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A MODEL FOR THE SIMULATION OF WATER FLOWS IN IRRIGATION DISTRICTS: I. DESCRIPTION

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ABSTRACT

Significant improvements in the profitability and sustainability of irrigated areas can be obtained by the application of new technologies. In this work, a model for the simulation of water flows in irrigation districts is presented. The model is based on the combination of a number of modules specialized on surface irrigation, open channel distribution networks, crop growth modeling, irrigation decision making and hydrosaline balances. These modules are executed in parallel, and are connected by a series of variables. The surface irrigation module is based on a numerical hydrodynamic routine solving the Saint Venant equations, including the heterogeneity of soil physical properties. The simulation of water conveyance is performed on the basis of the capacity of the elements of the conveyance network. Crop growth is simulated using a scheme derived from the well-know model CropWat. The irrigation decision making module satisfies water orders considering water stress, yield sensitivity to stress, multiple water sources and the network capacity. Finally, the

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hydrosaline module is based on a steady state approach, and provides estimations of the volume and salinity of the irrigation return flows for the whole irrigation season. The application of the model to district irrigation management and modernization studies may be limited by the volume of data required. In a companion paper, the model is calibrated, validated and applied to a real irrigation district.

CE Database subject headings: Surface irrigation, Irrigation districts, Water management, Reservoir management, Decision Support System.

INTRODUCTION

Applying new technologies to irrigation water management leads to improvements in the productivity and sustainability of agricultural systems (Burt and Styles, 1999, Vidal et al., 2001). Simulation models linked to decision support systems for the management of irrigated areas constitute powerful tools to achieve these goals (FAO, 1994; Hall, 1999; Walker, 1999; Playán et al., 2000). In the last decades, the development of such models has been boosted by developments in computer science and the widespread use of personal computers.

Different approaches have been used to simulate the processes characterizing an irrigated area. Chávez-Morales et al. (1987, 1992) and Hazrat et al. (2003) developed models which, based on the characteristics of reservoirs and water conveyance structures, optimized irrigation water allocation using linear programming. The goal of those models was to maximize economic output and water use, respectively. Kuo et al., (2000) developed a model to support crop and irrigation planning. They used genetic algorithms to determine the distribution of crops and the pattern of water allocation which optimized economic output in an area. Consideration was given to the physical characteristics of the irrigated area and to the capacity of the conveyance structures. Other authors have developed models oriented towards the optimization of rotational water allocation networks, seeking allocation patterns promoting equity and effectiveness (Suryavanshi and Reddy, 1986; Khepar et al., 2000).

In other cases, the organizational and social aspects of an irrigated area have been modeled together with the production techniques, in order to model farmers' water use. Ferguson (1989) established empirical relationships between management variables and quality in water delivery. Lamacq (1997) combined hydraulic models of water conveyance networks and action models, reproducing the process of farmers' decision making in different situations, thus reproducing the effect of management variables. Mateos et al. (2000)

analyzed the topological relationships between irrigation units in an irrigated area using a Geographic Information System (GIS). They simulated the effect of the organization of the irrigation units on system performance and water quality.

In a last group of research works, the functionality of irrigated areas is reproduced by the combined application of diverse simulation models. Detail analyses can be performed applying these tools to a series of scenarios. Merkley (1994), Yamashita and Walker (1994), and Prajamwong et al. (1997) developed models which departing from on-farm daily balances of water (and salts, in some cases) estimated the seasonal water demand and crop yield in an irrigated area. Crop yield functions, hydrosaline models and discharge aggregation routines in branching networks were used for this purpose. An extension of such models to the most common irrigation water management schemes worldwide is the Scheme Irrigation Management Information System (SIMIS), which adds to the simulation models administration utilities for irrigated areas and GIS capabilities (Mateos et al., 2002; Lozano and Mateos, 2003).

In this work, Ador-Simulation, a decision support system for irrigation planning and management is presented. This computer tool combines a number of modules whose integrated use permits one to simulate water flows in an irrigation district. Ador-Simulation reproduces the interaction between irrigation water and the conveyance and drainage network, agricultural production and the environment. This software has been designed to extend the insight on irrigation district performance which is gained through the process of irrigation evaluation (Lecina et al., 2005). The objective was to design an analytical tool capable of analyzing different scenarios in irrigation planning or management in an irrigation district. The model structure allows to estimate the effects of changes in the water conveyance and drainage networks, the irrigation systems, water management schemes, cultural practices, and crop distribution on irrigation water demand, irrigation efficiency, agricultural production and the quantity and quality of irrigation return flows. Such a model can be applied to manage drought periods (anticipating the effect on crop yield and irrigation water demand). Irrigation modernization can be assessed using the model capacity to evaluate modifications in the conveyance structures and the irrigation systems in terms of crop yield and water conservation.

Ador-Simulation has been developed within a research project titled "decision support on irrigation organization" (Ador). The goal of this project was to improve agricultural water use through the development of computer tools for irrigation districts. The other output of this project, Ador-Management (Playán et al, 2005), is a computer software for the daily management of irrigation districts. This software uses a relational database to store district data such as water users, plots and water structures. Ador-management organizes water use and bills water and fixed costs to the farmers and other water users. District management data are stored in the database and can be visually presented in a GIS. The simultaneous use of both Ador computer applications will benefit from sharing a continuously updated database on structures, crops, users and management.

In this paper, model development and preliminary tests are presented. In a companion paper, the model is calibrated, validated and applied to the simulation of the Irrigation District V (five) of Bardenas (Spain). This irrigation district is representative of traditional irrigation schemes in the Ebro Valley of Spain. These irrigation projects, often constructed by the mid twentieth century, are characterized by the use of surface irrigation, insufficient conveyance capacity, poor water management, and in some areas or moments, water scarcity.

MODEL DESCRIPTION

The model is composed of five simulation modules covering on-farm (surface) irrigation, crop growth, hydrosaline balance, water flow in the open-channel conveyance and drainage networks and decision making in water allocation to the farmers. The relationship between these modules is schematically described in Fig. 1. The plot is the spatial unit in which crop growth and the water and salt balances are simulated. A typical irrigation unit is characterized in each plot. Irrigation simulation is performed in it and then extended to the whole plot area.

The time step varies among modules, being instantaneous for the simulation of the irrigation events, daily for crop growth and seasonal for the hydrosalinity module. The simulation of water flows includes in-line reservoirs and secondary water sources, such as wells, natural streams and even water diversions from the drainage network to the irrigation network. In this module the time unit for water conveyance can be daily or hourly, depending on district water allocation policies, while the time unit for the drainage network is the whole simulation period. The decision making module gathers information from the daily water balance performed for each plot by the crop growth module. It also makes use of the capacity restrictions of the water conveyance network. This module decides among all the water demands to the district conveyance network in a given period of time, selecting a subset which is compatible with the network capacity.

These procedures allow Ador-Simulation to reproduce water flows within an irrigation district for a period of time which is typically a year. Model results are constituted by a series of indexes and counters which summarize district performance. Monitored variables include hourly discharges in the conveyance network, time evolution of soil water in each plot, and crop yield reductions due to water stress. Different planning or management scenarios can be simulated, and the results may be readily compared in terms of irrigation efficiency, water demand or salinity of the return flows.

In order to complete a simulation, a series of data must be supplied to Ador-simulation. These data characterize the physical characteristics of the district, the water structures and the water allocation scheme (Table 1 and Figure 1):

1. Meteorological data: including daily temperature, precipitation and reference evapotranspiration (ET_0).

2. Soils and water: for the implementation of soil water and hydrosaline balances, and the simulation of surface irrigation, a number of variables are required, including soil physical and chemical properties. These properties must be defined for each soil type identified in the district. The salinity of irrigation water must also be specified.

