A case study for irrigation modernisation:

I. Characterisation of the district and analysis of water delivery records

Faci, J. M.[1], Bensaci, A.[2], Slatni, A.[3] and Playán, E.[4]

Abstract

The analysis of water management in irrigated districts is highly relevant. The present work highlights the principal irrigation management problems of the irrigation district of Almudévar, a representative surface irrigation district located in the Northeast of Spain. The predominant irrigation system is blocked-end borders. The study included three phases: 1) Assessment of crop water requirements of the main crops of the study area; 2) Characterisation of soil depth and soil water retention; and 3) Analysis of the current irrigation practices based on the study of the 1994 water records of the district. The following irrigation management problems were identified: 1) The mean volume of water billed to the farmers was 43 % higher than the net irrigation requirements; 2) The volumes of water billed to the farmers were inversely related to the farm size; 3) Few, widely spaced, large irrigation events; 4) Large delay time in water delivery; and

---

[1] (○) Dept. Soils and Irrigation, Lab. for Agronomy and the Environment (DGA-CSIC). Servicio de Investigación Agroalimentaria, DGA. Apdo. 727. 50080 Zaragoza, Spain. EMail: faci@syrsig.mizar.csic.es

[2] Former graduate student, Dept. Soils and Irrigation, Lab. for Agronomy and the Environment (DGA-CSIC). Servicio de Investigación Agroalimentaria, DGA. Apdo. 727. 50080 Zaragoza, Spain.

[3] Institut National de Recherches en Genie Rural, Eaux et Forêt (INGREF). B.P. 10, 2080 Ariana, Tunisie.

[4] Dept. Genetics and Plant Production, Lab. for Agronomy and the Environment (DGA-CSIC). Estación Experimental de Aula Dei, CSIC. Apdo. 202. 50080 Zaragoza, Spain. Email: playan@eead.csic.es

5) In selected crops and / or areas, water billing was lower than the net irrigation requirements, indicating the presence of marginal areas or heavily subsidised crops. This research could be applied in other areas of traditional surface irrigation systems. The goal of this methodology is to diagnose the actual level of water management and to provide data for the modernisation of the irrigation district. In a companion paper, a decision support system for the modernisation of the district is presented.

Keywords: surface, irrigation, district, modernisation, management.

Introduction

Irrigation is the main user of water in Spain, and accounts for 80% of the total water demand. The irrigated area of Spain is $3.3\ 10^6$ ha and its water demand reaches $24.5\ 10^9\ m^3$/year (Mateo Box, 1996). Rainfall in Spain is irregularly distributed in time and space. As a consequence many hydrologic infrastructures are needed to distribute and manage the water resources. Water demand for irrigation has been continuously increasing for the last 50 years due to development of new irrigation areas.

In the irrigated areas of Spain, surface irrigation methods are used in more than 65% of the total irrigated land. In many of the traditional irrigation districts, irrigation management is not adequate. Typical problems include: distribution systems with capacity below the peak demand; inflexible delivery rates, usually in 24 hour shifts; poor on-farm land levelling; high ramification of the distribution systems; and small plots. These problems usually result in poor irrigation efficiency, especially in areas dominated by soils with high infiltration rates and low soil water retention characteristics. Poor irrigation management also results in important social, economical and environmental problems. Ensuring the sustainability of irrigated agriculture requires a complete modernisation of many Spanish irrigation districts.

The Almudévar irrigation district is representative of the numerous traditional surface irrigation districts. The district is located in the province of Huesca, in the Northeast of Spain. The total district area is 3,989 ha: 410 ha are dry farmed and 3,579 ha are irrigated. The actual population of the villages included in the district is 2,500 inhabitants, of which 863 are farmers. Only 20 % of the farmers are fully dedicated to agriculture and 85 % of them are over 50 years of age.

The Almudévar area was developed for irrigation in the 1950´s. The delivery system was designed to apply supplementary irrigation to winter cereal crops. Water demand in the area has increased since the 1970’s due to changes in cropping patterns. Presently, the distribution system is unable to meet the crop water requirements, even though a large area is still cropped with winter cereals. Adding to the problem is a deterioration of the infrastructure, a shortage of labour in the farms and very long irrigation times.

The district is surrounded by the main canals of the Monegros Project: Monegros, Santa Quiteria and Violada (Figure 1). The distribution system is composed of a large number of lined and unlined ditches operated 24 hours a day. As a result, the farmers have to irrigate during day and night shifts. The irrigation system used in the district is almost exclusively blocked-end borders. Often the plots owned or leased by a farmer are located in different areas of the district, making irrigation very time consuming and difficult.

The district management is formed by the president, the secretary and the board, all of whom are farmers. The staff is completed by the ditchriders, numbering 4 to 6, depending on the season. The district office is located in the village of Almudévar.

The Almudévar irrigation district manages its water delivery activities using a database computer application located at the district office. Water distribution in Almudévar is performed in two ways according to the classification proposed by Clemmens (1987): limited rate arranged schedule (LRA) in 80% of the area, and varied frequency rotation schedule (VFR) in the rest of the district. The plots on a LRA schedule are billed per surface and per volume of delivered water. LRA plots are charged a fixed amount of 75 Euro (European currency unit) per hectare and year plus 2.9 Euro per each thousand cubic meters of water. The plots on a VFR schedule are billed a fixed amount per surface.

For billing purposes, records are kept in the database regarding each individual water allocation to a LRA plot. No water allocation information is kept for water allocation to VFR plots. Farmers report to the district office when they need to file a water request for a LRA plot. Requests are made on a volume basis. The volume will be served at a discharge limited by (and close to) the ditch capacity. The district management schedules water allocation for each irrigation ditch considering the water requests. The time between the filing of the water request and the water delivery (delay time) is variable, depending on the number of concurrent water requests and the irrigation ditch capacity. In the event of coincident demands for a given irrigation ditch, the management can take measures like giving priority to plots irrigated at an earlier time and/or limit the requested duration. The daily delivery schedule for each irrigation ditch is posted at the office two days in advance.

During the peak of the irrigation season the district tries to enforce equity among water users, delivering the same volume per unit area. At this time, water delivery in both LRA and VFR plots is shifted to a rotation scheme (Clemmens, 1987). Under this scheme no arrangement is possible, and the ditchriders enforce the irrigation shifts and record the water allocation to LRA plots.

Palmer et al. (1991) reported the results of a study based on the water records of a surface irrigated district located in the Southwest of the USA. These authors concluded that the lack of internal water measurement and the poor quality of the district records were major limitations of their analysis. The study evidenced the complexity of the water management operations in the district and the relevance of the relationships between farm and district personnel. A similar problem is expected in the Almudévar irrigation district.

In this article we analyse irrigation management on the LRA plots in the irrigation district of Almudévar using district water ordering and billing records for the year 1994.

Materials and methods

Land tenure and irrigation management units

Many farmers in Almudévar own plots in different areas of the district. Each plot is composed of several borders. We have considered the area of all the plots owned by the same farmer as a single farm. Also, many farmers lease plots and manage irrigation in plots other than their own. The irrigation management units are composed of the plots belonging to the own farm plus the leased plots. Therefore, the irrigation management unit does not necessarily match farm or plot sizes.

Climate

The climatic characterisation of the study area was based on the mean monthly air temperature and precipitation for the 1929-1995 period at the station of "La Granja de Almudévar". The station is located within the district, at a North latitude of 42º 1' 45", an East longitude of 3º 6' 20" and an altitude of 395 m. In 1994 daily meteorological data of the same station were used to characterise the specific year of study and to calculate crop water requirements. Available data included maximum and minimum air temperature, wet and dry bulb temperature at 08:00 hours, wind run at 2 m height above the soil surface, sunshine duration and precipitation.

Soils

Physical soil properties in the Almudévar irrigation district area were studied using 310 sampling points to a depth of 1.20 m when possible (Slatni, 1996). At each point, soil texture, stoniness and soil depth were determined in situ. Sampling points were distributed over the total district area. Field capacity and wilting point were determined using the Richards membrane (Soil Moisture, Santa Barbara, California) with two replicates per sample. Soil samples were saturated for two days and then a pressure of 0.03 and 1.5 MPa (for field capacity and wilting point, respectively) was exerted until no further change in soil moisture was observed.

Bulk density was determined using 40 undisturbed soil samples taken at a depth of 15 cm. The management allowable deficit (MAD, mm), defined by Merriam and Keller (1978), was determined for each sample using the following equation:

$$MAD = \frac{2}{3} 10^3 \, p(\theta_{FC} - \theta_{WP}) \frac{\rho_b}{\rho_w} (1 - S) \qquad [1]$$

Where:

p = Soil depth (m)

θ_{FC} = Gravimetric water content ratio at field capacity

θ_{WP} = Gravimetric water content ratio at wilting point

ρ_b = Soil bulk density (Mg m^{-3})

ρ_w = Water density (Mg m^{-3})

S = Volumetric ratio of stoniness

Water delivery and drainage infrastructures

Water delivery infrastructure data were obtained from the irrigation district files (Bensaci, 1996). Additional water management data were collected from other sources (Torres, 1987; Rubio, 1995; Comunidad de Regantes de Almudévar, 1997).

