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ORIGINAL PAPER

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Evaluating irrigation performance in a Mediterranean environment

I. Model and general assessment of an irrigation scheme

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Abstract Assessment of irrigation performance is a prerequisite for improving water use in the agricultural sector to respond to perceived water scarcity. Between 1996 and 2000, we conducted a comprehensive assessment of the performance of the Genil–Cabra irrigation scheme (GCIS) located in Andalusia, southern Spain. The area has about 7,000 ha of irrigated lands distributed in 843 parcels and devoted to a diverse crop mix, with cereals, sunflower, cotton, garlic and olive trees as principal crops. Irrigation is on demand from a pressurized system and hand-moved sprinkler irrigation is the most popular application method. Six performance indicators were used to assess the physical and economic performance of irrigation water use and management in the GCIS, using parcel water-use records and a simulation model. The model simulates the water-balance processes on every field and computes an optimal irrigation schedule, which is then checked against actual schedules. Among the performance indicators, the average irrigation water supply:demand ratio (the ratio of measured irrigation supply to the simulated optimum demand) varied among years from 0.45 to 0.64, indicating that the area is under deficit irrigation. When rainfall was included, the supply:demand ratio increased up to 0.87 in one year, although it was only 0.72 in the driest year, showing that farmers did not fully compensate for the low rainfall with sufficient irrigation water. Nevertheless, farmers in the area made an efficient use of rainfall, as indicated by the relatively high values (0.72–0.83) for the ratio of actual:attainable crop yields. Water productivity (WP) in the GCIS oscillated between 0.72 €/m^3 and 1.99 €/m^3 during the 4 years and averaged 1.42 €/m^3 of water supplied for irrigation, while the irrigation water productivity (IWP) averaged 0.63 €/m^3 for the period studied. WP is higher than IWP because WP includes production generated by rainfall, while IWP includes only the production generated by irrigation.

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Introduction

The availability of water for irrigation will probably decrease in the future due to increased demands from other sectors, such as municipal, tourism, recreation and the environment. In Spain, fresh-water demand is estimated as 35×10^5 m^3/year with about 70% devoted to irrigation and the rest to other uses (MIMAM 1998). Additionally, the government anticipates that irrigation demand in Southern Spain will increase by about 17% in the next 10 years (MIMAM 2000).

Improvements in water management and the modernization/rehabilitation of the Spanish irrigation schemes are important objectives to achieve more efficient use of water. Only 27% of the irrigated area in Spain (approximately 915,000 ha) is less than 20 years old, whereas 37% is more than 90 years old (MAPA 1998). In recent years, the water administration emphasized system modernization and rehabilitation but comparatively little attention was paid to the improvement of irrigation management.

The improvement of water management in an irrigation scheme requires the assessment of irrigation performance as a point of departure. Computer simulation using hydrologic models has been useful for this task. Many models have been used to simulate parts of the hydrologic cycle in irrigated agriculture, from empirical or functional (Doorenbos and Pruitt 1977;

Doorenbos and Kassam 1979; Allen et al. 1998) to mechanistic (Van Aelst et al. 1988). Additionally, to facilitate data acquisition and carry out spatial analyses, recently developed tools, such as remote sensing (Kite 2000; Kite and Droogers 2000) and geographic information systems (GIS; Hartkamp et al. 1999), have been combined with hydrologic models to assess the behavior of irrigation schemes.

Several authors (Molden and Gates 1990; Kalu et al. 1995; Malano and Burton 2001) have defined sets of indicators that characterize irrigation system performance, intending to evaluate current practices and recommend improvements in irrigation efficiency and water productivity. These performance indicators are also used to quantify the system ability and to achieve the objectives established for an irrigation area or to assess the current performance of the system relative to its potential.

