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A MODEL FOR THE SIMULATION OF WATER FLOWS IN IRRIGATION DISTRICTS: II. APPLICATION

by

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ABSTRACT

In a companion paper a model for the simulation of water flows in irrigation districts was formulated. The model combines a series of modules specialized in surface irrigation, open channel distribution networks, crop growth modeling, irrigation decision making and hydrosaline balance. The objective of this paper is to calibrate, validate and apply the model, using the Irrigation District Five of Bardenas (Spain) as a study area. Two years of study were used for the analysis, which could be classified as normal (2000) and dry (2001) from the point of view of crop water requirements. Model calibration was performed in one of the eleven hydrological sectors in which the district is divided. The control variable was the monthly water demand, while the calibration variables were related to irrigation operation and scheduling. The seasonal differences in observed and simulated water demand

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amounted to 0.9 and 1.9 % for 2000 and 2001, respectively. Model Validation was performed in the rest of the Sectors, and the regression line of observed vs. simulated monthly water demand could not be distinguished from a 1:1 line in both years. Model application explored scenarios based on management improvement (controlling the irrigation time) and structural improvement (increasing drainage water reuse for irrigation). These scenarios permitted to sharply reduce water demand, halve the irrigation return flows and reduce the daily irrigation period from 24 to 16 hours.

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

INTRODUCTION

The irrigation district V (five) of Bardenas, with an irrigated area of 15,545 ha constitutes an example of a district requiring a modernization of its irrigation structures and management practices. Border irrigation started in the district in 1959, following the construction of the Yesa reservoir on the Aragón river and the Bardenas Canal. On farm and water conveyance structures were constructed in the 1960s. The water conveyance network was designed for the purpose of supplementary irrigation for winter cereals, and its capacity has only been moderately increased since its construction. However, the crop distribution has been strongly modified, and the most important crops are now corn and alfalfa. The high water requirements of these crops (as compared to wheat and barley) have resulted in a sharp increase in water demand in the district, which accentuates the capacity limitations of the conveyance network during the summer months. The water delivery scheme is based on arranged demand (Clemmens, 1987). Farmers order water to the district ditchriders, which allocate water for a negotiated duration and with the maximum service discharge of the irrigation ditch. In the peak of the summer the delivery system is more similar to a varied frequency rotation, in which all farmers receiving water from a given irrigation ditch irrigate in a sequential pattern. The daily irrigation period is 24 hours (irrigation is not stopped during the night time), and the irrigation interval often challenges the crop drought resistance. The use such long intervals permits the district to maximize the acreage of water demanding (summer) crops. In the last decade the district has performed a number of construction works (ditches and reservoirs) to store drainage flows and convey them back to the irrigation network. Some of them are gravitationally operated, while other require energy input. Despite this, some 20% of the district area (depending on the years) must be set to winter cereals or remain fallow. The present conveyance network could not support a full dedication to water demanding crops such as corn or alfalfa.

Lecina et al. (2005) presented an analysis of the irrigation district V (IDV) performed using irrigation evaluation and surface irrigation simulation techniques. They reported that 71 % of the district soils present high infiltration and a low Total Available Water (*TAW*) (Walker and Skogerboe, 1987; Allen et al. 1998). These soils are not adequate for surface irrigation, since deep percolation losses will be difficult to control. The situation is aggravated by the farmers reaction to the long irrigation intervals: they extend irrigation beyond the required time, in order to stock water in the soil for the whole interval. Unfortunately, this excess water can not be stored in the soil, and only serves to extend the irrigation intervals, which can reach 12-14 days. A total of 50 irrigation evaluations were performed. Their results were geographically extended to all the district, using a surface irrigation simulation model. As a result, it was estimated that the average application efficiency in the district was 49 %. The optimization in the on-farm irrigation time was also analyzed, concluding that an application efficiency of 76 % could be reached. These estimations were performed at the field level, and no indications could be reported on the effect of improving the irrigation time on the conveyance network or on agricultural production. However, these estimations could be contrasted using a set of hydrological data (canal water deliveries and crop evapotranspiration) for 2000 and 2001. The Seasonal Irrigation Performance Index (SIPI, Faci et al., 2000) can be considered as an estimation of irrigation efficiency. The district wide SIPI was 49 % in 2000, a year characterized by an adequate district water supply. In 2001, irrigation water supply was limited, and farmers were encouraged to improve their irrigation management. As a result, the district wide SIPI jumped to 66 % (without apparent yield loss, according to the IDV perception), revealing that there is a margin for improving irrigation efficiency even with the current structures. The key variable seemed to be the irrigation time, confirming the results of the irrigation evaluation campaign.

Canal water limitations in the IDV are recurrent over the years. These restrictions often affect the end of the irrigation season, and occasionally create problems during the whole season, with relevant restrictions to the planting of water demanding crops and/or affections to crop yield. The district has responded to these challenges with an improvement of water storage in the Bardenas Canal system. Alternative measures targeted at the substitution of the current surface irrigation systems by pressurized systems have not received much attention so far. This is why the modernization process of the IDV is currently oriented towards maintaining surface irrigation in place and improving its performance.

The large number of factors affecting irrigation modernization (agronomic, hydraulic, economic, sociologic, environmental…) make it a complex process. As a consequence, tools such as decision support systems or geographic information systems (GIS) result adequate for iteratively analyzing multiple alternative scenarios. Following this reasoning, the development of a computer model for the simulation of water flows in irrigation districts (Ador-Simulation) has been reported in the preceding companion paper. The model is composed of a number of modules which, executed in an interactive fashion, reproduce the basin hydrological processes in an irrigation district. These modules simulate surface irrigation (Ador-Surface), crop growth (Ador-Crop), water conveyance and drainage networks (Ador-Network), hydrosaline balance (Ador-Hydrosaline) and district decision making in water allocation (Ador-Decision).

This paper is set to demonstrate the capabilities of Ador-Decision, applying it to a real irrigation district, the IDV. A second goal of this work is therefore to contribute to decision making in the modernization of the IDV. The current district preference for surface irrigation has been considered. The application of the model to the IDV follows the classical calibration-validation process, which was applied to the 2000 and 2001 data sets.

Modernization scenarios based on the improvement of irrigation management and structures were then simulated and results were compared and discussed.

CHARACTERIZATION OF THE STUDY YEARS

The model was applied to the irrigation campaigns of 2000 and 2001. The meteorological conditions in both irrigation seasons were quite different, thus allowing to analyze the model behavior in a wide range of water demand conditions. In 2000, reference evapotranspiration (ET_0), determined according to the Penman-Monteith equation (Allen et al., 1998), was 1.085 mm. This value corresponds to an average year (50 % return probability). The precipitation (533 mm) was characteristic of a wet year (8 % return probability). On the contrary, 2001 was characterized by a high ET_0 (1,114 mm, with a 35 % return probability), and scarce precipitation (276 mm, 99% return probability). The meteorological data for the study years were registered by an automatic weather station installed in the district. The climatic characterization was performed using the 1965-1994 data set from the Santa Anastasia weather station (Lecina et al., 2005), located within the IDV.