3. Crops: for each crop considered in the model the phenological cycle, the crop coefficients and the water stress sensitivity coefficients must be specified, along with the maximum crop height and rooting depth.

4. Plot data: when defining the cadastral plots, besides their area and the dimensions of the surface irrigation units (basins or borders), a soil type must be assigned, and an initial soil water content must be set. A crop must be assigned to each plot, along with a sowing date. The plot information also includes the time of cut off (the irrigation time), which can be substituted by an order to determine the optimum time of cutoff (maximizing application efficiency). Each plot must be connected to an element of the conveyance and drainage networks, so that the model can assess how the plot is irrigated and where its return flows will be collected.

5. Data on conveyance and drainage structures: for each network element the conveyance capacity must be specified. Conveyance structures are also characterized by its service discharge. The networks must be strictly ramified, and the hierarchy of the network elements must be fully described. Other required data include the capacity of in-line reservoirs and the maximum discharge of each secondary water source (wells, natural streams…). In the case of water transfers from the drainage to the conveyance networks, the points of diversion and inflow must be specified, along with the maximum transfer discharge. Finally, the daily irrigation timing (start and end hour of irrigation operation) has to be specified.

Ador-Surface: Surface irrigation simulation module

Basin and border irrigation simulation is performed within Ador-Surface. This module is composed by a one-dimensional hydrodynamic numerical model solving with an explicit finite differences scheme the Saint Venant equations governing shallow water flow:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} + I = 0 \qquad [1]$$

$$\frac{1}{Ag}\frac{\partial Q}{\partial t} + \frac{2Q}{A^2 g}\frac{\partial Q}{\partial x} + \left(1 - F^2\right)\frac{\partial h}{\partial x} = S_0 - S_f \qquad [2]$$

where A is the area of a fluid section, Q is the discharge, I is the infiltration rate, t is the independent variable time, x is the independent variable space, g is the acceleration of gravity, F is the Froude number, h is the flow depth, S_0 is the field slope, and S_f is the friction slope, approximated by the Manning equation.

A one-dimensional version of the two-dimensional model B2D (Playán et al, 1994; Playán et al, 1996) was used for this purpose, simulating level-basin and border irrigation. Lecina et al. (2005) applied this one-dimensional model to the simulation of irrigation performance in an irrigation district of Spain. Surface irrigation models simulate the spatial distribution of irrigation water in the soil, and estimate irrigation performance indexes (Walker and Skogerboe, 1987). In Ador-Surface the user must define the number of computational nodes along the irrigation unit in which the simulation will be performed (a typical value is 50). On part of these nodes, evenly distributed along the field, crop growth and yield will be simulated by the crop growth module (Ador-Crop). A typical number of crop simulation nodes is 12. In order to improve the quality of simulation results, the model can simulate the effect of the spatial variability of soil surface elevation. For this purpose, the Standard Deviation of soil surface elevation has been chosen as the control variable. This issue is very relevant in surface elevation, through its influence on the advance time and on the distribution uniformity (Playán et al., 1996).

The target irrigation depth is the goal of irrigation water application (Cuenca, 1989). In surface irrigation an important part of the Total Available Water (*TAW*) (Walker and Skogerboe, 1987; Allen et al. 1998) is used as target irrigation depth *Zr*. Ador-Surface can use different values of *Zr* in different points of the field. This feature permits one to simulate the effect of soil spatial variability on irrigation performance and crop yield.

The surface irrigation module used in Ador permits one to introduce a parameter representing a constriction in water flow at the surface runoff downstream boundary condition. The need for such parameter resulted from a campaign of field irrigation evaluations including outflow measurements (Lecina et al., 2005). When simulating free-draining border irrigation surface runoff is customarily modeled using a normal flow boundary condition across the border width (Walker and Skogerboe, 1987). In many cases this is far from the real situation, since outflow often occurs through one or few discrete points across the border downstream end. Since this situation can not be properly modeled with a one-dimensional approach, the model permits one to use an *ad hoc* coefficient to reduce the normal outflow, reproducing the experimental values of runoff discharge.

In order to simulate irrigation in each plot of the district, Ador-Surface uses the properties of the soil type associated to each plot. The time of cut off and the characteristics of the representative irrigation unit (basin or border) of each plot are retrieved from the input data. The irrigation discharge is determined as the service discharge of the element of the conveyance network supplying the plot.

Besides simulating surface irrigation with the user defined time of cut off, the model can optimize this variable to obtain maximum application efficiency. In basins and blocked-end borders simulation begins by choosing the time of cut off equal to the time of advance. The time of cut off is iteratively reduced multiplying it by a coefficient (typically between 0.95 and 0.99). Iterations proceed until the irrigation depth in a certain percentage of the field area does not attain the average target irrigation depth. The time of cut off of the previous iteration is the optimum irrigation time.

Model output includes irrigation performance indexes (Burt et al., 1997) and the infiltrated depth in each computational node. The time required to irrigate the whole plot is determined from the time of cut off corresponding to the simulation of the characteristic irrigation unit (border or basin).

Ador-Crop: a crop simulation module

Ador-Crop is a module simulating crop growth and water requirements. Simulation is performed for each plot in part of the computational nodes described in Ador-Surface along the irrigation unit. This module requires crop, soil and meteorological data (including daily reference evapotranspiration, as previously discussed). When an irrigation is performed, the irrigation depth at the crop simulation nodes is transferred from Ador-Surface to Ador-Crop, in order to include the irrigation depth in each node's water balance for the day.

Just as discussed in the irrigation simulation module for soil surface elevation, the *TAW* and the effective rooting depth can take different values in each crop simulation node. This procedure reproduces the effect of the spatial variability of these soil physical parameters. The introduction of this variability, along with the variability in irrigation depth, has proven to produce results in close agreement with field observations (Zapata et al. 2000).

The principles used for the simulation of crop growth and water requirements have been based on the developments leading to the CropWat software (Smith, 1992). This decision was taken in consideration of its simplicity and the adequate response of CropWat to water stress in local conditions for corn (Cavero et al., 2000; Dechmi et al., 2004a).

The main improvement of Ador-Crop over CropWat is in the definition of the duration of the growth phases in terms of percentage of the crop thermal integral (Gallagher, 1979), instead of using days. Nielsen and Hinkle (1996) observed that the estimation of crop evapotranspiration is more precise when crop coefficients based on thermal time are used, since in this case the estimate is adjusted to the particular meteorological conditions of each year.

The estimation of crop water requirements followed the methodology proposed by Allen et al. (1998). A water balance is performed for each simulation point since, as previously indicated, the values of *TAW*, effective soil depth and irrigation water depth can differ along the irrigation unit.

Water balance is daily performed for the entire soil profile in a single calculation. The soil water content for each node varies as a function of the previous day soil water, precipitation, real evapotranspiration, irrigation depth, deep percolation (if the total available water is exceeded), and the soil water of the additional soil depth explored by the crop roots in their growth. This soil water is assumed to be equal to the user-defined initial soil water. The mathematical expression of soil water balance for day *j* in crop simulation node *i* is as follows:

$$D_{ij} = D_{i(j-1)} - ETcr_{ij} + P_j + ID_{ij} - DP_{ij} + D_{Rij} \quad [3]$$

where D is the soil water content (expressed in terms of water depth, mm), *ETcr* is the real crop evapotranspiration, *P* is the precipitation, *ID* is the irrigation depth, *DP* is the deep percolation, and D_R is the soil water content at the additional depth explored by the crop roots in its daily growth.