The district is irrigated from 9 turnouts in the Monegros canal, 14 turnouts in the Violada canal and 16 turnouts in the Santa Quiteria canal. The canal managers (operating the three canals), schedule the turnouts on a 24 hour-a-day basis. The turnouts consist of submerged orifices regulated by slide gates. Discharge is measured at each turnout considering the canal level and the slide gate opening.

The water distribution system (district- and farmer-owned) consists of 50 km of concrete lined ditches and 40 km of unlined ditches. The capacity of the district-owned ditches ranges between 50 and 300 L s^{-1}, although the discharge delivered to the farmers only ranges between 50 and 100 L s^{-1}. The irrigation district does not have reservoirs inside its perimeter. Therefore, irrigation is performed on a 24 hour per day basis. This fact, together with the small ditch capacity and the current crop intensity makes irrigation practice laborious and problematic. The differences between water supply and demand produce operational spills in the distribution network which are added to the losses produced on-farm.

In the VFR plots, the farmer usually irrigates every 14 to 20 days. In the LRA plots, the farmer submits a water order for the volume that he requires for the irrigation of his plot (in cubic meters). The administration office will grant him the water a few days later. The district personnel processes the water orders and determines the irrigation delivery sequence, which typically starts at the ditch upstream end and then proceeds in the downstream direction. This process of water order submission and water delivery is modified to meet the characteristics of some crops. In the case of corn, farmers submit water orders for pre-planting and the first irrigation. Subsequent water orders are automatically generated by the database with a frequency of 10 to 13 days, depending on the district-owned ditch characteristics. In the case of alfalfa, the district will try to minimise the delay between hay harvest and the subsequent irrigation. To do so, the district reserves the right to modify the water delivery schedule. Small family orchards and vegetable gardens are very common near the villages. Water is supplied to these plots on Saturdays. If precipitation occurs, the district delays water deliveries for a few days according to the estimated changes in net irrigation water requirements. The district requires a farmer receiving a water delivery to communicate to the next farmer in the schedule when he is going to complete his irrigation. The next farmer is required to use the water as soon as the previous user has finished his irrigation. According to our experience in the area, this set of rules should only be considered as a principle. The actual functioning of water delivery varies according to other unwritten rules and running agreements between water users and the district.

The drainage system of the study area is widespread. The whole drainage network is composed of 90 km of open ditch and buried pipe drains. There are two main open ditch drainage courses (Fig. 1). The Violada Creek collects irrigation return flows produced between the Monegros and the Violada canals. The Artasona Creek collects the return flows in the area between the Monegros and Santa Quiteria canals. The water flowing in the main drainage collectors is rarely used for irrigation in the district because its elevation is not enough to supply surface irrigation systems by gravity.

Crop water requirements

Crop distribution in Almudévar varies from year to year in response to market demands. The main crops in the arranged demand area during 1994 were: corn (38.2 %), alfalfa (26.7 %), wheat (22.8 %), sunflower (10.1 %) and other crops (2.2 %). Sunflower is not a common crop in the area but in 1994 its area increased due to the strong subsidy to this crop by the European Community.

In 1994 the reference evapotranspiration (ETo) was calculated on a daily and monthly basis using the Hargreaves (Hargreaves and Samani, 1985) and Penman-Monteith (Smith, 1993) methods. Mean monthly values of ETo for the mean year 1929-1995 were also computed. In this case the Hargreaves method was used.

Crop coefficients (Kc) were developed for the main crops according to the FAO guidelines (Doorenbos and Pruitt, 1977) and local agronomic information of the crops. For alfalfa a mean Kc of 0.89 was used. Monthly effective precipitation (Pe) was calculated for 1994 using the USDA, SCS method (Cuenca, 1989). Monthly values of net irrigation requirement (NIR) were computed as the difference between crop evapotranspiration (ETc) and Pe.

Hydrologic analysis of district water deliveries and use

The district database consists of 19 files containing irrigation water management and billing information, including: size of the plots, name of the owner, name of the irrigator, service discharge (cubic meters per 24 hours), crop, code of the district-owned ditch, date of the irrigation request and the date and volume of each irrigation event. The personal information needed to contact and bill farmers was included in the data base but was not used in this study.

During the irrigation season water orders as well as the delivery dates and the volumes delivered to each plot are written in the corresponding data files. Water delivery records of 1994 were used to analyse: 1) the structure of land tenure and irrigation management units, 2) the relationships between land tenure and water billing, 3) the total daily volumes of water billed to the farmers, 4) the time interval between the date of water order and the date of water delivery, and 5) the mean irrigation intervals for the main crops.

A seasonal irrigation performance index (SIPI) was used to characterise the global irrigation management practices in the district. The SIPI was defined as the seasonal percentage of the NIR to the volume of irrigation water delivered to the crops (Bensaci, 1996). SIPI is a practical implementation of Irrigation Efficency (IE), as defined by Burt et al. (1997), and Clemmens and Burt (1997). Three simplifications were introduced in the IE concept to develop the SIPI: the increment of storage of irrigation water over the season was assumed to be zero, the seasonal NIR was used instead of the volume of irrigation water beneficially used by the crop, and water billed was used instead of water applied. A relevant feature of the proposed index is that if a crop is water stressed, the value of SIPI can be higher than 100%. In fact, if the SIPI is higher than the potential application efficiency of the irrigation system, the crop will be water stressed.

The other index used to characterise water use in the area was the irrigation interval, also obtained from the database. Both the SIPI and the irrigation interval were computed for each crop and for all the area irrigated on a LRA schedule.

These indexes were represented using maps. Geostatistical techniques (Isaaks and Srivastava, 1989) were used to generate these maps using a set of georeferenced observations. In order to do so, the district was divided into several water distribution units. These units were delineated dividing the area irrigated by each district-owned ditch so that the average area of each unit fell between 15 and 20 ha. A total number of 155 units were defined. The water records of the plots in each unit were processed to compute estimates of the SIPI and the irrigation interval. The co-ordinates of the central point of each water distribution unit were digitised using a geographic information system.

Results and discussion

Climate

The mean annual temperature of 1994 in Almudévar was 16.8ºC. This value is significantly higher than the 66 year average mean temperature (12.8ºC). Monthly temperatures in 1994 were higher than the normal year, except for the months of October, November and December. Spring temperatures (April, May and June) were extremely high for the season, with an average increase over the average year of 8.3ºC. The total annual effective precipitation in 1994 (363.1 mm) was similar to the average year (384.9 mm). However, the distribution along 1994 was quite irregular. Only 15.9 mm of effective precipitation occurred during the months of June, July and August of 1994, while the average effective precipitation for these months totalled 79.3 mm (Table 1).

Annual reference evapotranspiration (ETo) in 1994 calculated by the Hargreaves method was 1326.9 mm. Data availability for the year allowed to compute ETo with the Penman-Monteith method. The results (Table 1) show a lower yearly value (1190.4 mm). The discrepancies in ETo between both methods are particularly important in spring, with the Hargreaves ETo 47% higher than the Penman Monteith figures (for the above mentioned three month period). A comparison between both methods under local conditions (Fuertes, 1995) revealed that, for a period of 14 years, Hargreaves-computed ETo was 11% higher than Penman Monteith ETo. Following FAO guidelines (Smith, 1993), the Penman-Monteith figures for 1994 were used to compute crop water requirements and the SIPI. Mean monthly values of ETo were maximum in July with a value of 212.8 mm which represents 6.9 mm day $^{-1}$, and minimum in December with a value of 23.5 mm (0.8 mm day $^{-1}$).

Table 2 presents the crop water requirements for the main crops in the study area. Data are presented for 1994, the average year and a dry year characterised by a 20% return probability. ETc for all crops in 1994 was higher than the average year and also higher than the dry year. This gives an indication of the drought conditions that occurred in Almudévar in 1994.

Soils

Figure 2 shows the spatial variability of soil depth in the study area. A geostatistical analysis (data not shown) indicated that this variable does not have a spatial structure at the sampling scale. Possible reasons for this finding are the limited number of samples and the experimental restriction of soil sampling to 120 cm. Due to the limited number of bulk density samples, no attempt was made to characterise its spatial structure.

The areas with shallow soils are located in the Northeast range of the study area. The soils in this area also have a coarse texture, a high percentage of stoniness (sometimes higher than 30%), and a bulk density of about 1.2 g cm^{-3} . Locally, these soils are called "sasos", and are located on high platforms some 15 m above the level of the creeks. The soils in the rest of the area (mainly constituted by the valley bottoms along the creeks) are deeper, with lower stoniness (not above 4 %), and bulk density on the order of 1.4 g cm^{-3}.

The field capacity of the soils varies between 20 and 50 % in volume and the wilting point varies between 10 and 30 % in volume. The lower values for both variables are found at the platforms and the higher values at the valley bottoms.

The geostatistical analysis performed on MAD revealed a spatial structure for this variable. The semivariogram was of spherical type with a nugget value of 400 mm^2, a sill of 960 mm^2 and a range of 3,300 m (Figure 3). The range indicates that for distances larger than about 3 km the MAD is statistically independent.

Figure 4 presents the MAD of the soils in the Almudévar area. In the high platforms, the MAD is very low, often lower than 50 mm. However, in the rest of the district water retention increases up to 100 mm. These differences are mainly due to the differences in soil depth, water retention, and stoniness. A comparison between figures 2 and 4 reveals the high association between soil depth and MAD. Soils with low values of MAD are not well suited for border irrigation, since the application depths are often higher than the soil water retention capability. Poor efficiencies should therefore be expected in the high platforms.