A relevant feature of the climatic data set is the high precipitation registered during the winter-fall period of 2000 (210 mm between November 2000 and February 2001, as compared to the interannual average of 133 mm). Due to the high precipitations, the sowing of winter cereals from November onwards was almost impossible. As a consequence, the area devoted to winter cereals was less than half in 2001 than in 2000. Correspondingly, summer crops (like corn and alfalfa) increased their acreages in 2001, reaching 75% of the cropped area in the IDV (Table 1). The combination or increased district-wide crop water requirements and a reduced water availability in the Bardenas Canal resulted in a complicated season for the district managers. The district water allocation only increased moderately: 146,5 hm^3 in 2000 *vs.* 155,9 in 2001, according to the IDV records.

SIMULATION DATA SOURCES AND PROCESSING

The basic data for the simulations presented in this paper were drawn from the analysis of the IDV presented by Lecina et al. (2005). Such data included on-farm irrigation water management, land tenure, morphology of the irrigation systems, water conveyance structures and soil survey. Simulations were performed for irrigation seasons starting in November and ending in October, in order to properly accommodate winter cereals (the 2000 irrigation season ends in October 2000).

In Ador-Simulation, the plot is the basic geographical unit. A typical irrigation unit (a border in this case) is characterized in each plot. Irrigation simulation is performed in the typical irrigation unit and extended to the whole plot area. In a large irrigation district, such as the IDV, it would be unmanageable to identify, characterize and simulate all borders in all cadastral plots. Therefore, the same methodology applied by Lecina et al. (2005) for IDV on-farm irrigation simulation was used. A typical border was defined as characteristic of each of the irrigation "turns". These areas correspond to the group of plots irrigated with one irrigation module and from the same irrigation ditch when the district operates on a rotation schedule.

A total of 147 turns were identified in the IDV. The turns can be grouped into 11 hydrological sectors (Figures 1 and 2). Sectors were introduced by the Government at the time of district construction, and their boundaries are coincident with the main drainage collectors. Each turn comprises a number of plots, which must be considered during the simulation process. The number and area of the plots present in each turn was obtained from the management database of the IDV. The crops present in the plots in each of the study years were also downloaded from the database. A total of 1,619 plots were identified in the database. This number only represents an approximation to reality, since the district database does not use cadastral reference. In fact, the IDV definition of plot corresponds to an area irrigated in a given turn and devoted to one crop. The IDV plots can be part of a cadastral plot or composed of different cadastral plots. The use of this spatial unit results convenient to the district management, since it simplifies the real structure of land tenure. Ador-Simulation plots were created for each plot in the management database. One of the two soil types characterized by Lecina et al. (2005) adapting the geomorphological map presented by Basso (1994), was assigned to each plot. The area of the plots with each soil type within each turn was adjusted to meet the cartographic soil type area.

A relevant part of the district area (10%, corresponding to the municipality of Biota, in the North of the IDV) is not properly levelled, and its irrigation system can be better described as wild flooding. This area was not implemented in Ador-Simulation.

The initial soil water depletion at the onset of the simulation period was estimated from the meteorological conditions prevailing during the weeks preceding sowing. Depletion was established as a percent of *TAW*. The sowing date for each crop was statistically assigned, following the statistical distribution derived from the IDV farmers' interviews performed by Causapé (2004), corresponding to the years 2000 and 2001.

Each plot was related to a water conveyance network element (an irrigation ditch), and to the drainage network. In the case of the irrigation network, each element was characterized by a service and a conveyance discharge, which were obtained from ditchriders' interviews and the district network of broad crested weirs (Bos et al., 1984). A total of 238 irrigation ditches and 156 drainage collectors were identified. Figure 2 displays a graphical presentation of both networks. The water transfer works (from the drainage to the irrigation network) and the two existing in-line reservoirs were characterized from the district records. A total of sixteen water transfers were documented. Two reservoirs for drainage water were described, with a compound capacity of 1.20 hm^3.

Crop growth and irrigation simulations were performed at the typical border of each plot. A total of 50 nodes were used for irrigation simulation, and 12 for crop growth. An irrigation was requested when 25 % of the border area was water stressed. The only criterion used for decision making in water allocation was the number of days each plot had been requesting an irrigation event. This last criterion was based on field observations.

The spatial variability of *TAW* and effective soil depth was considered in the case of the platform soils, given their natural heterogeneity. The statistical distribution of these properties, as measured in the soil survey, was used to assign different values of these properties to different simulation nodes of Ador-Surface and Ador-Crop.

Crop simulation required the introduction of data on phenology, water stress sensitivity and agronomy. The duration of the phenological phases and the crop coefficients was obtained from Martínez-Cob et al. (1998). The values of the thermal integral and the related temperature threshold were derived from local experiences (Cavero et al., 2000), or from general references (Loomis and Connor, 1992; Maroto, 1990). The Stewart coefficients for the determination of water stress sensitivity were obtained from the work by Doorembos and Kassam (1979). The common irrigation practices were gathered from farmers' and ditchriders interviews, and used to establish the relationship between agronomy and irrigation: pre-sowing irrigation, irrigation events following alfalfa and forage harvest.

In the simulation of surface irrigation a reduction coefficient (0.03) for the runoff discharge was applied to all simulations, following the experimental evidence supplied by Lecina et al. (2005). This coefficient reproduces the reduction in the runoff volume (approximately to one half) resulting from constrictions in the runoff outlet of the borders. All the on-farm water losses were assumed to be intercepted and conveyed by the drainage collectors. This assumption follows the findings of Causapé (2004) in the IDV and in neighbouring irrigation districts in the Ebro valley (Isidoro et al., 2004).

Irrigation in the district was modelled with the border irrigation model, although other irrigation systems were present. The sprinkler irrigated area (450 ha) was not specifically considered, and surface irrigation was assigned to the whole district. The irrigation systems were not documented in the district management database, and therefore it would have been complicated to simulate the spatial distribution of sprinkler irrigation. Furrow irrigation was linked to horticultural crops, and accounted for 603 and 438 ha in 2000 and 2001, respectively (Table 1). The border irrigation model was adjusted to reproduce the irrigation depth observed in furrow irrigation evaluation (Lecina et al., 2005). A similar procedure was followed with rice. This crop, with an extension of 577 ha in 2000 and 652 ha in 2001, received simulated irrigations which amounted to the seasonal irrigation depth typical of this crop and area (Olga Pérez, personal communication). This treatment of rice, with an irrigation interval typical of border irrigation, is not unusual in the area, since the delivery network does not guarantee a continuous, small discharge to rice farmers. As a consequence, many of them have resorted to building small private reservoirs to produce continuous flow from punctual water deliveries.

Surface irrigation simulation was performed only once for each irrigation event. Simulation results were stored in a library for each combination of border geometry, soil type (determining infiltration, border slope and target irrigation depth) and crop (determining the manning n). This procedure resulted in an optimisation of the simulation time. In a personal computer equipped with a 2.66 GHz Intel® Pentium® 4 processor, surface irrigation simulation in all plots took 56 min. Simulating the yearly district water flows took an additional 80 min.

Ador-Hydrosaline was not applied to this case study, due to the lack of specific data, including a soil salinity map. The abundance of water reuse structures (and different water qualities) would have created additional problems, as reported in the companion paper.