In parallel to the daily water balance, the soil allowable depletion is computed from the type of crop, the phenological stage and the crop evapotranspiration. This leads to the estimation of the soil water level below which the crop is water stressed. The following equation (Allen et al., 1998) was proposed for this matter:

$$AD_{ij} = p_{ij} \, TAW_{ij} \quad [4]$$

where AD_{ij} is the allowable depletion level at the crop simulation node *i* for day *j*, *p* is the fraction of allowable depletion, determined from the crop type and the evapotranspiration, and *TAW* is the total allowable depletion. A comparison between soil water depletion (*TAW* - *D*) and *AD* in all crop simulation nodes is used to determine the number of water stressed nodes. The user can define the threshold number of water stressed nodes which lead to the request of an irrigation.

If an irrigation is requested, the irrigation discharge will be equal to the service discharge in the conveyance network element irrigating the plot. The model includes the possibility of demanding an irrigation event based on soil water content or on the cultural practices of each crop. In this way, the farmers' decision rules have partially been reproduced. These decisions can be composed of additional factors unrelated to soil water (Lamacq, 1997; Labbé et al., 2000), whose modeling goes far beyond the objectives of this research.

As a consequence of this plot irrigation management (the user defined threshold), and of the capacity of the water conveyance network (which can set a given water demand on hold for a number of days), the crop can suffer a certain degree of water stress (localized in parts of the irrigation unit or even generalized). This water stress can lead to a sensible decrease in crop evapotranspiration and therefore, in crop yield.

The real crop evapotranspiration (*ETcr*), taking into account the effect of water stress, can be estimated from the soil water content and the allowable depletion, following the equation proposed by Allen et al. (1998):

$$ETcr_{ij} = ETc_{j} \qquad \qquad if \;\; TAW_{i(j-1)} - D_{i(j-1)} < AD_{ij} \qquad [5]$$

$$ETcr_{ij} = ETc_j \frac{D_{i(j-1)}}{\left(TAW_{ij} - AD_{ij}\right)} \qquad if \;\; TAW_{i(j-1)} - D_{i(j-1)} > AD_{ij} \qquad [6]$$

where ETc is the crop evapotranspiration.

The effect of water stress on crop yield has been modeled using the response factors for each crop developmental stage proposed by Stewart et al. (1975) and developed by Doorenbos and Kassam (1979). The cumulative yield reduction determined along the crop cycle can be determined from (Doorenbos and Kassam, 1979):

$$\frac{y_i}{y_{max}} = \prod_{f=1}^{4}\left[1 - ky_f\left(1 - \frac{ETcr_{if}}{ETc_f}\right)\right] \qquad [7]$$

where y_i is the actual crop yield for node i, y_{max} is the maximum yield in optimum water supply conditions and ky_f is the response factor for each developmental stage f.

Besides simulating crop development during the crop cycle, the model performs a water balance during the no crop time. This balance takes place in one step for the whole period, previously determining soil evaporation through a user supplied coefficient for evaporation from bare soil. This procedure permits one to extend the balance of the hydrosalinity module beyond the crop cycle.

Dechmi et al. (2004b) recently combined a similar crop model and a ballistic sprinkler irrigation model. The crop growth model was validated under field conditions, and a number of exploratory runs were performed to calibrate variables such as the number of water stressed simulation nodes (Dechmi et al., 2004b). This work has established the basis for the future extension of Ador-Simulation to sprinkler irrigation.

Ador-Hydrosaline: hydrosalinity simulation module

Ador-Hydrosaline has been adapted from the hydrosalinity conceptual model CIRFLE for the simulation of salt fluxes in irrigation return flows. This model, developed by Aragüés et al. (1990) and Quílez (1999) following the original developments by Tanji (1977), is composed of a hydrological and a salinity module. CIRFLE is based on mass conservation, incorporates the efficiency in the leaching of soil soluble salts and focuses on the crop root zone. The model predicts the concentration and mass of salts percolating under the root zone.

In its application to the irrigated area of Bardenas I (Zaragoza, Spain), CIRFLE satisfactorily estimated the salinity of irrigation return flows for areas with varying degrees of salinity, as well as the concentration and mass of irrigation return flows in an irrigation district (Quílez, 1999). Due to the nature of the model, its application to new areas must be previously subjected to a calibration process.

The adaptation of CIRFLE performed in Ador-Hydrosaline is applied to each plot, considering the results of the water balance performed for the complete simulation period in Ador-Crop, as well as the physico-chemical properties of the soil type assigned to the plot. Since the hydrological parameters are taken from the crop module, only the salinity submodel of CIRFLE has been implemented in Ador-Hydrosaline. This submodel includes the possibility that the irrigation water precipitates or dissolves calcium carbonate, and/or dissolves gypsum if present in the soil. For calcium carbonate, the model incorporates a locally obtained regression equation between the leaching fraction and the difference in concentration between the precipitated and the dissolved salt. In the case of gypsum, its contribution is treated in a separate way, assuming the presence of sufficient mineral gypsum as to saturate the soil solution. For these reasons, if the study area is characterized by a limited gypsum content or an abundance of other soluble salts, its applicability may be questionable. Transient models should be used in that case (Tanji et al., 1972).

The salt balance applied to each plot for the simulation period can be expressed as (Quílez, 1999):

$$\frac{dM}{dt} = M_{diw} + M_{isw} + M_{sp} + M_{gsp} + M_{p} - M_{dp} - M_{sd} - M_{fsw} - M_{sirf} = 0 \qquad [8]$$

where dM/dt is the rate of change in salt storage in the root zone, M_{diw} is the mass of salts in the irrigation water, M_{isw} is the mass of salts in the initial soil water, M_{sp} is the mass of precipitated salts, M_{gsp} is the mass of gypsum really dissolved in the soil water, M_{p} is the mass of salts in the precipitate, M_{dp} is the mass of salts in the deep percolation water, M_{sd} is the mass of dissolved salts, M_{fsw} is the mass of salts in the final soil water, and M_{sirf} is the mass of salts in the irrigation return flows. In the application of this equation the existence of seepage has been neglected, and the initial and final soil water contents have been assumed equal.

Ador-Hydrosaline estimates the mass and concentration of salts percolating from each plot. By aggregation, this model estimates the mass of salts circulating in the drainage network during the simulation period. A relevant limitation of this conceptual framework is that if secondary water sources with water quality differing from that of the main water source (as is the case in the connections from the drainage to the irrigation networks), the model looses its predictive capability. The reason is that the fate of the irrigation water can not be determined *a priori* according to its origin. As a consequence, it is impossible to estimate the salt exports from each plot with a model which is not robust enough to perform daily hydrosalinity balances.

Ador-Network: water conveyance simulation module

This module is composed by several submodules. The first one focuses on water conveyance, including one main water source (an irrigation canal), the in-line reservoirs and the secondary water sources. This module aggregates water demands from the plots, which are generated by the irrigation decision making module. This submodule determines if the water conveyance network is capable of transporting the requested water flows. Additionally, the submodule determines the demand which can be supplied by the reservoir storage plus the secondary water sources.