Land tenure and irrigation management units

Figure 5 presents the cumulative histograms for the plot, the farm and the irrigation management unit areas. The average plot area is about 3 ha, and all plots are smaller than 28 ha. The farm size is considerably higher (approximately 10 ha on average) and 80% of the farmers own areas smaller than 25 ha. The irrigation management units are larger than the farms (with an average size of 15 ha) and 70 % of the farmers manage areas smaller than 25 ha.

A common procedure in Spain is to consolidate the properties of a district as a first step of the rehabilitation process. As a result of this process, a farmer would get a single plot in the district with an area similar to the amount of land he owned before the property consolidation. The consequence of such a measure, as shown in Fig. 5, is that the plot curve would move to the right to meet the farm curve. This change would greatly simplify irrigation and infrastructure management. Unfortunately, this would not be a complete solution to the land tenure problem, since the farm size would not be changed. The resulting farms would remain too small to ensure the economical sustainability of full-time farmers with the current crop mix of cereals and alfalfa. The long-term solution to the problem seems to be an increase in the area of the irrigation management units. Farmers should therefore concentrate their efforts on the creation of large management units based on land leasing.

A study was conducted to assess the relationship between plot size and the seasonal volume of water billed to each plot. The volume of water billed was inversely proportional to plot size (Figure 6). The average volume of water billed to the farmers in 1994 was 14,109 m^3 ha^{-1}. The mean seasonal volume of water billed to plots smaller than 0.5 ha was 49,170 m^3 ha^{-1} while the mean values for plots bigger than 5 ha was only 9,100 m^3 ha^{-1}.

There are several reasons for this strong inverse relationship. First, the irrigation district of Almudévar bills the farmers in multiples of 1,000 m^3. This volume is the minimum amount that can be charged to a farmer, independently of the volume of water actually diverted to the plot. This administrative rule actually allows multiple billing of a given volume of water to different farmers, particularly in small plots. A second reason could be that the water ordered but not used is lost in the form of operational spills. The district management perceives that this is particularly true in small plots and during the night. Finally, figure 6 could indicate that small plots are less efficient than large plots. Clemmens and Dedrick (1992) found the same kind of relationship when analysing a surface irrigated district in the Southwest of the USA, although farm sizes were substantially larger than in the present study.

Water delivery management

Figure 7 presents the daily volumes of water billed by the Almudévar irrigation district during the irrigation season of 1994. Irrigation started on January 8th and finished on October 7th . Daily volumes had high fluctuations along the irrigation season, varying between 326,000 m^3 on July 21st and 1,000 m^3 on October 1st. The season begins with scattered water deliveries attributed to non-standard practices. Early in spring deliveries increase due to irrigation of winter cereals and alfalfa. Deliveries further intensify in March-April, when farmers apply the pre-planting irrigation for corn. At this time, peak deliveries are attained for the first time of the season. The drop in water deliveries that occurs at the end of May is due to the end of the irrigation season for winter cereals, a period of low NIR for corn (following planting), and increased precipitation (69.7 mm in May).

The second peak period of the season was attained in summer, between the middle of June and the beginning of September, when corn and alfalfa are frequently irrigated. The mean volume in this period is 250,000 m^3 day^{-1}. It is interesting to note a localised drop that occurs the second week of September, when the farmers enjoy the local holidays of Almudévar and reduce the agricultural activities to a minimum for a period of five days.

Figure 8 presents the evolution of the delay time (the time between an order and its delivery). Delay times were higher in the summer season (day 180 till day 260) than in the spring season (day 80 till day 150). In the summer season 60 % of the delay times had a duration between 7 and 8 days, while in the spring season 64 % of the delay times had only a duration between 3 and 4 days. The delay time is highly correlated with the daily volumes of water billed (data not presented).

Analysis of figures 7 and 8 suggest that the maximum system delivery capacity was attained in spring, and maintained through the summer. Nevertheless, water demand continued to grow during the summer, as indicated by an increasing delay time. These results suggest that the system capacity constrained the farmers irrigation practises. Originally, the district delivery system was designed for supplementary irrigation to winter cereals. The use of more intensive crops has made system capacity a limiting factor, although farmers are continuously involved in construction works aimed at increasing the conveyance capacity.

The interval between irrigations can be used in Almudévar as an indication of irrigation adequacy. This is due to the fact that in this type of surface irrigation the irrigation depth can not be controlled by the farmer. Actually, the irrigation depth depends on physical factors such as infiltration, roughness, discharge, slope or field dimensions (Walker, 1989).

From the number and dates of water deliveries, the mean interval between irrigations was estimated for corn and sunflower. Figure 9 shows the contour maps of these intervals district-wide. Mean values of 12.4 and 16.8 days were obtained for corn and sunflower, respectively. To estimate the variability of the irrigation interval, the percentage area comprised between the contour lines for the average irrigation interval ± one day was computed for each crop respect to the total area. The resulting values were 75% and 57% for corn and sunflower, respectively (i.e., 75% of the map area for corn shows irrigation intervals between 11.4 and 13.4 days). These figures confirm the visual observation that the irrigation interval in corn is lower and more uniform than in sunflower.

Some water deficit could occur in sunflower as compared to corn, because of the extended irrigation interval. Both crops do not differ much in their water requirements (616 mm for corn *vs.* 539 mm for sunflower), although sunflower is much more drought resistant than corn (Bremmer and Preston, 1990; Lamm et al., 1994). Sunflower was heavily subsidised during the study year, with subsidies applied by the hectare. Sunflower yield was not considered the main source of income by the farmers, who were more interested in collecting the subsidy. At the same time, Almudévar farmers are not very experienced in cropping sunflower. These could be additional reasons for the large irrigation intervals detected in this crop. The district was free to buy from the canal management as much water as required to irrigate all crops satisfactorily.

However, the limiting factor was the conveyance capacity within the district (see Figs. 7 and 8), leading to some drought. Under these circumstances, farmers preferred to devote their water to crops where the economic value of the yield was high, like corn.

The irrigation interval contours (Figs. 7 and 8) differ from those obtained for MAD (Fig. 4). Therefore, the irrigation interval does not appear to depend on the soil water holding characteristics. Nevertheless, some similarities can be appreciated between both irrigation interval maps and the MAD map at the area surrounding the middle course of the Violada creek. In this area the irrigation intervals for corn and sunflower are above the mean and MAD is at its maximum (over 75 mm). The large value of MAD permits irrigation intervals between 2 and 4 days above the average for both crops.

From the maps, it can be concluded that some irrigation planning was applied for corn, whereas sunflower was irrigated whenever it was possible. Actually, in sunflower, some irrigation intervals are greater than 25 days, a value that seems highly inappropriate, considering the values of MAD and sunflower NIR.

Analysis of the seasonal irrigation performance index (SIPI)

Contour maps of the SIPI for corn and sunflower are presented in Figure 10. The SIPI district-wide mean values were 50% and 116% for corn and sunflower, respectively. The average corn SIPI seems reasonable for an index that resembles irrigation efficiency (Burt et al., 1997; Clemmens and Burt, 1997). The value obtained for sunflower can not be interpreted as an estimation of efficiency, because of the presumably low irrigation volumes applied to this crop. Under these conditions, SIPI gives unrealistic estimations of efficiency, because the numerator of the index corresponds to the NIR. To highlight the differences between both crops, the percentage of the area with SIPI values between 20 and 60% was computed. The resulting values were 75% and 4% for corn and sunflower, respectively.

The SIPI map for corn shows certain similarity with the MAD map (Fig. 4), indicating that the seasonal volumes of water delivered to corn were influenced by the soil characteristics. Since the relationship between MAD and the irrigation interval was not very clear, we believe that the application depths for individual irrigations were much higher in the platforms than in the valley bottoms. Irrigation depths are large in the high platform areas because of the high infiltration rates associated with coarse soil textures and high stoniness. In the valley bottoms, soil texture is fine, infiltration is low and water applications are smaller. In the Northwest corner of the SIPI corn map, there is a small area with SIPI values greater than 150%, indicating insufficient irrigation to this crop. This could be due to the marginality of plots in this area: the high gypsum content of the soil induces piping erosion at the field dikes and makes surface irrigation a very complicated task.

The sunflower SIPI behaved very differently from the corn SIPI. In general, the SIPI values were higher and more variable for the former than for the latter. It is believed that this result is due to sunflower being subsidised in 1994, coupled with lack of experience in cultivating sunflower in this area. A spot with SIPI values beyond 150% can be located in the central-eastern part of the district, suggesting that this area was virtually not irrigated during the season. It is possible that district records do not reflect the actual irrigation practices in this area.

In order to obtain a global view of the behaviour of the Almudévar irrigation district, the contour map of the SIPI values for the whole area is presented in Figure 11. The mean SIPI value was 70%, indicating that the volumes of billed irrigation water were around 43% higher than the net irrigation requirements of the crops. The percentage of the area with SIPI values comprised in the 20 to 60% interval was 41%. Again, the range of SIPI values is greater than that found for corn, due to the inclusion of all crops cultivated in the study area. Sunflower and winter cereals (data not shown) introduced large amounts of variability due to the low economic revenue of the crop yield (sunflower) and the low number of irrigations (cereals). Nevertheless, the resulting map shows some similarity with the corn SIPI map (Fig. 10 a) and the MAD map (Fig. 4).