MODEL CALIBRATION AND VALIDATION

The calibration and validation of Ador-Simulation in the IDV was limited by the nature and quality of the available data. The only contrasted data source for this purpose was the monthly volume of district water demand to the Bardenas Canal. Other variables which would have been valuable for these purposes (such as the volume of irrigation return flows, the volume of water transfers from the drainage to the irrigation network or crop yield) have very limited records in space and time, if any (Causapé, 2004).

Even in the case of monthly water demand there is a relevant level of uncertainty. This water demand is recorded for billing purposes by the Watershed Water Authority (*Confederación Hidrográfica del Ebro*, CHE), using water meters located at the canal outlets; and by the IDV, from the farmer billing records derived from time allocation to the farmers and their own network of Broad Crested Weirs. The yearly differences between both sources of data were 2.6 % in 2000 and 21.0 % in 2001 (percentages referred to the CHE data).

Model calibration was performed in sector XIX of the IDV. The choice of this sector was due to the fact that the only water source was the Bardenas canal. There are no water transfers or reservoirs in this sector. The calibration parameters were operational in nature. This choice is justified by the fact that irrigation decision making is dictated by factors not related to water balance (Lamacq, 1997, Labbé et al., 2000) which have not been modelled in Ador-Simulation. These operational parameters are the minimum irrigation interval (explicitly restricted by the IDV), the limitation of irrigation from September onwards (following limitations in the water source), and the irrigation decision making regarding the irrigation time and duration, which is performed by individual farmers. These operational parameters heavily depend on the district and farmers attitude towards water availability in the main canal reservoir, *Yesa*. This information has not been included in the simulation model. As a consequence, individual calibrations were performed for 2000 (a wet year) and 2001 (a dry year).

In 2000 a minimum irrigation interval of 12 days was considered for corn and horticultural crops. This irrigation interval is commonly enforced by the ditchriders when a rotation delivery scheme is adopted. According to the district database, the seasonal number of irrigations was 7-8 for corn and 9-12 for horticultural crops. The introduction of the minimum irrigation interval resulted in similar simulated results. This restriction is redundant in many areas of the district, since the limitations in the capacity of the irrigation conveyance network would control the irrigation interval in any case. However, in the case of plots with platform soils, irrigated from irrigation ditches with large capacity, the number of seasonal irrigations would reach 20-25 if a specific restriction was not enforced. Such frequent irrigations are not permitted by the IDV managers because the seasonal water use would exceed 20.000 m^3 ha^{-1} in these plots.

A second group of crops requiring limitations in the irrigation interval was composed by those crops which only receive supplemental irrigation, or which are the target of relevant water stress for agronomic or economic reasons. Such is the case of vetch, sunflower and winter cereals, whose minimum irrigation intervals were adjusted to reproduce those reflected in the district database. Finally, no limitations were imposed on the minimum intervals for alfalfa and forages. Their irrigation scheduling was already limited by the local restriction of avoiding irrigation four days before hay harvesting.

Water restrictions at the end of the irrigation season were introduced by limiting irrigation following a phenological rule: those crops reaching the last phenological phase by September 8 would not be further irrigated. This procedure limited irrigation and minimized yield reductions.

The time of cutoff for 2000 was extrapolated from the results of the irrigation evaluations performed in 1999 and 2000 (Lecina et al., 2005). Both years were considered as average in terms of crop water requirements. This time of cutoff is larger than the optimum value.

Regarding the calibration for 2001, the variations respect to 2000 were: 1) The minimum irrigation interval for corn and horticultural crops was 13 days; 2) the irrigation restriction was enforced in September 7; and 3) the irrigation time of cutoff was serverly reduced for all crops, following the findings of Lecina et al. (2005). The time of cutoff in 2001 was 75% of the value used in 2000. As a direct consequence, a relevant reduction in water demand was observed, without resulting in yield loss.

Figure 3 presents the model calibration curves for 2000 and 2001, based on the monthly water demand. Both sources of calibration data (CHE and IDV) are presented in the figures. In both years the simulated demand reproduces the evolution of the measured data. On a cumulative basis, the differences amount to 0.9% in 2000 and 1.9% in 2001 (percentages based on the average of CHE and IDV data). On a monthly analysis, during the peak of the season the differences do not attain 4.5% in both years, except for June 2001, reaching 7.6%. In spring the differences are highly variable, reaching values in the vicinity of 30%. These differences can be attributed to the agronomic practices of the farmers, which are difficult to establish and model. Additionally, soil infiltration during the first irrigation of the season is usually very large. This could reveal an additional model limitation, since only one equation was used for each soil type. Water demand during the spring period was not significantly influenced by the sowing date or the initial soil water content. The differences in September are relatively low (below 6% on the average).

The spatial variability of soil physical properties proved to have a significant effect on cumulative water demand. Simulations considering uniform soil properties resulted in water demands 9.5 and 6.6 % lower than the spatially varied cases for 2000 and 2001, respectively. These differences result from the beginning and end of the irrigation season, since in the peak of the season water allocation is restricted by the network capacity.

The calibration rules elaborated in Sector XIX for both years of study were extrapolated to the whole district (with the exception of the calibration sector) in order to validate the model. Figure 4 presents the monthly evolution of water demand. The simulation results compare well with the CHE and IDV data, with a seasonal cumulative difference of 0.3 % in 2000 and 3.5 % en 2001 (compared to the average of both data sources). On a monthly basis, the model reproduces the experimental curves, and the differences with the observed data are slightly larger than for the calibration data set. In June and August the maximum difference is 5.4 %, with a larger error in June 2001 (13.1 %). In spring the average error is 23.0 %, while in September an error of 12.5 % was observed.

Figure 5 presents the relationship between the seasonal simulated water demand and the observed CHE and IDV values for each Sector (except for Sector XIX) during 2000 and 2001. In both irrigation seasons the scatter plot is distributed along the 1:1 line. This trend is confirmed by the regression analyses presented in the Figure. In both study years the slope and the intercept of the regression line for CHE and IDV data are not statistically different from 1 and 0, respectively (with a probability level of 0.95).

WATER USE IN THE IDV DURING 2000 AND 2001

Water flows in the IDV were simulated for 2000 and 2001 using the calibration parameters described in the previous chapter. Table 2 presents a synthesis of the results. The main difference in district management was the reduction in the irrigation time. The impact of this variable on the aggregated results has been very important. Since the previous models and decision support systems do not include the simulation of the irrigation system (Merkley, 1994, Yamashita and Walker, 1994, Prajamwong et al. 1997, Mateos et al., 2002), Ador-Simulation presents the unique feature of analysing the interaction between on-farm and district irrigation management.