The calculations performed within this module to aggregate water demands are based on a hierarchy matrix. This matrix is a double entry table for the elements of the irrigation network (canal reaches). For each network element, a value of 1 is set for all network elements which are directly of indirectly water supplied by it. A value of 0 is set otherwise. The same matrices are used to establish the network elements which can be water supplied from each in-line reservoir or secondary water source. This scheme permits one to evaluate on an hourly basis the conveyance capacity of the open channel distribution network, without resorting to hydraulic models of open channel flow. Such models would not result in a radical improvement in Ador-Simulation modeling accuracy, but would require intense data collection and parameter estimation.

The assessment of distribution water losses is performed in each irrigation event from the service discharge and the time interval between the end of the irrigation in one plot and the beginning of the next hour. This procedure accommodates the common district policy of allocating water to the farmers at o'clock hours. This model implementation supposes a relevant simplification of reality, and does only partially address the causes for operational water spills in irrigation districts.

The submodule corresponding to the drainage network uses the same routine applied to the conveyance network. As a consequence, the drainage network must also be strictly ramified. This submodule aggregates the volume of water lost to surface runoff and deep percolation, plus the losses in water distribution. The masses of salts in the return flows (determined for each plot in Ador-hydrosaline) are also aggregated by reaches of the drainage network. Since the response time of the drainage network can be in the order of days for the deep percolation losses, the simulation is performed at the end of the simulation period, and for the whole period. Hydrogeological models would be required to perform daily simulations. For the purposes of Ador-Simulation it is enough to have an estimation of the mass of leached salts and the salinity of the return flows. These values can be estimated at different points of the drainage network, draining different areas of the irrigation district.

The user can specify the percentage of deep percolation losses which is recovered by the drainage network. This estimation should be based on previous research results. Ador-Network considers that all the losses of each plot appear in the associated element of the drainage network. Since this information is based on the aggregation of different plots, the quality of these results will benefit from the representation of a large area.

As previously discussed, it is possible to introduce connections between the drainage and the conveyance networks, leading to additional water inflows. These connections are treated as secondary water sources, and are limited by the maximum discharge of the connection (physically limited by a pump or a canal capacity). Ador-Network records the water transferred during the simulation period, which is deduced from the volume of water circulating through the drainage network.

Ador-Decision: irrigation decision making simulation module

Ador-Decision is the core module of Ador-Simulation, since it is responsible for reproducing decision making in water allocation, and therefore implements the water policies of the simulated irrigation district. The module can perform water allocation following an arranged demand, fixed discharge scheme (Clemmens, 1987). When the capacity of the network is not sufficient to accommodate water demand, this allocation scheme reproduces rotation irrigation.

The module is executed at an hourly time step. It analyses the water demands received from the plots through Ador-Crop, and faces these new demands with the current occupation of the conveyance network, resulting from the plots which started irrigation in the previous hours and which are still irrigating. The model starts the simulation assigning the water demands to the different water sources. If secondary water sources are available, their discharges will be used to assign water to the plots requesting water within their domain. Preference is given to plots which have already started irrigation from this water source and to plots which are close to the source. This treatment of the secondary sources stems from the consideration that these have a small capacity, capable of simultaneously satisfying a few plots at the maximum.

In the next steps, in-line reservoirs are considered (if present in the district). Water orders are selected which fall in the domain of a reservoir. Once identified, Ador-Network determines if the conveyance network can transport the demanded discharge. If this is the case, the next step is to verify if the reservoir has enough storage to supply the water demand. This verification is performed on a daily basis, instead of an hourly basis, in order to guarantee a dependable water supply to the plots which are reservoir supplied. If not all the water requests can be serviced, due to limitations in the conveyance capacity or in the reservoir storage, water will be allocated to the different water orders following a preference list, until the conveyance capacity is reached or the reservoir storage is depleted. The preference list is elaborated by Ador-Decision following different user-defined criteria. The first criterion is to respect the continuity of irrigation in the plots which had already started irrigation. This criterion is automatically enforced. The remaining water demands are selected one by one. The first step is to check if the water order can be supplied by the conveyance network and the reservoirs, once the plots where irrigation had previously started and the water demands approved at this time step have been considered. The orders that can be supplied can be ordered following two criteria: 1) the number of consecutive days that this plot has been requesting water; and 2) criterion 1 plus the value of the response factor to water stress (*ky*, Eq. 7), which is an index of sensibility to water stress dependent on the crop and its phenological stage (Stewart et al., 1975). These two criteria lead to the distinction of two simplified types of district water management, related to the technical skills of the water managers. More elaborated criteria, including additional managerial or economic information could be included in Ador-Decision.

Once the water orders are assigned for the in-line reservoirs, the second step is to assign water from the main water source, whose domain is the whole district. The procedure is essentially the same as for the reservoirs. In this case, the considered water orders are those that could not be satisfied from the reservoirs, because they were not within their domain, because the conveyance capacity was limited or because the reservoir storage was depleted.

Once Ador-Decision assigns water to all the water orders that can be fit in the conveyance capacity, it evaluates the possibility to increase reservoir storage during the simulated hourly period. The module determines the maximum discharge which can be allocated to the reservoirs. This determination is performed by Ador-Network for the route separating the main and all the secondary water sources from the reservoirs. Just like in the case of the water orders, a preference list is elaborated for the reservoirs (if not all of them can be refilled). This list follows two criteria: 1) the current irrigation water requests from every reservoir; and 2) the ratio between current and maximum storage.

This puts and end to the process of water allocation to the plots. The result is a list of plots which are to be irrigated in the following hourly period, the irrigation discharge and the discharge of each element in the conveyance network. This list is sent to Ador-Surface to simulate irrigation in the plots where irrigation is to be started. In order to moderate execution time, only one irrigation simulation is performed in each plot. The results (infiltrated depth at each crop simulation node) are stored in a database to be used every time an irrigation event is applied to this particular plot along the season. In each particular case, irrigation performance will be computed from the nodal values of irrigation depth and soil water depletion.

If the daily irrigation period is smaller than 24 hours, once the decision making procedure reaches the hour of end of water service to the farms, the objective is to refill the in-line reservoirs. For this matter, Ador-Decision continues to analyze the network capacity on an hourly basis, considering as the first preference criterion only the plots which have already started irrigation, and preferentially refilling the reservoirs which can service them.

COMPUTER MODEL IMPLEMENTATION

Ador-Simulation has been developed using the C++ programming language. The interest of this programming language derives from its capacity for structured calculus through the representation of the objects to be simulated. Object-oriented programming permits one to represent the physical and the functional part of the objects, following the definition of variables (describing properties of the objects) and methods (describing the actions they can undertake). This programming technique eases the computer implementation of complex simulation models, standardizing the computer code and compartmentalizing it in independent modules.

An example of the programming technique in Ador-Simulation is the object “border”. The variables in this object include its characteristics (border geometric, soils and irrigation data), and the results of the different actions. Such variables include the length and width, the slope, the standard deviation of soil surface elevation, the infiltration parameters, the provision for surface runoff, the number of computational nodes for simulation purposes, and the simulation results. The methods for the border include simulating an irrigation, storing the border data in the respective variables, or retrieving information from the simulation results. The definition of this object with its variables and methods constitute the standard code for all the borders within a district. Thus, the homogeneity of the code is ensured, and error tracking in complex models is greatly facilitated.

Figure 2 presents a simplified diagram of the objects defined in Ador-Simulation. The methods defined for each object are detailed. Method names preceded by “set” transfer values to the objects, while method names preceded by “get” return the values stored in the object variables. The sub index i indicated at the end of a number of methods refers to the same function applied to different object variables.

MODEL APPLICATION EXAMPLE

In order to demonstrate the capabilities of Ador-Simulation, an application example is presented in the following paragraphs. In this example water flows are simulated in a hypothetical irrigation district for a whole year.