Conclusions

The methodology used in the analysis of irrigation management in the Almudévar irrigation district has been a useful tool to characterise and quantify the principal irrigation management problems of the study area. The average total volume of water billed to the farmers in 1994 was 14,109 m^3 ha^{-1} . This value is higher than the net crop water requirements of the combination of crops cultivated in the district in 1994. However, the average irrigation interval was too long, at least for sunflower, indicating that some water stress was produced. Farmers applied the water stress to crops where yield reductions could produce less damage to their economies.

The seasonal volumes of irrigation water billed to the plots were inversely related to the plot size. In plots smaller than 0.5 ha the average seasonal volume of irrigation water billed was an astonishing 49,170 m^3 ha^{-1}, while in plots larger than 5.0 ha this value was only 9,100 m^3 ha^{-1}. The administrative practices of the district are partly responsible for this type of relation between size of the plot and water billing. The district delivers water in amounts multiple of 1,000 m^3 and this amount can be much larger than the irrigation requirement of a very small plot. With this practice the excess water that the farmer does not use is billed to the next farmer too or it is lost in the form of operational spills. The district database would therefore assign the same volume of water twice, creating some over estimation of water delivery in the records.

The distribution system of the district was not able to provide a flexible and dependable supply of irrigation water to the farmers. In the summer months the farmers had to wait to irrigate for 7 to 8 days on average from the date they requested the water to the district. In the spring months, with a lower irrigation water demand, the average delay time was of 3 to 4 days.

The seasonal irrigation performance index (SIPI) showed important irrigation problems in the studied area. For sunflower, the mean SIPI was 116%, indicating that the seasonal volumes of billed irrigation water were lower than the net sunflower irrigation requirements. However, the SIPI for corn had a mean value of 50%, indicating that the billed volumes of irrigation water doubled the net irrigation requirements. Since corn was properly irrigated to protect its high economic yield, we believe that the SIPI for corn could be used as an estimation of irrigation efficiency.

Problems of very low SIPI were identified at the high platforms, which had low MAD and high infiltration rates. The average SIPI value for the whole area was 70%.

This study has evidenced the complex nature of irrigation management in the traditional irrigation district of Almudévar. Often, the relationships between the district management and the farmers follow unwritten rules that can make district records insufficient for the analysis, inaccurate or difficult to interpret. In this sense, our findings agree with those of Palmer et al. (1991).

The small size of the farms, the high number of plots managed by the same farmer, the limitations of the water distribution system, the irrigation shifts lasting 24 hours, and the presumed low irrigation efficiency make irrigation practices difficult and unsustainable. In the actual situation, a rehabilitation process of this district is much needed in order to maintain its productivity and to avoid the actual sociological and economical problems. In a companion paper some modernisation scenarios are studied.

Acknowledgement

The authors would like to thank the management and farmers of the Almudévar irrigation district for their support. This work was sponsored in part by the INIA (Institute of Agricultural Research of the Government of Spain). The Mediterranean Agronomic Institute of Zaragoza (IAMZ-CIHEAM) awarded scholarships to A. Bensaci and A. Slatni that made this research possible.

References

Bensaci, A., 1996. Problemática actual y mejora del manejo del riego en la Comunidad de Regantes de Almudévar (Huesca). MSc thesis, Instituto Agronómico Mediterráneo de Zaragoza (CIHEAM). 163 pp.

Bremmer, P. M. and Preston, G. K. 1990. A field comparison of sunflower (Helianthus annuus) and sorghum (Sorghum bicolor) in a long drying cycle. II. Plant water relations, growth and yield. Aust. J. Agric. Res. 41 (3): 463-478.

Burt, C. M., Clemmens, A. J,. Strelkoff, T. S., Solomon, K. H., Bliesner, R. D., Hardy, L. A., Howell, T. A., Eisenhauer, D. E. 1997. Irrigation performance measures: efficiency and uniformity. J. Irrig. Drain. Engrg., ASCE, 123(6): 423-442.

Clemmens, A. J. 1987. Delivery system schedules and required capacities. Proccedings of “planning, operation, rehabilitation and automation of irrigation water delivery systems” Irrigation Division, ASCE, Portland, Oregon, USA. 18-34.

Clemmens, A. J. and Dedrick, A. R. 1992. Identifying factors that influence farm water use. Technical Papers, Conferencia Regional Panamericana, Volume II. Mazatlán, México. 10 pp.

Clemmens, A. J. and Burt, C. M. 1997. Accuracy of irrigation efficiency estimates. J. Irrig. Drain. Engrg., ASCE, 123(6): 443-453.

Comunidad de Regantes de Almudévar. 1997. Memoria de actividades. Almudévar, Huesca, Spain. 33 pp.

Cuenca, R. H., 1989. Irrigation System Design: An engineering approach. Prentice-Hall Inc., Englewood Cliffs, New Jersey, U.S.A. 552 pp.

Doorenbos, J. and Pruitt, W. O., 1977. Crop water requirements. Food and Agricultural Organisation (FAO), Irrig. And Drain. Paper 24, Rome, Italy, 144 pp.

Fuertes, S. 1995. Calibración de métodos de cálculo de la evapotranspiración de referencia (ETo) con lisímetros. Escuela Univ. Polit. de La Almunia de D. Godina, Spain. 149 pp.

Hargreaves, G. H. and Samani, Z. A., 1985. Reference crop evapotranspiration from temperature. Applied Engineering in Agriculture 1(2): 96-99.

Isaaks, E. and Srivastava, R. M. 1989. An introduction to applied geostatistics. Oxford University, New York, U.S.A., 551 pp.

Lamm, F. R., Rogers, D. H. and Manges, H. L. 1994. Irrigation scheduling with planned soil water depletion. Trans. ASAE , 37: 1491-1497

Mateo Box, J. M., 1996. Consumo de agua en los regadíos. Agricultura, 764: 242-247.

Merriam, J. L. and Keller, J., 1978. Farm irrigation system evaluation: a guide for management. Utah State University, Logan, Utah. 271 pp.

Palmer, J. D., Clemmens, A. J., Dedrick, A. R., Replogle, J. A. and Clyma, W., 1991. Delivery system performance case study: Welton Mohawk irrigation and drainage district, USA. Irrigation and drainage systems, 5:89-109.

Rubio, E., 1995. Investigación y perspectivas en el regadío. Crecimiento integral y armónico de Aragón. Actas del segundo encuentro de Investigación, Ciencia y Tecnología a ambos lados de los Pirineos. Comunidad de Trabajo de los Pirineos. Font Romeu / Odeillo / Via. Francia. pp. 363-370.

Smith, M.,1993. CROPWAT: A computer program for irrigation planning and management. Food and Agricultural Organisation (FAO), Irrig. and Drain. Paper 46, Rome, Italy, 126 pp.

Slatni, A. 1996. Elaboration et evaluation des alternatives por l'amélioration de l'utilisation de l'eau au sein de la communauté d'irrigants d'Almudévar. MSc thesis, Instituto Agronómico Mediterráneo de Zaragoza (CIHEAM). 132 pp.

Torres, M., 1987. Transformaciones ecológicas por la puesta en regadío: ejemplo del polígono de la Violada. Revista de estudios agro-sociales, 139:127-153.

Walker, W. R., 1989. Guidelines for designing and evaluating surface irrigation systems. Food and Agriculture Organisation (FAO). Irrig. and Drain. Paper 45, Rome, Italy, 137 pp.

Tables

Table 1. *Monthly climatic data for the average year (1929-1995 series) and 1994 in Almudévar: Mean temperature, reference evapotranspiration (ETo), using the Hargreaves and Penman-Monteith methods and effective precipitation (Pe).*

	Average year			1994			
Mo.	Mean Temp. (ºC)	ETo Hargreaves (mm)	Pe (mm)	Mean Temp. (ºC)	ETo Hargreaves (mm)	ETo Penman-Monteith (mm)	Pe (mm)
Jan.	4.1	27.0	25.2	4.5	36.0	38.0	12.1
Feb.	5.5	39.8	26.0	10.8	44.0	49.5	33.5
Mar.	8.7	73.5	32.1	13.3	89.6	85.9	1.3
Apr.	11.1	101.7	39.4	17.3	145.2	97.8	8.9
May.	14.8	142.0	47.4	25.8	206.2	119.7	69.7
Jun.	19.3	172.5	36.1	27.1	227.1	176.0	6.9
Jul.	22.3	196.2	19.0	25.7	184.1	212.8	4.0
Aug.	22.1	170.5	24.2	23.3	171.4	185.1	5.0
Sept.	18.7	115.2	34.2	17.6	88.5	121.6	92.7
Oct.	13.5	70.1	33.4	12.2	69.8	49.0	54.3
Nov.	8.1	36.0	35.5	11.7	32.1	31.5	59.2
Dec.	5.0	24.8	32.4	12.1	32.9	23.5	15.7
Ann	12.8	1169.3	384.9	16.8	1326.9	1190.4	363.1

Table 2. *Monthly evapotranspiration (mm) for the main crops in Almudévar for 1994, for the average year (1929-1995 series) and for a dry year (characterised by a return probability of 20%). The Penman-Monteith method was used for 1994, and the Hargreaves method was used for the rest.*