Since the district soils are generally characterized by a low *TAW*, reducing the irrigation time reduces the irrigation depth, increases the average on-farm irrigation efficiency ($\overline{IE}$) (Burt et al., 1997) from 38.8 to 47.1 % and reduces the volume of return flows. However, part of this reduction is due to the decrease in precipitation during 2001. The benefits from reducing the irrigation time were translated to the average yield reduction ($\overline{YR}$), which resulted slightly lower than in 2000 (from 25.3 to 24.3 %). This result is quite interesting, since the cropped acreage increased in 2001 by 175 ha, the crops were more water demanding, and 2001 was a dry year. The values of $\overline{YR}$ in the IDV are very relevant, and seem to be due to the low capacity of the conveyance network and the fact that most of the soils are not suited for surface irrigation. Yield reductions are common in traditional irrigation schemes in the Ebro valley (Playán, et al., 2000) and elsewhere in the world (Vidal et al., 2001, Unal et al., 2004).

The increment of the acreage of water demanding crops in 2001 is responsible for the increases in crop ET (by more than 5 hm^3). However, the increase in irrigation efficiency resulted in a moderate increase in water demand (3 hm^3). The spatial distribution of irrigation efficiency in the different turns of the IDV reveals the importance of the soil type in both years of study (Fig. 6). While alluvial soils surpass 50 %, platform soils rarely reach 40 % efficiency (see sectors XXVIII, XXX, XXXI y XXXII). This difference was not so clear in the analysis of Lecina et al. (2005), who presented maps of average application efficiency (*Ea*). It is interesting to note that the average application efficiency (49.3%) resulted sensibly higher than the average irrigation efficiency in both years. This difference supports the use of the proposed model to obtain more adequate estimates on the functioning of the irrigation district.

Figure 7 presents the spatial distribution of crop yield reduction in the different turns for 2000 and 2001. Although the effect of the soils can still be appreciated, the effect is not so clear. This is partially due to the differences in irrigation practices between crops: sunflower and vetch are regularly water stressed, independently of the soil type.

The analysis of these two years suggests that farmers responded to meteorological drought and water scarcity by improving their level of irrigation management, and that this did not lead to additional yield decreases. As a consequence, there is a significant margin to increase irrigation efficiency in the IDV by improving management alone. The volume of reused return flows was not affected by the year of study, with the transfers from the drainage to the irrigation network remaining at about 12 hm^3. The operational losses also remained unchanged, at about 2.5% of the water demand. Although the model is unable to detect changes in these variables, it seems reasonable to expect water reuse to increase and operational losses to decrease under 2001 conditions. The difficulties in modelling the response of these variables to changes in water management would have required a specific calibration. Since continuous records of return flows, reuse and operational losses were not available this calibration could not be performed.

SCENARIOS TO IMPROVE WATER USE IN THE IDV

In order to evaluate the model capacity to evaluate district modernization alternatives, two scenarios were designed for the IDV. The scenarios focused on improving the irrigation management and the irrigation structures. Since the scenarios are exploratory in nature, simulations were only performed for the conditions of 2000. The scenarios are as follows:

- Scenario 1: improving water management by a reduction of 25 % in the irrigation time assigned to 2000, according to the irrigation evaluations reported by Lecina et al. (2005). The analysis of 2001 confirmed that this is a feasible alternative. More intense reductions would take application efficiency closer to potential application efficiency, but could be difficult to implement (Lecina et al., 2005), and have not been considered. Since this alternative liberates part of the capacity of the conveyance network, reductions in the daily irrigation period were additionally considered. In this case, in-line reservoirs will be required to store irrigation water during the hours with no irrigation service.

- Scenario 2: combining Scenario 1 with an improvement in irrigation structures based on increasing the transfer of return flows to the irrigation network. This scenario is based on creating three reuse structures at the locations indicated in Figure 2. New water conveyance structures and pumping stations will be required for this purpose.

The simulation of these scenarios made use of the previously discussed calibration parameters. The only difference was the minimum irrigation interval for corn and horticultural crops, which was reduced to 9 days. Reducing the irrigation time permits farmers to irrigate the crops more often, even without increasing the capacity of the conveyance network. The proposed value of the irrigation interval corresponds to the time required to deplete an average platform soil with a corn crop during the peak of the season.

Table 2 presents a summary of the simulation results for scenario 1 with a daily irrigation period of 24 h. Reducing the irrigation time results in better crop yields, switching from abundant to frequent irrigation events. The district aggregated water demand was reduced by more than 12 % respect to the original 2000 simulation. Since at the same time crop ET increased by 5 % as a result of a better irrigation scheduling, $\overline{IE}$ attained a value of 47.7 %. Additionally, the return flows would be decreased by 21.7 %.

Following these findings, it would be interesting to reduce the daily irrigation period, a measure which would be very well accepted by farmers. A number of in-line reservoirs, with a compound approximate capacity of 0.30 hm^3 would be required to accommodate canal supply and district demand during the off hours. Reducing the daily irrigation period would lead to additional yield reductions, since the peaks in water demand would not be met by the reduced conveyance capacity. The district *ET* and water demand would therefore be decreased, and irrigation efficiency would increase. This reasoning explains the results presented in Figure 8, in which these variables are presented as a function of the daily irrigation period. Reducing the irrigation period from 24 to 16 hours results in an additional 5 % decrease in crop yield and an associated decrease in annual district water demand of 20 hm^3. An economic analysis on the results of Fig. 8, considering the cost of water and labour , the investment required for each m^3 of reservoir capacity and the value of the agricultural production, could lead to a decision on the optimum duration of the daily irrigation period. This decision could be modified along the irrigation season, returning to a 24 hour irrigation period during the peak of the season, when a shorter irrigation period could lead to significant decreases in crop yield.

For the simulation of scenario 2 (combining an improvement in irrigation management and structures), an irrigation period of 16 h was chosen. This choice results in a crop yield similar to the current situation in both 2000 and 2001. This scenario requires construction of the reservoirs in the canal turnouts described for scenario 1 plus three additional reservoirs at the new reuse structures. The combined capacity of these three reservoirs was estimated as 0.04 hm^3, according to the average water reuse discharges obtained from the simulations. Statistical and economical analyses should be performed to assess the adequacy of this estimation for design purposes.

The simulation results for this second scenario indicate that water reuse was increased by 11.5 hm^3 as compared to the current situation, reaching a total reuse of 23.6 hm^3. This increased reuse resulted in a reduction of district water demand to 91.8 hm^3, a 36.0% reduction from the current situation and a 11.8% reduction from scenario 1 (16 h of irrigation operation). The seasonal volume of irrigation return flows for 2000 was almost halved: from 115.7 to 65.8 hm^3. The $\overline{IE}$ and crop yield would remain the same as in scenario 1, since the on-farm irrigation conditions have not been modified (Table 2).

The district farmers should make an effort to moderate the irrigation time. A number of managerial and farming constrains may turn this task difficult (Lecina et al., 2005). However, the results of 2001 have proven that a 25% reduction can be readily obtained. In this dry year farmers could concentrate on profitable crops, and still maintain their productive capability. It the same effort was applied in a normal year, farmers could either increase their yields or further decrease the daily irrigation period. Simulation results also suggest that the district can increase their water reuse potential. This will lead to additional reductions in water demand and return flows.

The adoption of sprinkler and/or drip irrigation in the district would lead to frequent, light irrigations. Given the low TAW of most district soils, this would result in a relevant increase in irrigation efficiency and crop yield if proper irrigation scheduling techniques were used.