This irrigation district has an area of 125 ha, and its schematic representation is displayed in Figure 3. The district is divided in ten plots, each containing a number of free draining borders. The dimensions of the typical border of each plot are presented in Fig. 3. Two types of soils have been identified in the district. Soil type A is characterized by the spatial homogeneity of its physical properties (*Zr* = 72 mm), while soil type B is heterogeneous. The spatial variability of *Zr* in soil B is characterized by a normal statistical distribution with an average of 65 mm and a standard deviation of 32 mm. The saturated soil extract electrical conductivity (*ECe*) is 0.9 and 0.5 dS m^{-1} (25 ºC) for soil types A and B, respectively. The Kostiakov infiltration equations for soils A and B are:

$$\begin{aligned} Z_A &= 0.015\ \tau^{0.31} \\ Z_B &= 0.010\ \tau^{0.45} \end{aligned} \qquad [9]$$

where Z is the cumulative infiltration (m) and τ is the infiltration opportunity time (min). The field slope is related to the soil type, and is 0.0008 for soil A and 0.0012 for soil B.

The simulated climate presents an annual precipitation of 416 mm and a reference evapotranspiration of 1,088 mm. This data set corresponds to the records of the Aula Dei meteorological station (Zaragoza, Spain) in 1997. The crops present in the simulated district are corn, alfalfa and sunflower (Fig. 3).

The irrigation structures are composed of a network of concrete lined ditches, branching from a main canal. The maximum conveyance capacity is 0.150 m^3 s^{-1}, and the service discharge is 0.125 m^3 s^{-1}. These discharges are insufficient to guarantee the adequate water supply to the district crops. At the upstream end of the district there is an in-line reservoir with a capacity of 5.000 m^3, which can be supplied from the main canal and from a creek (with a continuous discharge of 0,050 m^3 s^{-1} during the irrigation hours). At the beginning of the season the reservoir is full. The electrical conductivity of irrigation water (*ECiw*), from the canal and the stream is 0.4 dS m^{-1} (25 ºC).

The water delivery scheme is restricted arranged, and the daily irrigation period is 16 h. The drainage network is composed of collectors conveying the irrigation return flows. All the deep percolation losses generated during the season are collected at the drainage network.

With this initial situation, a number of simulations were performed using Ador-Simulation. The goal was to reproduce the current situation and to evaluate an scenario for the improvement of on-farm irrigation. This exercise served to evaluate the influence of farmers' decision making on the irrigation district. The improvement of irrigation management was based on an optimization of the time of cut off to maximize application efficiency. This was achieved using the optimization routine within Ador-Surface. An irrigation request was issued by Ador-Crop when 25 % of the crop simulation nodes were water stressed in a given plot. Throughout the simulations, 50 computational nodes and 12 crop simulation nodes were used. The criterion for decision making in water allocation to the plots was the number of consecutive days demanding an irrigation. This criterion was applied in both the current and optimum scenarios.

Model results are first presented for the optimum scenario. Figure 4 presents the evolution of soil water depletion and allowable depletion in plot 1, with a corn crop. Figure 4a presents average values for the 25 % of the most stressed Ador-Crop nodes (3 nodes). In the plot, the effects of irrigation and precipitation can be appreciated. The periods in which soil water depletion exceeds allowable depletion are due to the low capacity of the irrigation network, which was unable to satisfy water demand. Figure 4b presents the same information, but for the average of the 12 crop simulation nodes. Towards the end of the simulation period, the decrease in the evaporative demand implies that the delay in irrigation does not result in average water stress.

It is interesting to note that both soil water depletion and allowable depletion are smaller in the average of the 25 % most stressed nodes. This is due to the spatial variability of soil physical properties: the stressed nodes have very small TAW, and as a consequence, a small allowable depletion (Eq. 4). The differences between both subfigures endorse the use of a number of crop simulation nodes per plot. Severe water stress can occur in a significant field area while the average figures reflect an almost adequate water supply.

Figure 4 reveals that on June 15 an irrigation was applied to plot 1. This irrigation event was applied after three consecutive days of water stress (Fig. 4a), since the conveyance network was busy serving previous water demands. Figure 5 presents the optimum irrigation event applied on that day, displaying the irrigation depth, the soil water depletion and the allowable depletion along the typical border, represented by the 12 Ador-Crop simulation nodes. As previously discussed, the *TAW* is spatially varied, and so are the soil water depletion and the allowable depletion. In more than three nodes (nodes 5, 6, 10 and 12) soil water depletion exceeds the allowable limit, thus justifying the water order. Figure 5 evidences lack of adjustment between average soil water deficit and average irrigation infiltrated depth. This difference leads to a low application efficiency (37 %), and is due to the high infiltration rate, which results in a large irrigation depth even for optimum time of cut off.

Figure 6 presents the evolution of the in-line reservoir inflow and outflow discharges (Fig. 6a) and water storage (Fig. 6b) for a period of five days between June 11 and 16. The hydrograph differs among days due to the satisfied water orders in the different plots. In June 11 two plots (plots 3 and 8) were simultaneously irrigated, just like in June 12. In the last two hours of operation the outflow discharge from the reservoir is halved following the end of irrigation in plot 8. The next day only plot 2 irrigates. In the last two days of the period two plots irrigate simultaneously (plots 2 and 9 in June 14; plots 1 and 9 in June 15). The inflow discharge to the reservoir from the main canal remains constant at 0.150 m^3 s^{-1} (equal to the maximum capacity of network element #1 for 22 hours a day. This discharge, together with the stream diversion during the irrigation period (0.050 m^3 s^{-1}), ensures the reservoir refill before the start of the next irrigation day. During the day in which only one plot is irrigated the main canal demand is reduced to 0,075 m^3 s^{-1}, which added to the stream discharge can supply the plot without contribution from the reservoir.

Table 2 displays a number of performance indicators from the two scenarios analyzed with Ador-Simulation. The positive effect of irrigation management improvement at the farm level can be appreciated. This results in direct benefits to the farmers (*i.e.*, reducing by 1 h ha^{-1} the average irrigation time), but also in indirect benefits, permitting a better functioning of the irrigation district. These improvements derive from the improvement of irrigation efficiency (percentage of applied water which is used to satisfy beneficial uses, like crop evapotranspiration, for a given period of time) as a consequence of reducing the time of cut off. Since the improvements have been exclusively performed at the farm level, no improvements have been produced at the conveyance efficiency (percentage of diverted water which is applied by farmers). The improvements in irrigation efficiency have led to a significant decrease in aggregated water demand and in the volume of irrigation return flows. Therefore, the volume of water transported by the conveyance system has decreased. As a consequence, farmers have received a better service, and the delay time for water order service has been reduced. This, in turn, has resulted in a reduction in crop water stress and therefore in an increment in real crop evapotranspiration and yield. Another consequence of the increment in irrigation efficiency is the reduction in the mass of exported salts. However, the EC of the return flows has been moderately increased.

CONCLUSIONS

The Ador-Simulation model simulates water flows in irrigation districts, connecting the variables affecting water use, agricultural production and the environment in an irrigated agricultural system. The model can be used for the evaluation of different management and planning alternatives at the plot level or at the district level. The structure of Ador-Surface, and its interaction with Ador-Crop, permits one to simulate the spatial distribution of water stress within an irrigated field, leading to the demand on a new irrigation. The combination of all these variables and capabilities at the irrigation district level constitutes a contribution to the state of the art, linking agronomy to on-farm and district water management.