	Alfalfa			Corn			Wheat			Sunflower		
Mo.	1994	Ave.	Dry	1994	Ave.	Dry	1994	Ave.	Dry	1994	Ave.	Dry
Jan.	33.4	8.0	18.5				29.3	7.3	17.5			
Feb.	43.6	11.3	26.3				46.0	18.1	29.3			
Mar.	75.6	41.3	59.2				92.8	55.1	75.8			
Apr.	86.1	55.6	77.5				106.6	75.0	99.4			
May.	105.3	88.5	113.5	64.6	44.9	64.3	128.1	113.3	140.9	43.0	43.2	62.4
Jun.	154.9	118.7	148.7	133.8	102.8	131.9	64.5	65.9	90.2	126.7	92.7	121.3
Jul.	187.2	150.9	166.0	229.8	191.8	210.2				232.0	193.6	212.4
Aug.	162.9	125.7	145.4	205.5	162.5	184.7				201.8	159.3	181.3
Sept.	107.0	73.0	95.0	116.7	85.9	109.4				52.7	50.1	68.3
Oct.	43.1	35.9	54.7	4.8	28.4	51.2						
Nov.	27.7	7.6	17.7									
Dec.	20.7	6.8	15.3				17.4	8.1	19.2			
Total	1048	723	938	755	616	752	485	343	472	656	539	646

Figures

Figure 1. *Location of the Almudévar irrigation district. Axes values in UTM co-ordinates.*

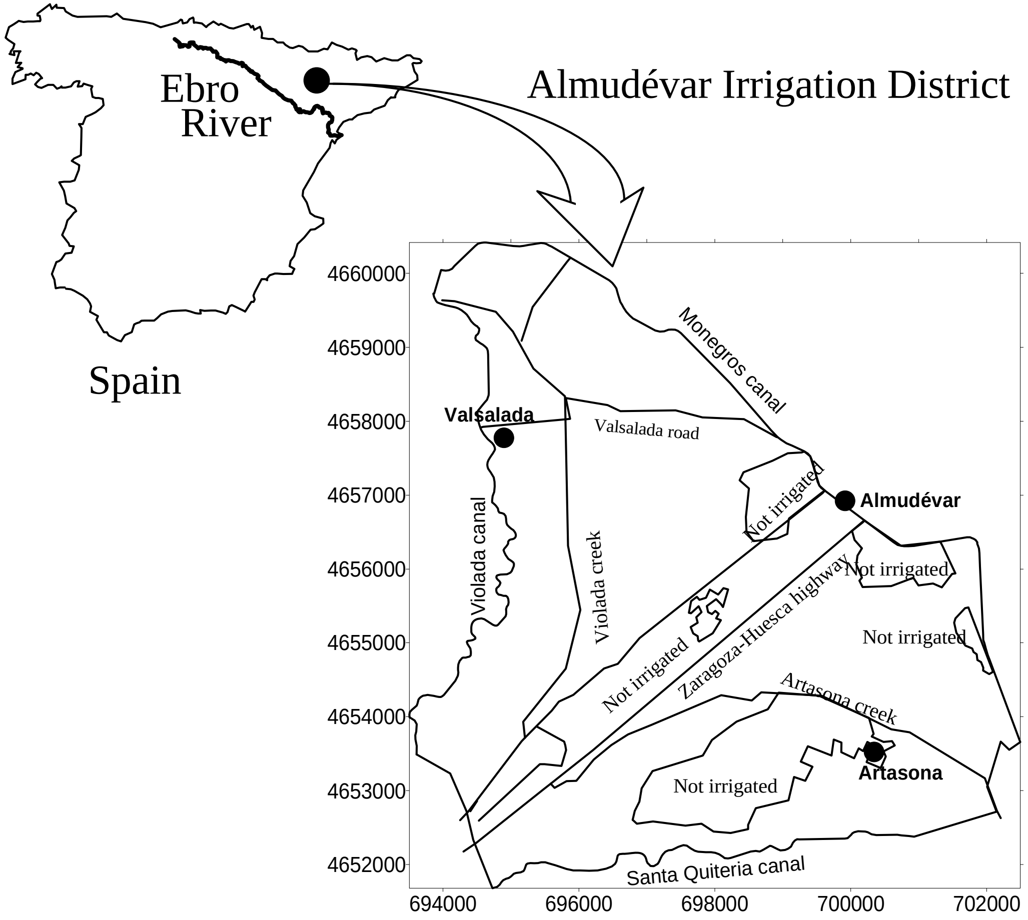

Figure 2. *Contour map of soil depth (cm). Axes values in UTM co-ordinates.*

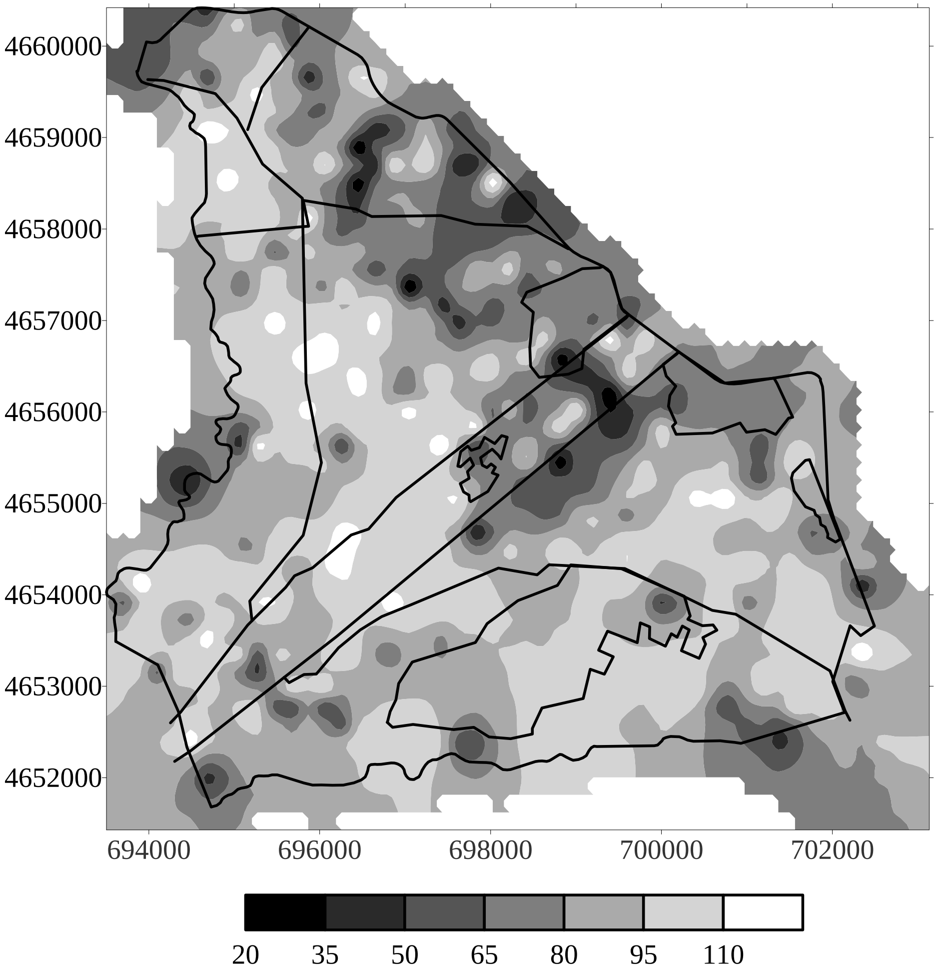

Figure 3. *Experimental (symbols) and theoretical (lines) Semivariograms for Management Allowable Depletion (MAD, mm).*