This irrigation modernization would imply a severe modification of the hydrological balance in the district. Improving $\overline{IE}$ would lead to a decrease in irrigation water demand and an increased water availability at the *Yesa* reservoir. However, the improved irrigation adequacy would lead to an increase in crop *ET*, and therefore a decreased water availability at the watershed. It is reasonable to think that pressurized irrigation systems would bring actual crop *ET* to the potential level. At the same time, a new conveyance network would lead to crop intensification, increasing the acreage of water intensive, profitable crops. This effect has already been shown in the simulations reported in this paper. In Scenario 1 (24 hours of irrigation) the gross water demand was reduced by 17 hm^3, but *ET* increased by 4 hm^3. These results confirm that the modernization of an irrigation district will reduce water demand from the reservoirs, but at the same time decrease the watershed available resources. This conceptual framework was signaled by Willardson et al. (1994). These findings call for a detailed analysis of the hydrological implications of irrigation modernization at a watershed scale (Perry, 1999).

CONCLUSIONS

The application of Ador-Simulation to the IDV has proven its capability to generate information supporting irrigation planning and management. One of the key features of the model lies in the connection between on-farm irrigation and district wide management and performance. The consideration of the crop cycle permits one to estimate irrigation efficiency, and therefore to overcome the analyses based on application efficiency (Lecina et al., 2005). The wide set of factors determining farmer irrigation decision making and water allocation within the district greatly difficult the simulation of these processes. As a consequence, prior knowledge of the irrigation rules adopted by the farmers and the district in response to each particular year has been required to calibrate the model. Due to data scarcity in the IDV, the calibration was limited to the monthly gross water demand in a given sector, while the validation was performed on the rest of the district. Increased predictive capability would have been attained if additional data such as the monthly volume of irrigation return flows and reused water had been available.

The lack of a homogeneous dataset on the water flows, the structures or the cadastral plots of the IDV has been a limiting factor to the model application. The use of specialized relational databases enforcing water traceability in irrigation districts (such as Ador-Management, the companion to Ador-Simulation) will contribute to the quality and accessibility of the information, making it accessible to Ador-Simulation. Field work will still be required to complete input data with variables such as infiltration or *TAW*.

The application of Ador-Simulation to the IDV has proven that the model can contribute to the endeavours of water engineers and scientists. Engineers can find support to irrigation modernization, to district management improvement programs, and to the agronomic planning of water scarce seasons. From the scientific point of view, the model can contribute to determine the effect of the natural or managerial constrains of an irrigated district on the environment or crop yield. The linkage of on-farm the sprinkler irrigation module presented by Dechmi et al. (2004) will enlarge the capabilities of the model.

The simulated scenarios revealed that an irrigation efficiency of about 50 % can be guaranteed in the IDV if farmers control the irrigation time in normal years in the same way they do in water scarce years. This threshold of on-farm efficiency can not be easily surpassed, but the extension of the district water reuse strategy has proven useful to further reduce the irrigation water demand and the volume of irrigation return flows. These environmental aspects were completed by the social benefit derived from a reduction of the daily irrigation period from 24 to 16 hours a day.

In its application to the IDV, Ador-Simulation has shown that the reduced soil *TAW* of most district soils requires a transformation to pressurized irrigation in order to obtain a relevant increase in irrigation efficiency. Such a situation would lead to a drastic modification of the district hydrology, which should be analysed from a watershed perspective.

ACKNOWLEDGEMENT

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APPENDIX II: LIST OF TABLES

Table 1. *Crop acreages (ha) by sectors in the IDV during the irrigation seasons of 2000 and 2001.*

Sector	**Corn**		**Alfalfa and other Forages**		**Sunflower**		**Winter crops[1]**		**Horticultural crops[2]**		**Rice**		**Total**	
	2000	**2001**	**2000**	**2001**	**2000**	**2001**	**2000**	**2001**	**2000**	**2001**	**2000**	**2001**	**2000**	**2001**
XVIII	594	707	826	858	77	81	170	58	77	44	71	65	1,814	1,814
XIX	722	957	1,008	1,088	122	63	326	201	38	22	78	88	2,293	2,419
XXIV	133	273	152	165	126	130	256	69	3	3	60	77	730	718
XXV	164	300	366	374	98	84	167	11	9	9	173	200	978	978
XXVI	431	494	367	442	157	132	135	69	64	44	120	138	1,274	1,320
XXVII	125	134	197	222	3	25	81	37	13	2	55	55	475	475
XXVIII	481	552	374	374	17	22	43	13	102	68	0	0	1,016	1,029
XXIX	268	309	423	394	31	32	62	61	28	38	0	10	811	845
XXX	490	500	407	413	46	35	101	122	89	62	0	0	1,133	1,133
XXXI	539	557	277	289	52	55	176	81	113	83	0	0	1,157	1,065
XXXII	462	574	864	973	55	60	242	86	68	61	19	20	1,710	1,775
Total	4,407	5,359	5,260	5,593	785	721	1,760	808	603	438	577	652	13,392	13,570

(1) Wheat, Barley, Vetch, Peas

(2) Tomato, Pepper, Onion and Leeks.

Table 2. *Summary of simulation results obtained through the application of Ador-Simulation to the current situation of the IDV during 2000 and 2001, and to different future scenarios.*

Variable	Current Situation 2000	Current Situation 2001	Scenario 1 (24 h) 2000	Scenario 1 (16 h) 2000	Scenario 2 (16 h) 2000
Daily Irrigation Period, h	24.0	24.0	24.0	16.0	16.0
Irrigation Time, h ha^{-1}	2.9	2.2	2.2	2.2	2.2
Average Irrigation Efficiency, %	38.8	47.1	47.7	50.3	50.4
Crop Yield Reduction, %	25.3	24.3	19.7	24.8	24.9
Seasonal Water Demand, m^3 ha^{-1}	11,528.0	11,495.0	10,040.0	8,522.0	8,504.0
Seasonal Water Demand, hm^3	143.3	146.8	125.8	106.6	91.9
Irrigation and Rain Return Flows, hm^3	115.7	109.9	90.5	80.8	65.8
Water Reuse, hm^3	12.0	11.6	10.0	9.1	23.6
Crop Evapotranspiration, hm^3	79.4	84.8	83.5	78.7	78.7

APPENDIX III: LIST OF FIGURES

Figure 1. *Irrigation "turns" in the IDV, presented over an adaptation of the geomorphologic map of the study area elaborated by Basso (1994), with an original scale of 1:25,000.*