The model constitutes an adequate tool for the support to decision making on irrigation management and planning, and for the modernization of the conveyance structures. The use of the model will be limited by the required intensity in data collection. Preparing the required data set requires analyzing the natural and human limitations to the simulated irrigation district. The combined use of Ador-Management and Ador-Simulation will permit the latter to gain access to this information in a systematic and continuously updated manner.

The capacities described in Ador-Simulation must be verified applying the model to a real situation in order to determine the reliability of its results and perform the necessary calibrations. This objective is addressed in a companion paper, in which the model is calibrated and validated using real field data.

In the current state of model development the relationships between the different modules have been established. These relationships constitute the basis for the implementation of additional modules in the future. Increasing the number of supported water delivery schemes, extending the simulation to furrow irrigation, adding a module for the computation of farm revenues, generalizing the results of the hydrosaline balance or incorporating an advanced crop simulation module (estimating nitrate leaching and/or the effect of salinity on crop yield) seem to be adequate goals for the future. The automatic link of model data input and results display to a GIS would also result in extended model applicability.

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APPENDIX II: NOTATION

The following symbols are used in this paper:

A	=	area of a fluid section
AD	=	allowable depletion level at the crop simulation node *i* for day *j*
D	=	soil water content
D_R	=	soil water content at the additional depth explored by the crop roots in its daily growth
dM/dt	=	rate of change in salt storage in the root zone
DP	=	deep percolation
ECe	=	saturated soil extract electrical conductivity
ETc	=	crop evapotranspiration
$ETcr$	=	real crop evapotranspiration
F	=	Froude number
g	=	acceleration of gravity
h	=	flow depth
I	=	infiltration rate
i	=	node i
ID	=	irrigation depth
j	=	day j
ky_f	=	factor for each developmental stage *f*
M_{diw}	=	mass of salts in the irrigation water
M_{dp}	=	mass of salts in the deep percolation water
M_{fsw}	=	mass of salts in the final soil water
M_{gsp}	=	mass of gypsum really dissolved in the soil water
M_{isw}	=	mass of salts in the initial soil water
M_p	=	mass of salts in the precipitate
M_{sd}	=	mass of dissolved salts
M_{sirf}	=	mass of salts in the irrigation return flows
M_{sp}	=	mass of precipitated salts
P	=	precipitation
p	=	fraction of allowable depletion
Q	=	discharge
S_0	=	field slope
S_f	=	friction slope
t	=	independent variable time
x	=	independent variable space

y = actual crop yield

y_{max} = maximum yield in optimum water supply conditions

Z = cumulative infiltration

Zr = target irrigation depth

τ = infiltration opportunity time

APPENDIX III: LIST OF TABLES

Table 1. *Input data to Ador-simulation.*

Type	Variables
Meteorological	Day, Month, Year, Precipitation, Maximum temperature, Minimum temperature, Solar radiation, Average relative humidity, Average wind speed, Reference evapotranspiration
Soil	Rooting depth, Field capacity, Total available soil water in the root zone, Bulk density, Saturation water content, Coefficient k and the exponent a of the Kostiakov equation, Saturated soil extract electrical conductivity, Gypsum content, Leaching efficiency
Water	Electrical conductivity of irrigation water, Electrical conductivity of precipitation water
Crop	Duration of the phenological stages, Crop coefficients, Thermal integral, Temperature threshold, Duration of the water stress sensitivity stages, Stewart coefficients, Fraction of allowable depletion, Initial root depth, Maximum root depth, Maximum crop height
Plot	Cadastral reference, Area, Dimensions and slope of the basin or border, Runoff outlet in borders, Reduction coefficient for the runoff discharge, Soil type, Irrigation Ditch, Drainage element, Initial soil water content, Crop, Sowing date, Irrigation type, Irrigation time, Manning coefficient n, Standard deviation of soil surface elevation
Conveyance and Drainage structures	Conveyance capacity, Service discharge, Network hierarchy, Start and end hour of irrigation operation Secondary water sources: Point of diversion, Maximum discharge, Initial conveyance element, Final conveyance element In-line reservoirs: Reservoir point, Capacity, Associated network hierarchy
Other parameters:	Coefficient for optimising irrigation time, Percentage of deep percolation losses recovered by the drainage network, Number of computational nodes, Number of crop simulation nodes, Threshold of water stressed nodes leading to the request of an irrigation

Table 2. *Performance indicators corresponding to both simulated scenarios.*

Simulation Results	**Current Scenario**	**Optimized Scenario**
Irrigation time, h ha^{-1}	2.7	1.9
Crop yield, % relative to potential yield	85.4	92.3
Irrigation efficiency, %	34.3	43.6
Conveyance efficiency, %	98.2	98.2
Seasonal irrigation volume, m^3 ha^{-1}	14,990.0	12,251.0
Global seasonal irrigation volume, hm^3	1.91	1.56
Demand satisfied by the creek, %	23.2	25. 5
Global seasonal crop evapotranspiration, m^3	773,871.0	808,191.0
Seasonal precipitation and irrigation return flows, hm^3	1.5	1.1
Total seasonal mass of exported salts, Mg	755.1	659.6
Average electric conductivity of return flows, dS m^{-1} (25 ºC)	0. 8	0.9

