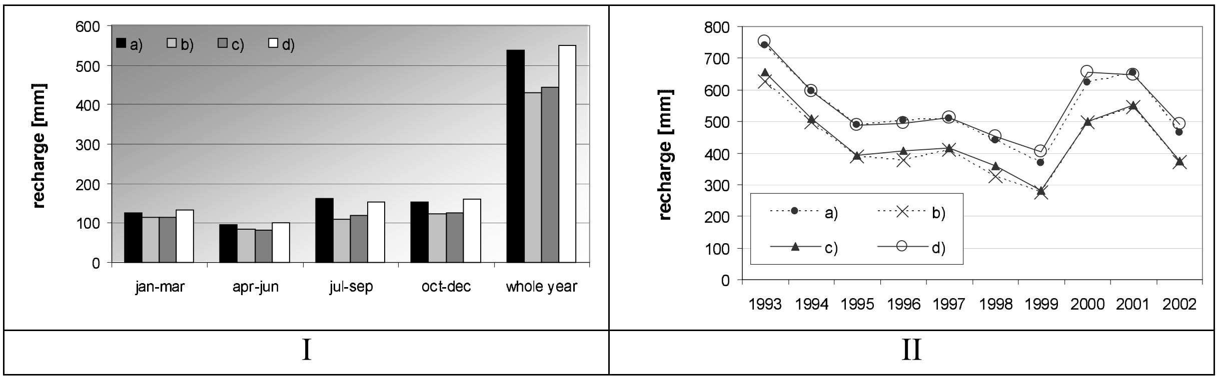


Figure 3 - I: three-monthly average recharge for the period 1993-2002 over the study area – II: pattern of the annual values

Table 2 reports the average values of recharge over the simulation period, together with the deviation from the "base case" scenario and the ratio between recharge and rainfall plus irrigation. The values of this ratio are influenced by both crop water use and rainfall interception. In fact, the higher value of scenario (d) is mainly due to the longest period in the year during which the soil is bare.

Table 2 - Average values of water balance components over the period 1993-2002 for all the scenarios

	average values for the period 1993-2002				deviation from (a) [%]		
SCENARIO	(a)	(b)	(c)	(d)	(b)	(c)	(d)
standard evapotraspiration							
annual value [mm]	691.12	569.86	569.86	442.57	100.00	82.45	64.04
irrigation season value [mm]	621.57	503.59	503.59	432.20	100.00	81.02	69.53
irrigation							
annual volume [Mm^3]	345.37	240.83	230.19	274.86	69.73	66.65	79.58
depth over irrigated crop [mm]	670.38	467.46	678.10	523.07	69.73	101.15	78.02
recharge							
annual recharge [mm]	538.48	431.59	445.04	549.64	80.15	82.65	102.07
available water (rain+irr) [mm]	1448.02	1278.19	1260.91	1260.91			
recharge / available water [%]	37.19	33.77	35.30	43.59			

The spatial distribution of average recharge for scenarios (a) and (b) are plotted in Figures 4.I and 4.II, while the effect of the modified recharge on groundwater is illustrated in Figure 4.III, showing the difference in average water table depth between the two scenarios. It can be seen that differences, which are obviously small in the vicinity of the fixed head boundaries, reach values of approximately 1 m in the Southern part of the study area.

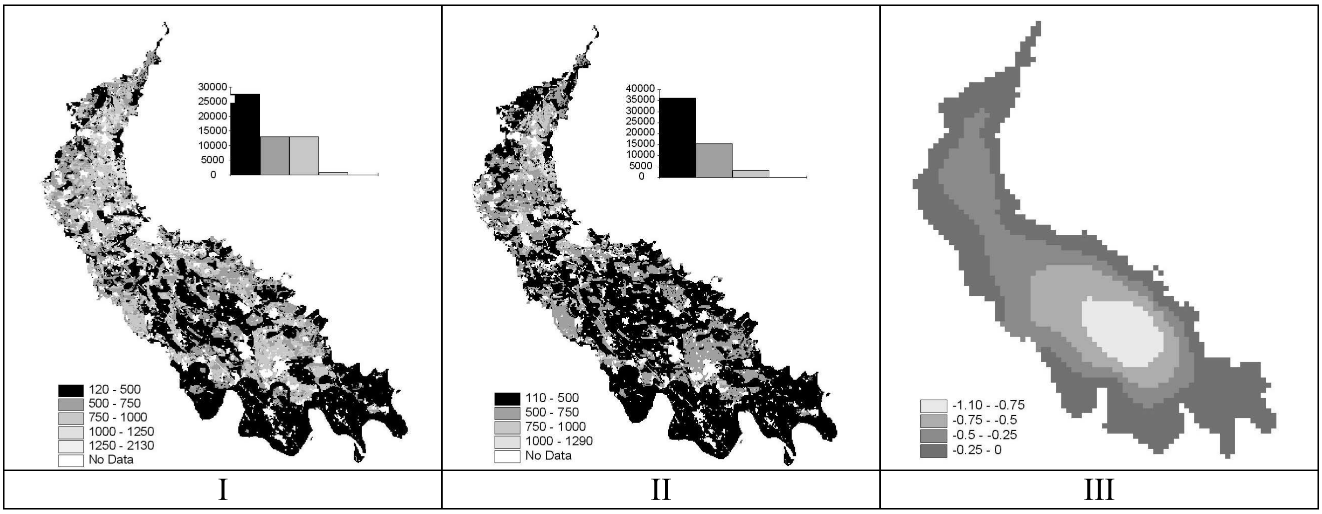


Figure 4 – Spatial distributions of average values over the period 1993-2002; I: average yearly recharge [mm] in (a) scenario; II: average yearly recharge [mm] in (b) scenario; III difference [m] between average water table depths in (a) and (b) scenarios.