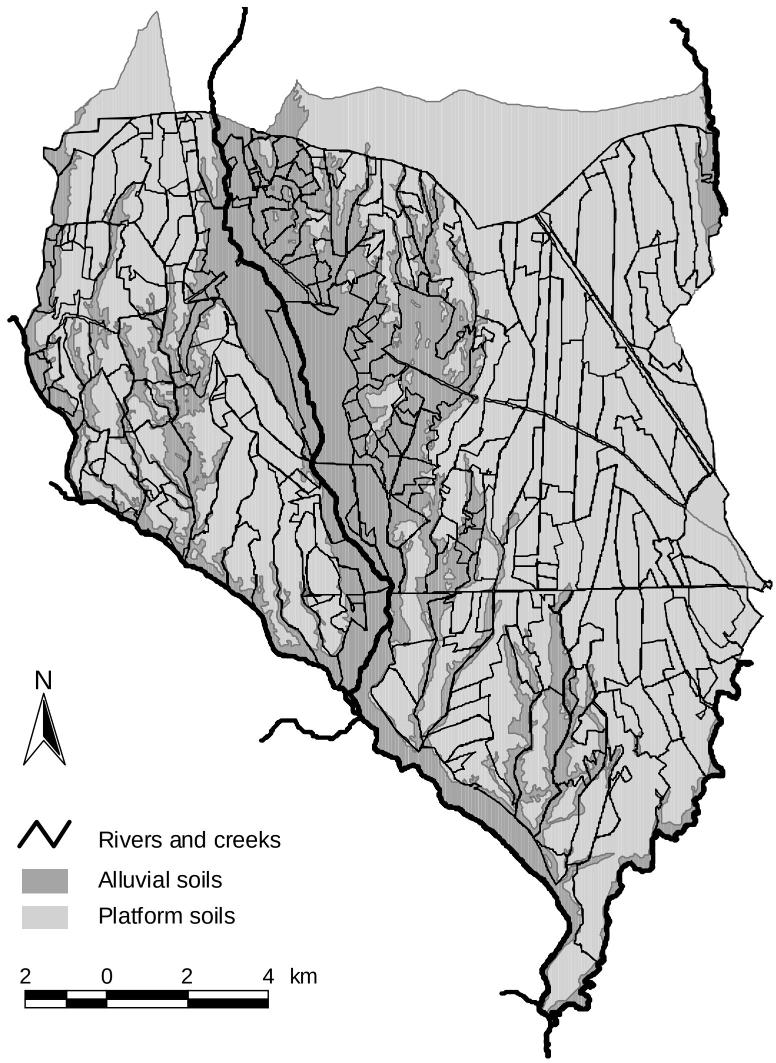

Figure 2. *Water conveyance and drainage structures, Sectors of the IDV, and diversion points for the additional water transfer structures proposed in scenario 2.*

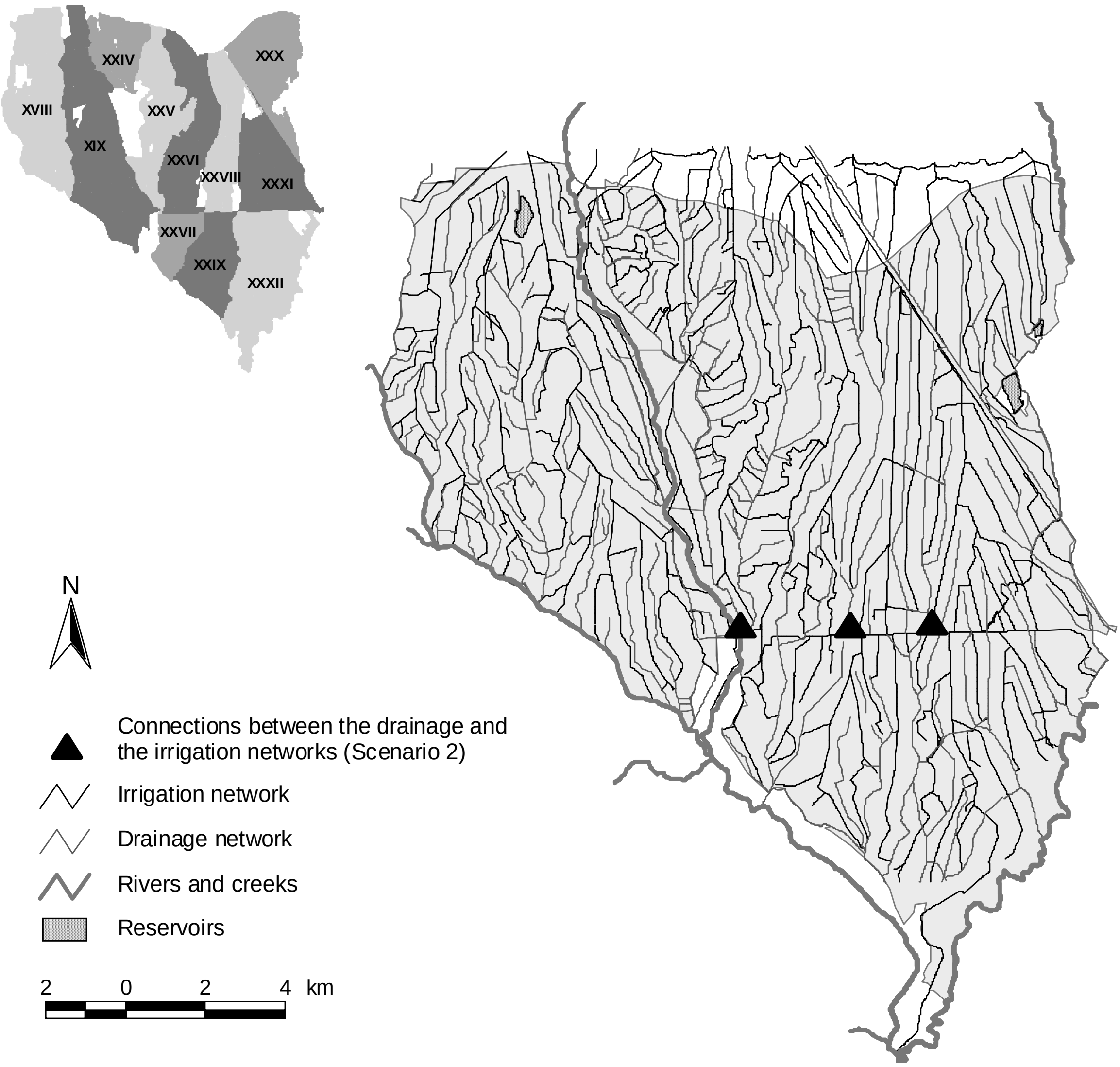

Figure 3. *Water demands as registered (by CHE and the IDV) and simulated by Ador-Simulation in Sector XIX of the IDV for 2000 and 2001.*