APPENDIX IV: LIST OF FIGURES

Figure.1. *Schematic description of Ador-Simulation data, modules and results.*

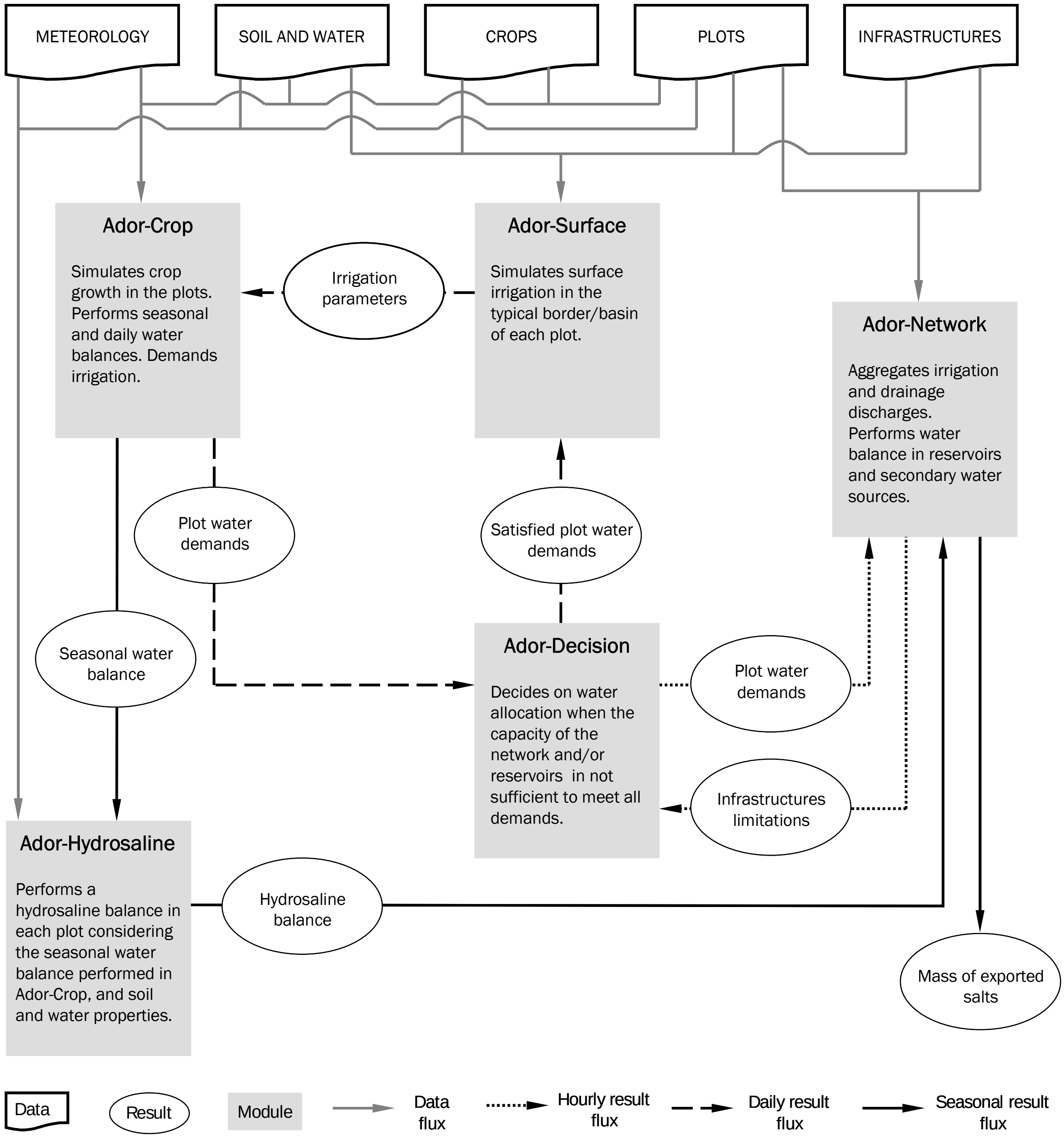


Figure 2. *Simplified object diagram for Ador-Simulation, including reference to the object methods.*

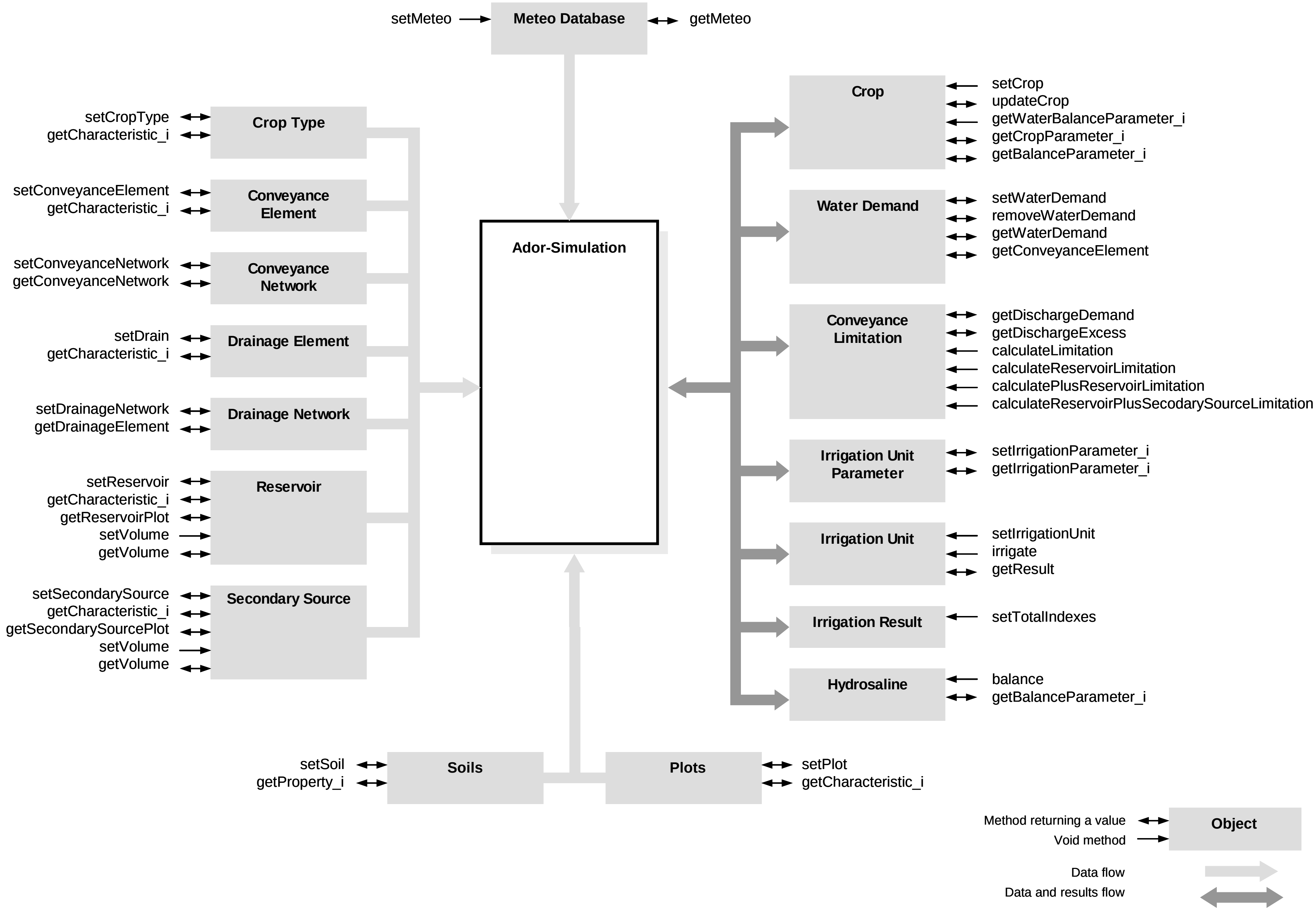
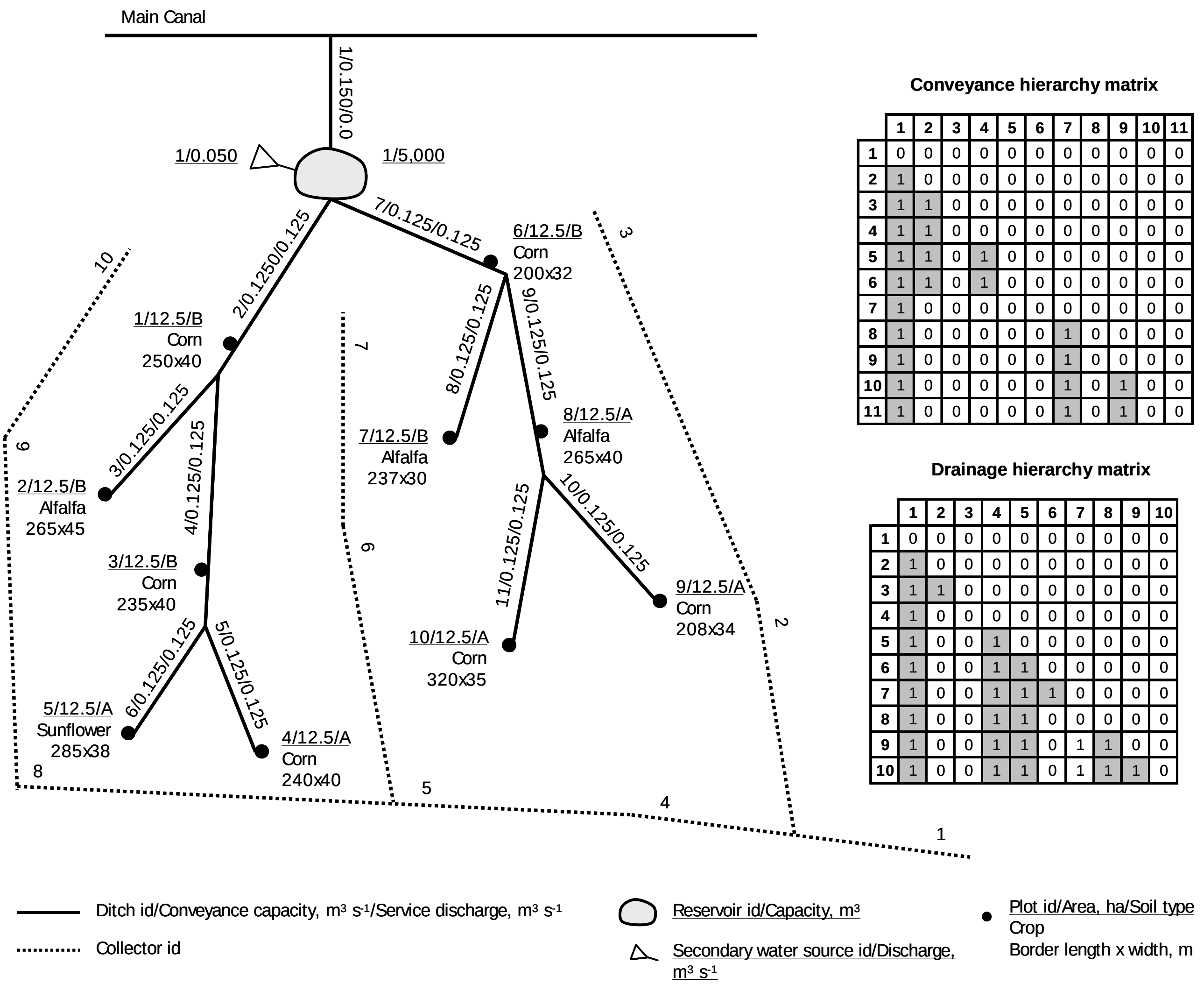