CONCLUDING REMARKS

Understanding the interaction between soil, vegetation and atmosphere processes and groundwater dynamics is of paramount importance in water resources planning and management in extensively irrigated alluvial plains. 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 effects of selected planning decisions or likely changes in the climate patterns.

The simulation system presented in the paper includes all the most important processes at the regional scale 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 and groundwater hydraulic properties. It was first calibrated and then applied to the Muzza Bassa Lodigiana irrigation district (northern Italy) to simulate a number of scenarios, including possible changes in land use and irrigation water supply, as well as a "base" scenario defined considering current land use and water availability for irrigation. Indeed, comparative analysis of the different scenarios was the major focus of the study, rather than predicting the specific amount of the water balance components for each scenario. All simulation were run using the same meteorological data set (years 1993-2002) and assuming constant land use, cropping and irrigation practices, water delivery policy and irrigation scheduling criterion over the simulation period. The following points emerge from the analysis of the results.

- Land use changes, that may be induced by Agenda2000 in the study area, significantly alter total crop water requirement. The two land-use change scenarios that were analysed, (c) and (d), cause a reduction of crop water requirement of approximately 30 and 20%, respectively. It must be underlined that both scenarios represent quite extreme cases, with very significant land use changes. Therefore they can be considered as upper bounds to the impact of Agenda2000 on water requirements.

- The present water supply meets crop water requirement under the conditions of current land use and irrigation practices (scenario (a)). It becomes overabundant when modified land use scenarios, (c) and (d), are considered.
- Under the current irrigation practices a reduction of annual irrigation volume of 30% causes a 13% deficit in transpiration. Therefore, from the crop water use point of view, the overall irrigation system efficiency increases; however, the deficit is concentrated in July and August, when it may be critical for maize crops. Moreover it must be underlined that changes in water allocation to irrigation imply modifying the management and, possibly, structural characteristics of the conveyance and distribution networks; these aspects were not analyzed here.
- Aquifer recharge varies significantly with the different scenarios (20% and 17% decrease compared to the "base case scenario" for scenario (b) and (c), respectively). This is reflected in changes in the average aquifer depth reaching 1 m in the southern part of the study area.

REFERENCES

Allen R.G., Pereira L.S., Raes D., Smith M. "Crop Evapotraspiration", FAO Irrigation and Drainage Paper 56, 1998.

Borgarello M., Catenacci G., Cavicchioli C., Parini S. "Indagini sulla deposizione secca" Rapporto CISE-SAA-93-042, CISE, Milan, 1993.

Facchi A., Gandolfi C., Ortuani B., Maggi D. "Modellistica integrata acque superficiali-sotterranee per la pianificazione delle risorse idriche a scala di bacino", Proceedings of "XXVII Convegno di Idraulica e Costruzioni Idrauliche", Potenza, Italy, Vol. 5, 329-338, 2002.

Gandolfi C., Giura R., De Wrachien D. "Groundwater management under critical conditions: a case study"; Proceedings 2nd Inter-Regional Conference on Environment-Water, Lausanne, Switzerland, 1999.

Gandolfi C., Facchi A., Ortuani B., Maggi D. "A distributed simulation system for irrigation planning at the catchment scale", Proceedings of "IESMM 2002", Lugano, Switzerland, Vol. 1, 299-304, 2002.

Giura R., DeWrachien D., Savi F. "Ground-water simulation for the control of the hydraulic behaviour of a densely-settled alluvial plain: a case study", ICID Journal, vol. 44, pp. 51-71, 1995.

Huygen, J.C., van Dam J.C., Kroes J.G., Wesseling J.G. "SWAP 2.0: input and output manual". Technical document, WAU and DLO-Staring Centrum, Wageningen, Holland, 1997.

McDonald M.G., Harbaugh A.W. "Techniques of water-resource investigations of the United States Geological Survey – A modular three-dimensional finite-difference ground-water flow model", chapter A1, U.S. Government Printing Office, Washington, 1988.

Ortuani B. "Processi di costruzione e validazione di modelli per la simulazione di sistemi acquiferi", PhD Thesis, University of Milan, Italy, 2002

Rawls W.J., Brakensiek D.L. "Estimation of Soil Water Retention and Hydraulic Properties", Unsaturated Flow in Hydrological Modeling, Theory and Practice, 275-300, 1989.