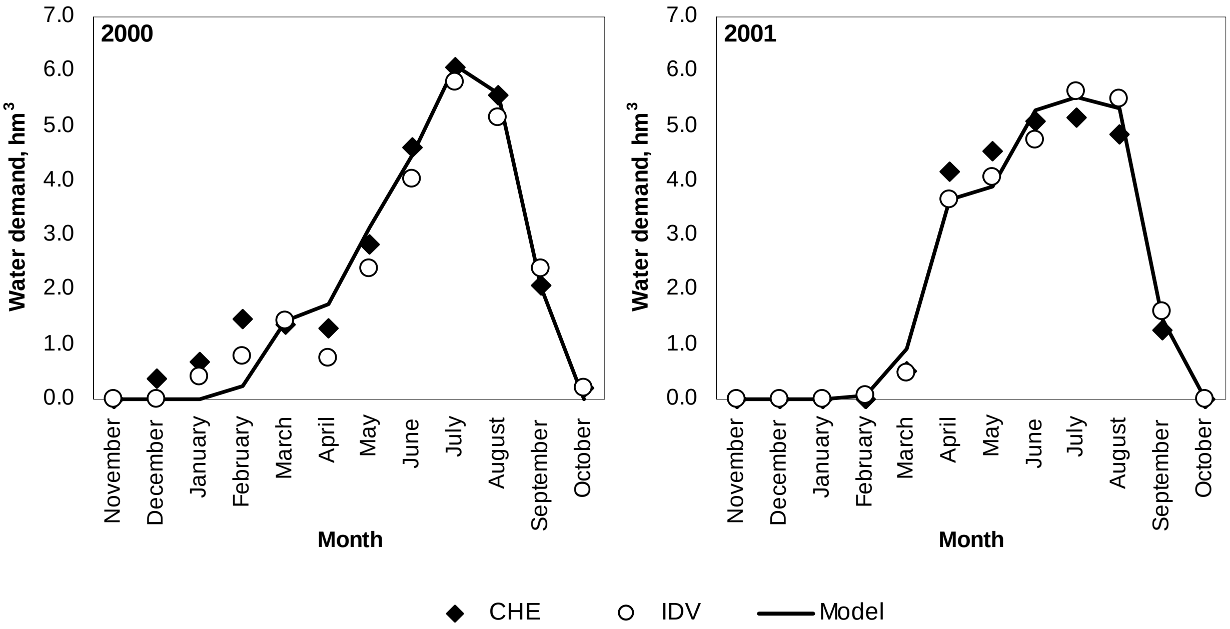

Figure 4. *Monthly evolution of water demand as registered (by CHE and IDV) and simulated with Ador-Simulation for the IDV (except Sector XIX), for 2000 and 2001.*

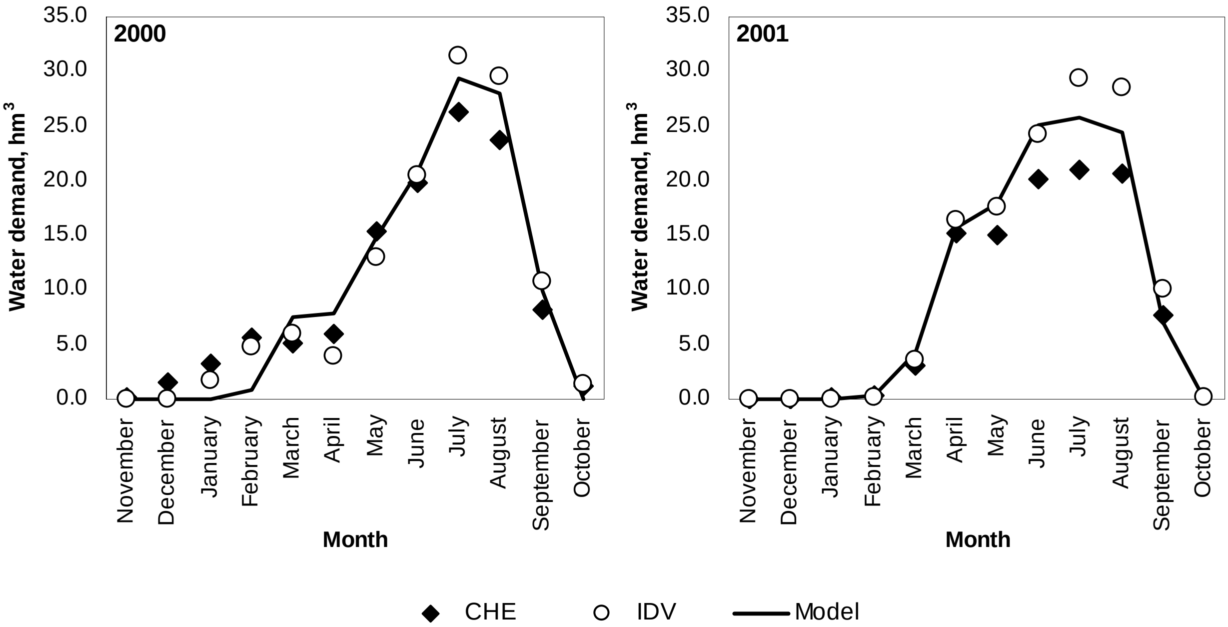

Figure 5. *Seasonal water demand: registered (by CHE and IDV) vs. Simulated with Ador-Simulation for each Sector of the IDV, except for sector XIX, for 2000 and 2001.*

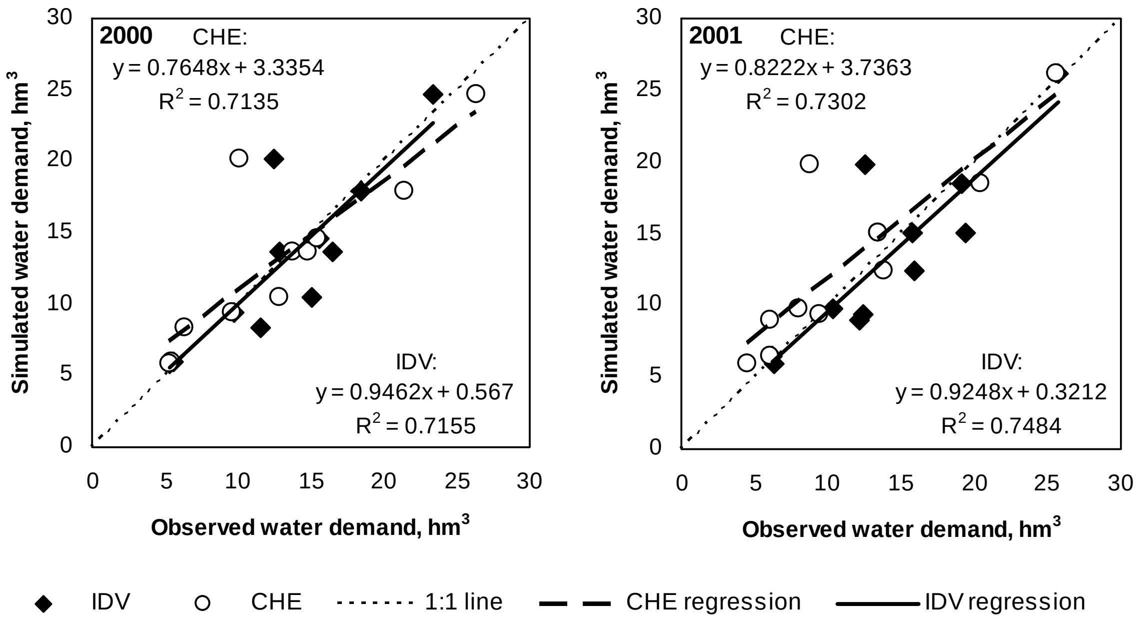

Figure 6. Map of simulated irrigation efficiency in the IDV for the current situation in 2000 and 2001.