Figure 3. *Schematic representation of the irrigation district and the hierarchy matrices of the conveyance and drainage networks.*



Conveyance hierarchy matrix

	1	2	3	4	5	6	7	8	9	10	11
1	0	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	0	0
3	1	1	0	0	0	0	0	0	0	0	0
4	1	1	0	0	0	0	0	0	0	0	0
5	1	1	0	1	0	0	0	0	0	0	0
6	1	1	0	1	0	0	0	0	0	0	0
7	1	0	0	0	0	0	0	0	0	0	0
8	1	0	0	0	0	0	1	0	0	0	0
9	1	0	0	0	0	0	1	0	0	0	0
10	1	0	0	0	0	0	1	0	1	0	0
11	1	0	0	0	0	0	1	0	1	0	0

Drainage hierarchy matrix

	1	2	3	4	5	6	7	8	9	10
1	0	0	0	0	0	0	0	0	0	0
2	1	0	0	0	0	0	0	0	0	0
3	1	1	0	0	0	0	0	0	0	0
4	1	0	0	0	0	0	0	0	0	0
5	1	0	0	1	0	0	0	0	0	0
6	1	0	0	1	1	0	0	0	0	0
7	1	0	0	1	1	1	0	0	0	0
8	1	0	0	1	1	0	0	0	0	0
9	1	0	0	1	1	0	1	1	0	0
10	1	0	0	1	1	0	1	1	1	0

Figure 4. *Time evolution of soil water depletion and allowable depletion for a corn crop in plot #1. a) Average of 25 % most stressed nodes; and b) average of all simulation nodes.*

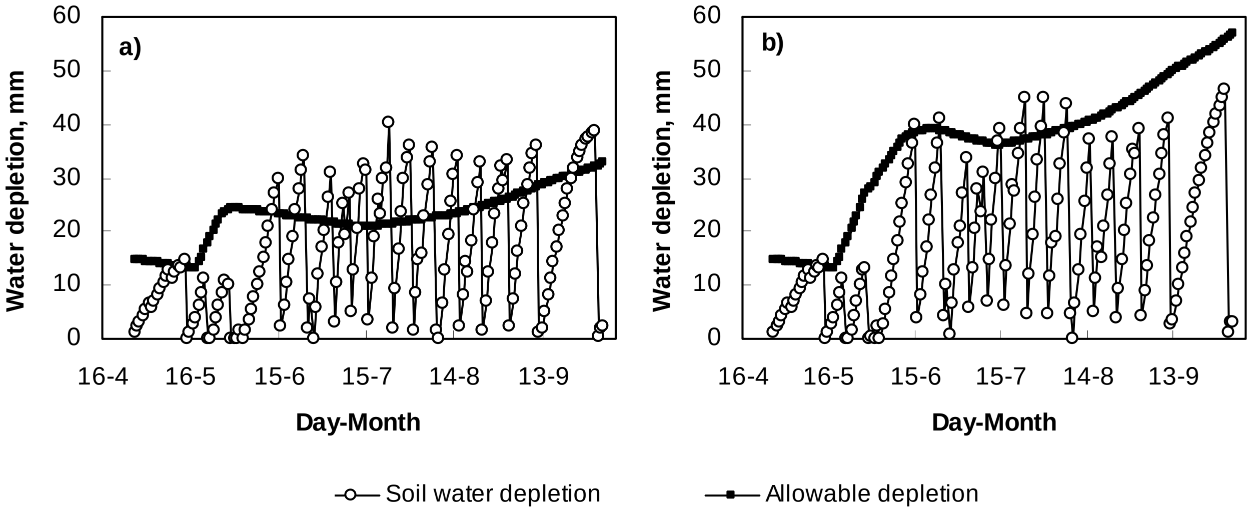


Figure 5. *Soil water depletion, allowable depletion and Irrigation depth along the typical border of plot #1 for the irrigation event dated June 15.*

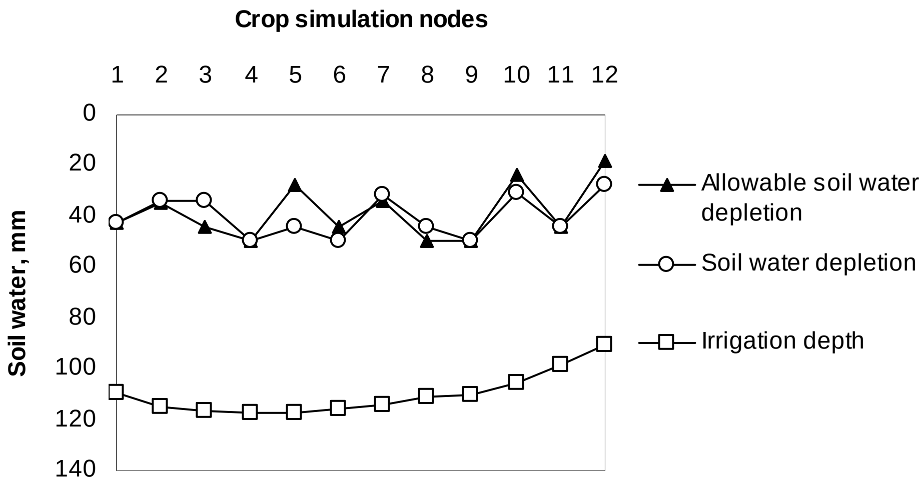


Figure 6. *Time evolution of a) In-line reservoir inflow (from ditch #1) and outflow; and b) Reservoir storage. The time period is June 11-16.*