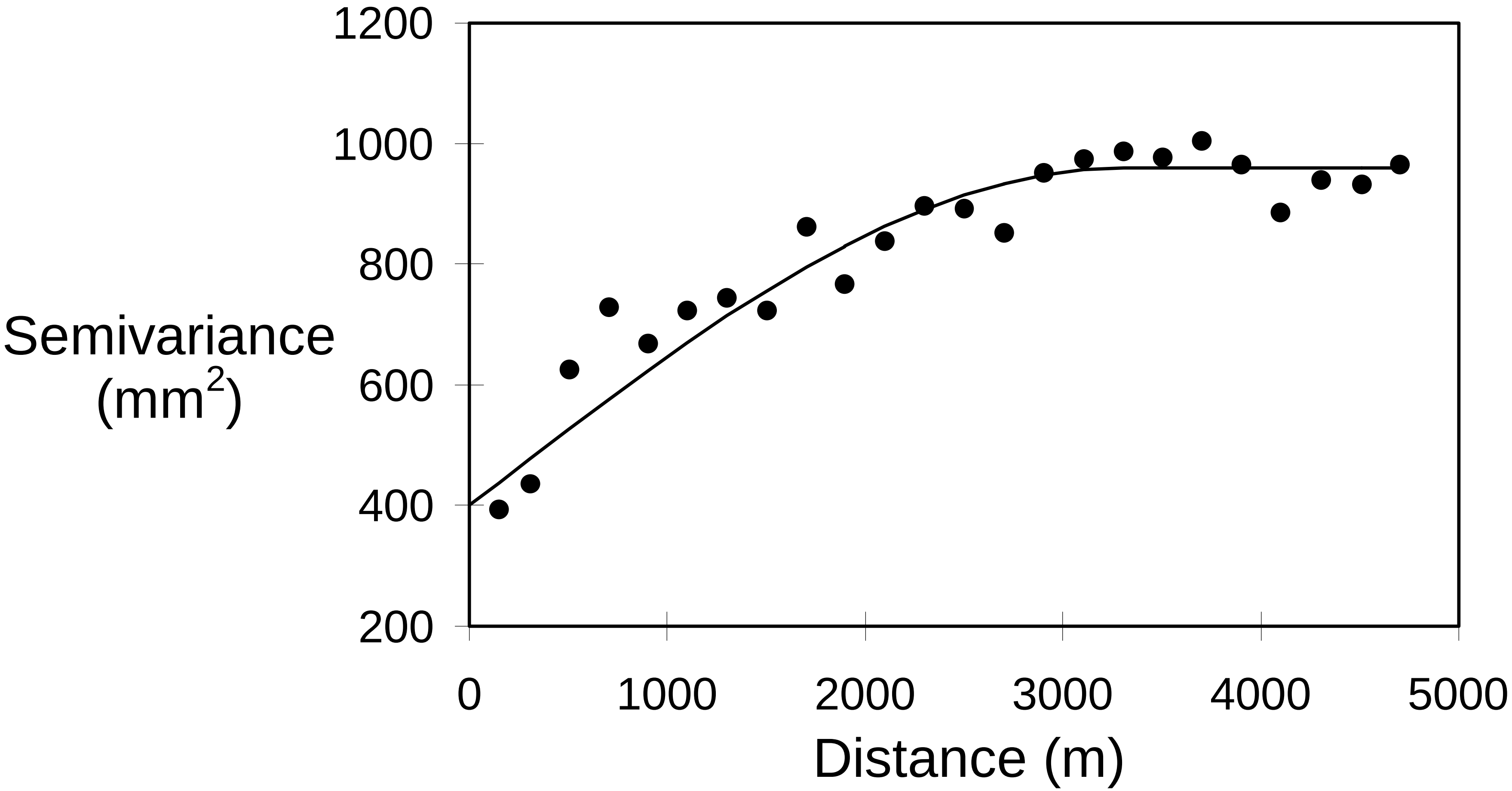

Figure 4. *Contour map of Management Allowable Depletion (MAD, mm). Axes values in UTM co-ordinates.*

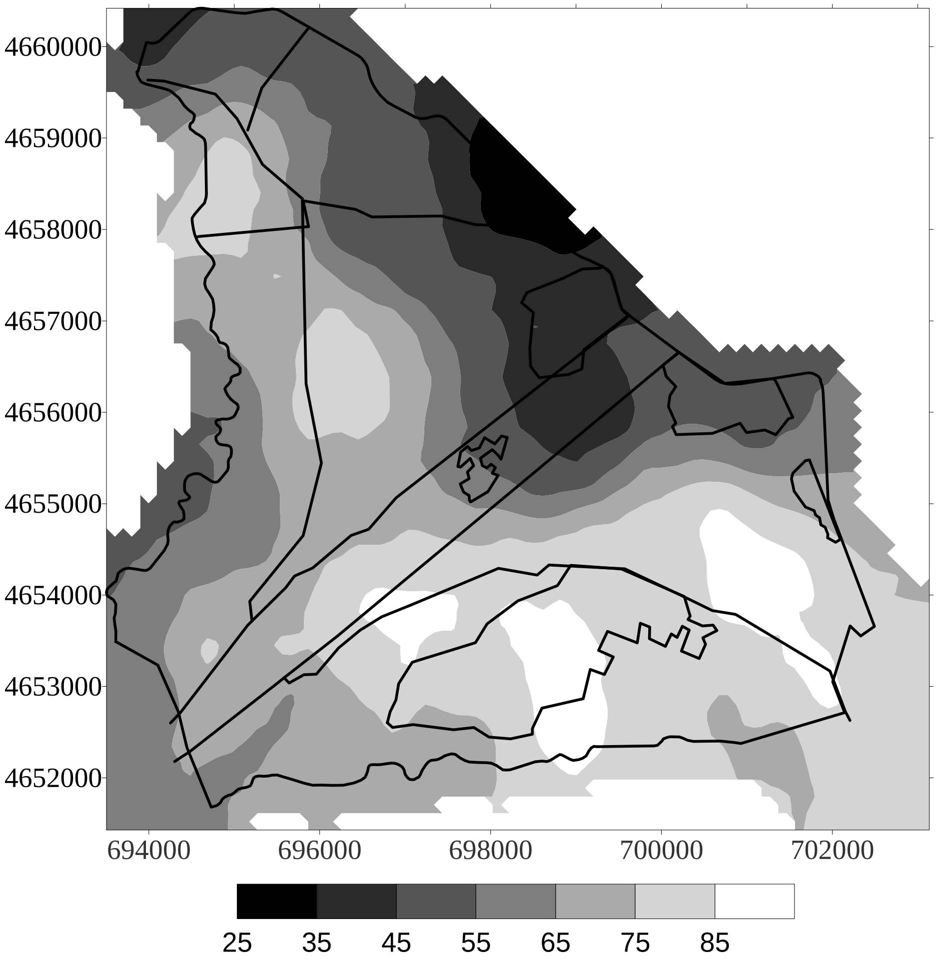

Figure 5. *Structure of land tenure: cumulative histograms of the area of plots, farms and irrigation management units.*

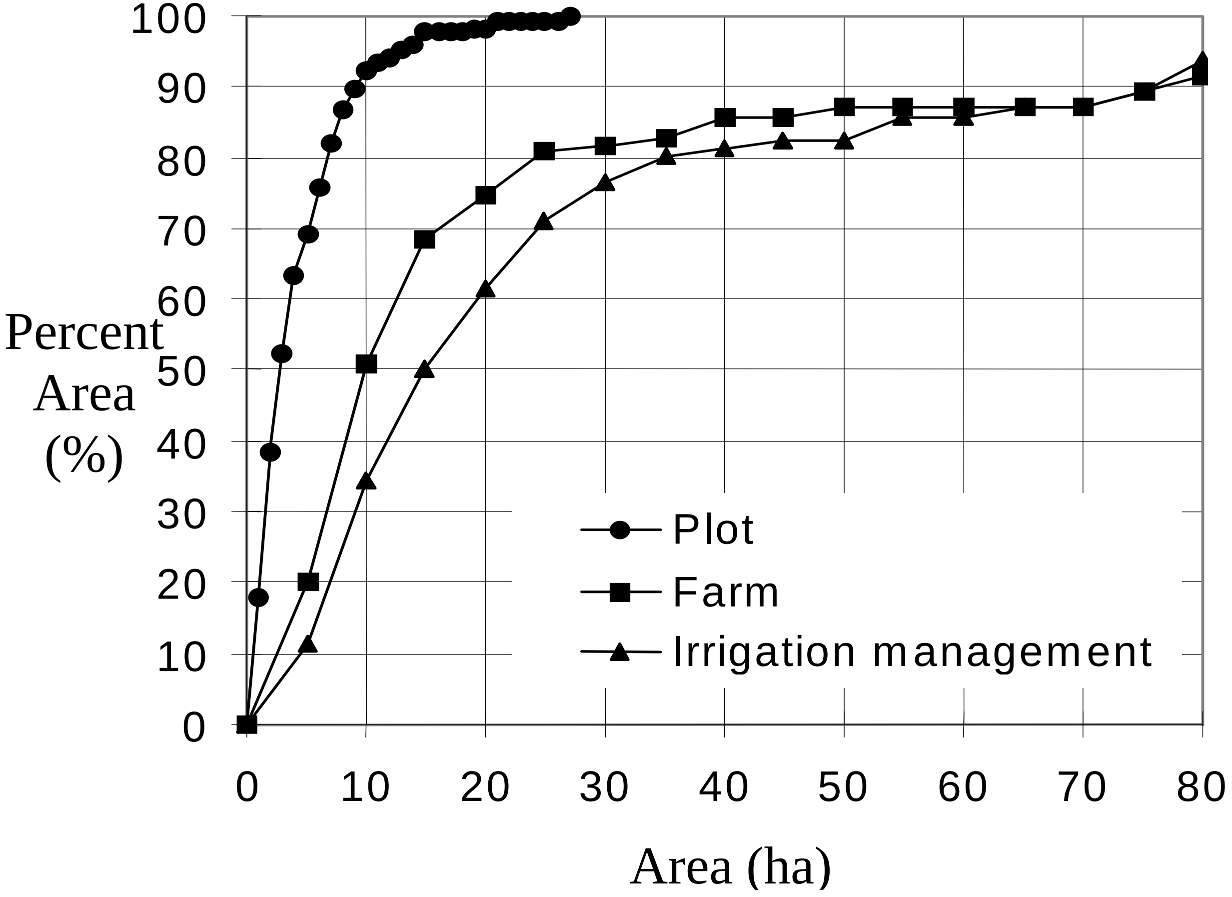

Figure 6. *Gross irrigation volume of water billed to the farmers vs. plot area*.