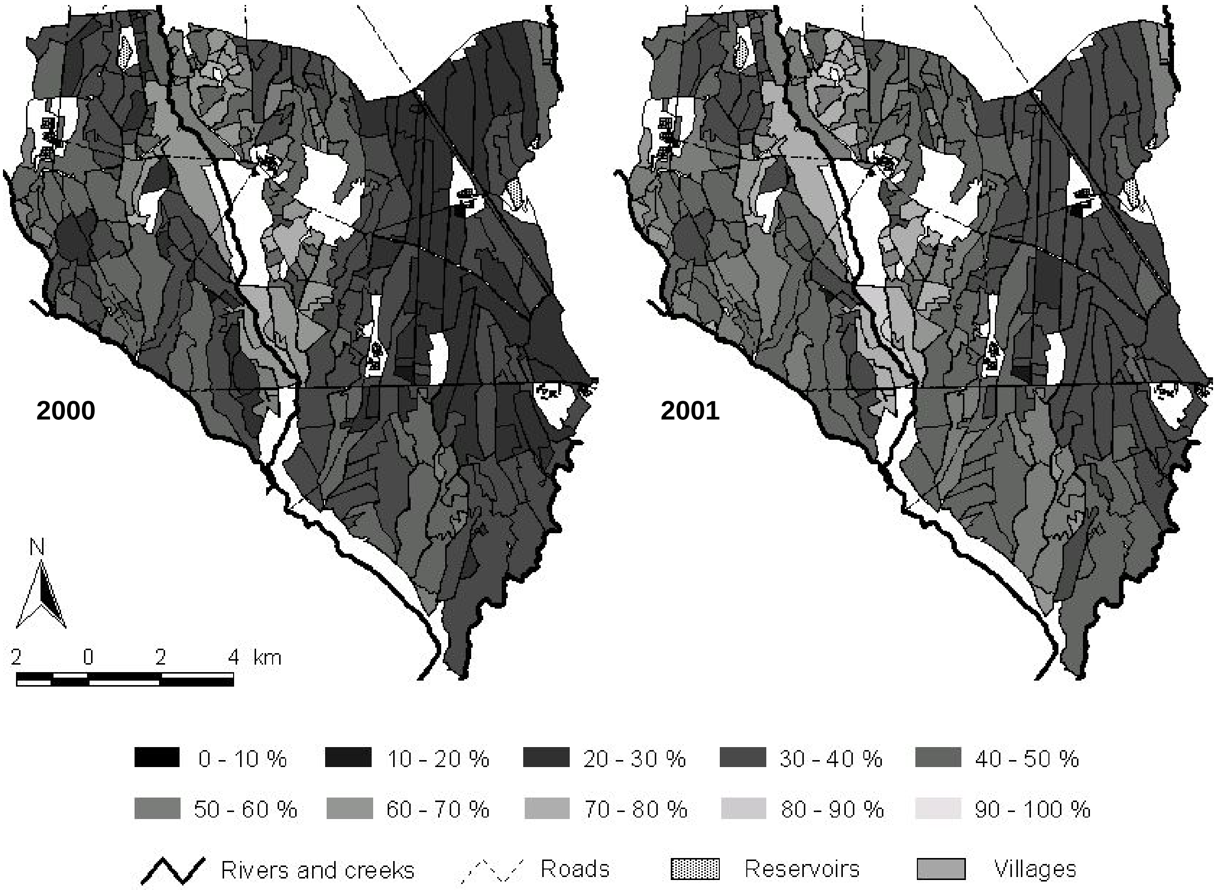

Figure 7. Map of simulated crop yield reduction in the IDV for the current situation in 2000 and 2001.

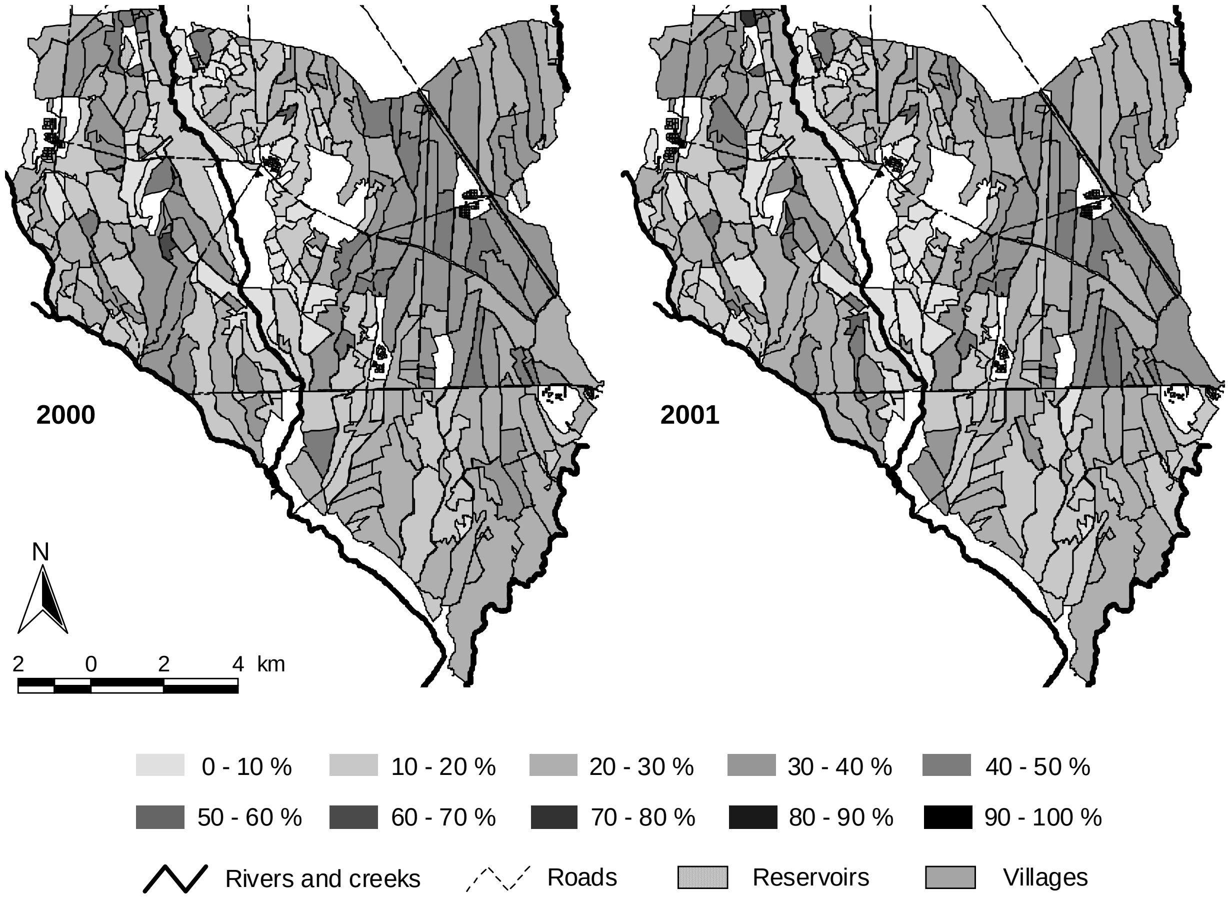

Figure 8. Evolution of *water demand (hm³),* $\overline{IE}$ (%), $\overline{YR}$ (%), and ET_c *(hm³) as a function of the duration of the daily irrigation period for scenario 1.*