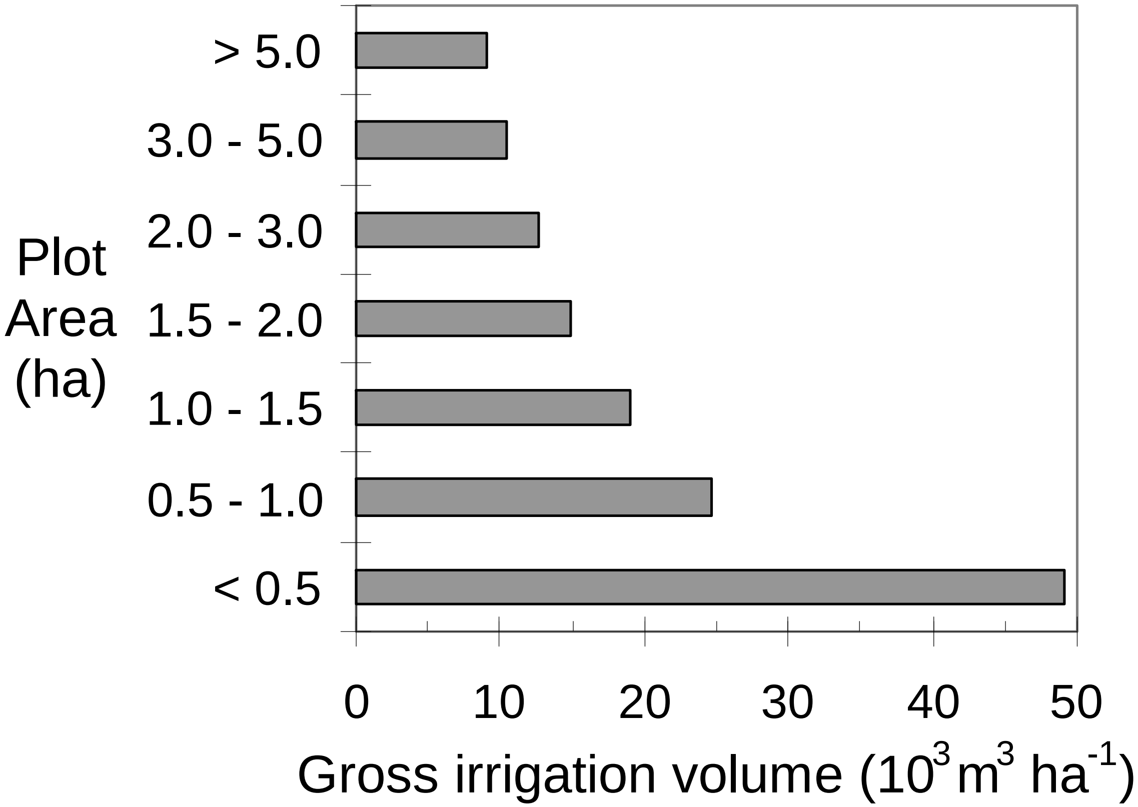

Figure 7. *Daily volumes of irrigation water delivery vs. day of the year (DOY).*

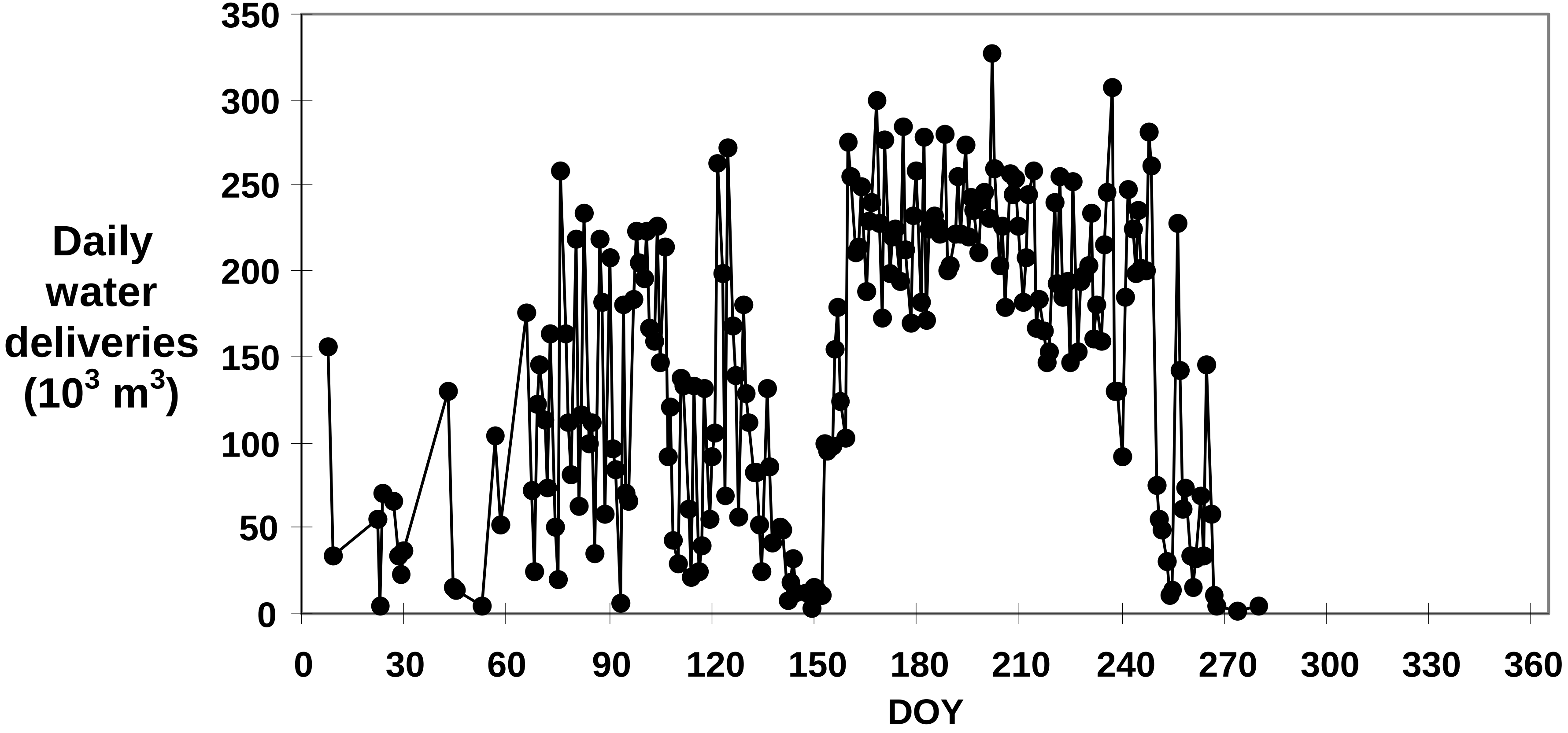

Figure 8. *Delay time vs. day of the year (DOY).*

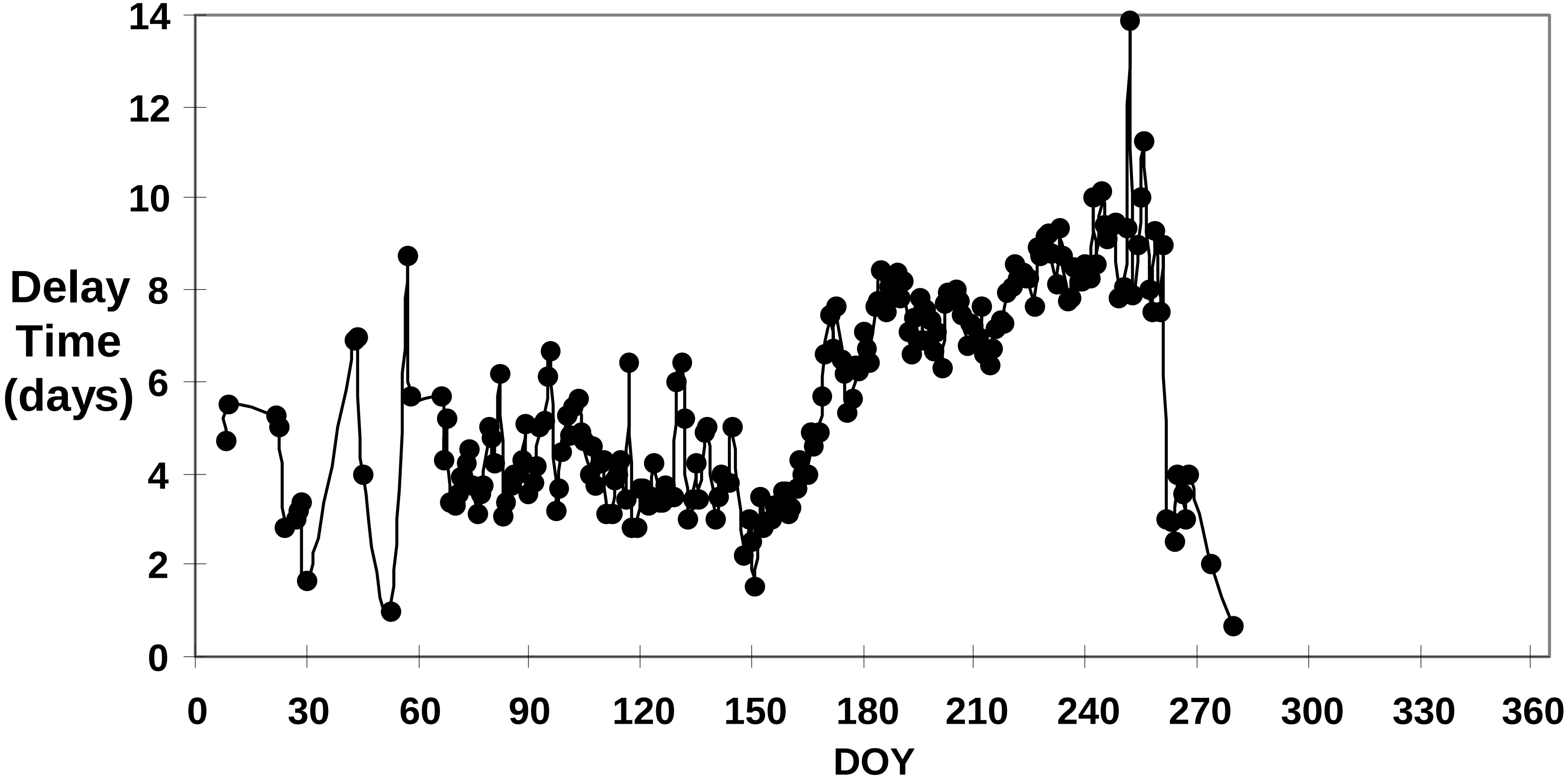

Figure 9. *Contour maps of the interval between irrigations (days) for corn (a) and sunflower (b). Axes values in UTM co-ordinates.*

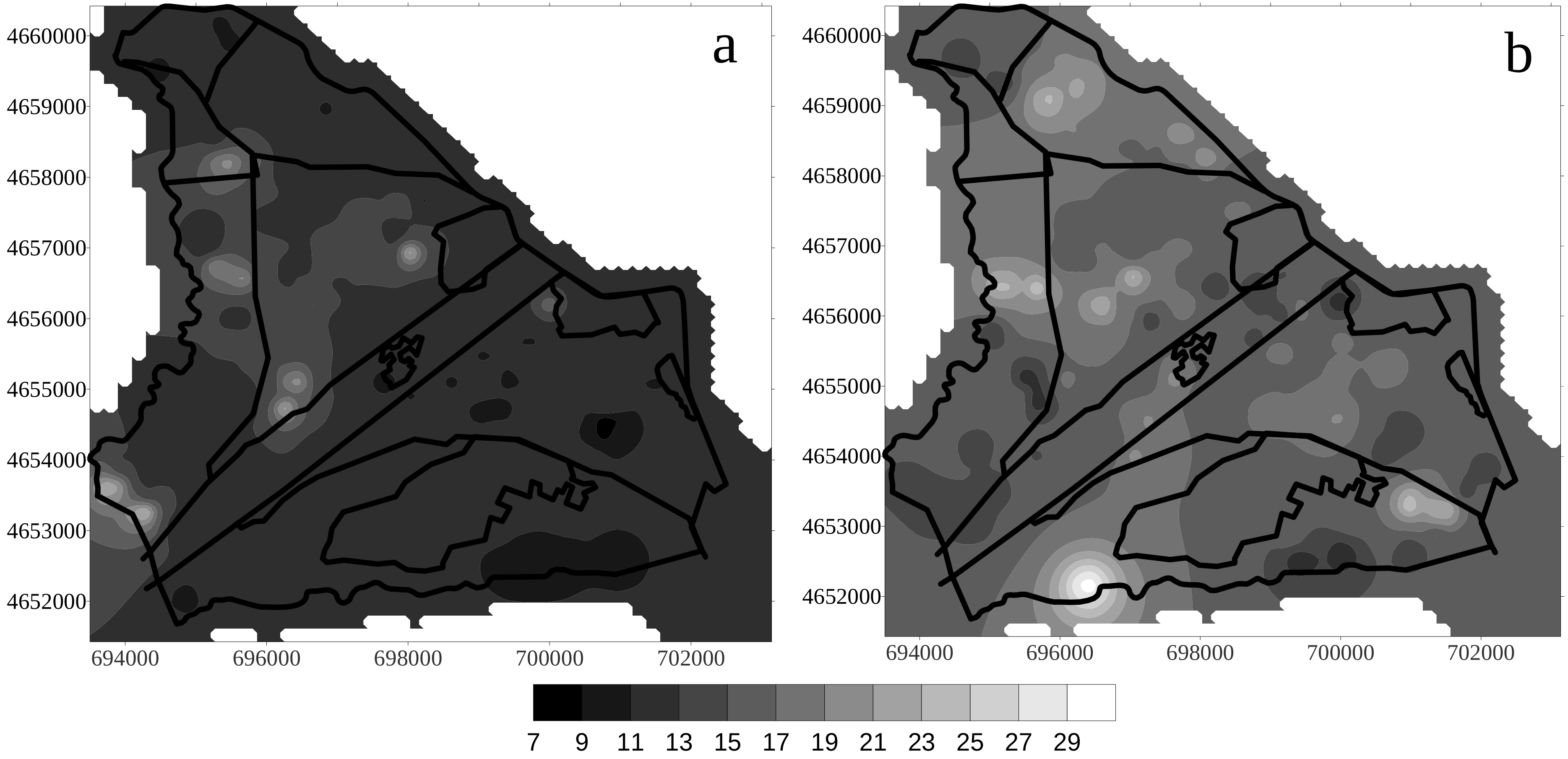

Figure 10. *Contour maps of the seasonal irrigation performance index (SIPI, %) for corn (a) and sunflower (b). Axes values in UTM co-ordinates.*

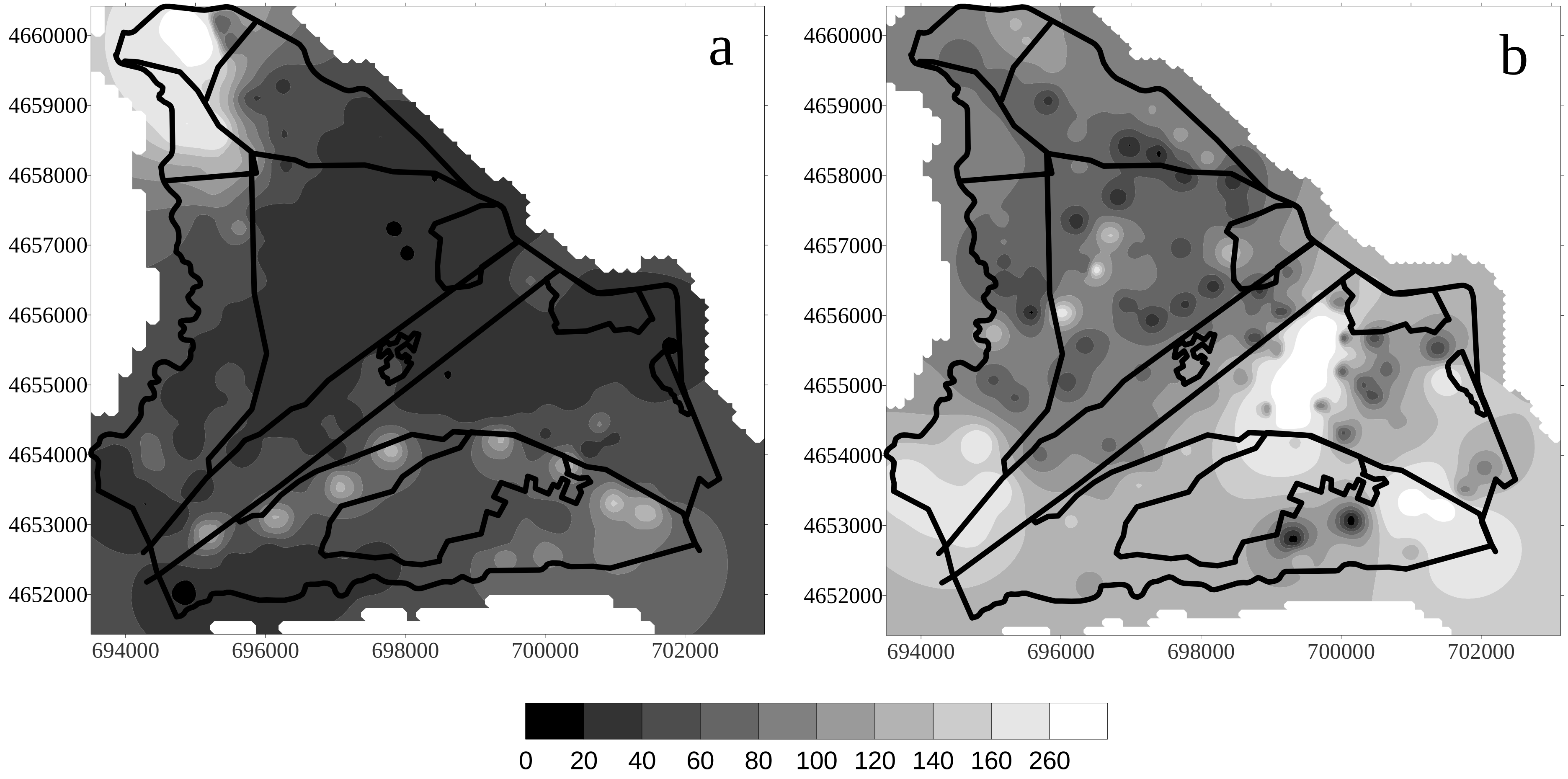

Figure 11. *Contour map of the seasonal irrigation performance index (SIPI, %) for the whole area. Axes values in UTM co-ordinates.*