The different types of performance indicators are related to: (1) the water balance, (2) economic, environmental and social objectives, or (3) system maintenance (Bos 1997). Several authors have used these indicators for: (1) assessing trends in performance (Sarma and Rao 1997; Droogers and Kite 1999; Droogers et al. 2000; Dechmi et al. 2003), (2) comparing performance among irrigation schemes (Burt and Styles 1999), (3) resource optimization (Molden and Gates 1990) and (4) determining a compromise solution between equity and efficiency within an irrigation area (Kalu et al. 1995). The complexity of models used for calculating the water balance-based performance indicators varies from a one-dimensional, physically based, hydrologic model (Feddes 1988; Droogers and Kite 1999) to very simplified models, such as those based on the FAO methodology (Dechmi et al. 2003). At the scheme level, input information to compute performance indicators is normally obtained from total water delivery records and from water consumption estimates derived from the cropped areas. Such information often has substantial uncertainty and does not allow for in-depth analysis at levels below the scheme. Nevertheless, scheme-level assessments are needed for comparative purposes and are the only approach feasible when there is no access to information at sub-scheme levels.

The objective of this work was to conduct a comprehensive assessment of the irrigation performance of an area using on-farm water-use information and a simulation model. The area selected was the Genil–Cabra irrigation scheme (GCIS) located in Andalusia, southern Spain. This area was chosen because it was possible to obtain accurate information on water use and on the cropping patterns of individual parcels during four irrigation seasons.

Materials and methods

Area description

The study area was located within the GCIS, near the town of Cordoba, Spain (37° 31′ N, 4° 51′ W). The area that was evaluated encompasses 6,990 ha of irrigated land and was developed around 1990, being under full water supply since 1995.

The climate is Mediterranean continental with an annual average precipitation of 606 mm and a rainless summer. The average air temperature ranges from 10 °C in winter to over 27 °C in summer. The predominant soils in the area are Chromic Haploxererts (35%) and Typic Xerorthent (34.7%).

Cropping patterns are fairly diverse. The most important crops in the area are winter cereals, sunflower, cotton and garlic, representing 27%, 19%, 16% and 15% of the irrigated area, respectively, over the study period. Other relevant crops in the area include olive, sugar beet, beans, maize and several horticultural crops (Table 1).

The area is serviced by a modern pressurized irrigation-delivery system, which allows complete flexibility of frequency, rate and duration of water delivery. Approximately 2,600 ha in the lower part of the area are watered from a gravity-fed branched network. The remaining area (4,400 ha) is supplied by another branched network fed from a central pumping station. Both networks start at the same point, where all the water is diverted and filtered from a main canal.

The whole area is divided into command areas, each composed of one or more parcels, depending on the size of the parcels. A parcel is an administrative unit within a unique boundary that belongs to a single owner. A parcel may be divided into several fields, which comprise the crop-management units. The pressurized network supplies water to 44 command areas and the gravity network supplies water to 39 command areas. Water delivery is measured at the inlet of each parcel. Farmers pay for irrigation water at a rate of 0.02 €/m^3 to cover the energy costs of pumping. Additionally, there is an annual fee of about 150 €/ha to cover the operation and maintenance costs and recover part of the investment cost.

Table 1 Surface area for major crops

	1996/1997		1997/1998		1998/1999		1999/2000	
	Area (ha)	%	Area (ha)	%	Area (ha)	%	Area (ha)	%
Winter cereals	1,805	29.2	1,829	28.4	1,954	28.6	1,559	22.4
Sunflower	1,133	18.4	1,603	24.9	874	12.8	1,342	19.3
Cotton	1,120	18.1	988	15.4	1,164	17.0	907	13.0
Garlic	839	13.6	647	10.1	933	13.7	1,036	14.9
Olive	535	8.7	599	9.3	609	8.9	656	9.4
Sugar beet	230	3.7	231	3.6	366	5.4	680	9.8
Beans	193	3.1	53	0.8	405	5.9	224	3.2
Maize	96	1.6	255	4.0	192	2.8	146	2.1
Asparagus	82	1.3	105	1.6	149	2.2	188	2.7
Others	141	2.3	122	1.9	190	2.8	224	3.3
Total planted area	6,174		6,432		6,836		6,962	

Land tenure has the following structure: there are 290 parcels of less than 2 ha (occupying 4.3% of the area), about 360 parcels of 2–10 ha (representing 22.6% of the area) and 190 parcels of 10–100 ha (65.7% of the area). There are three parcels that are over 100 ha, occupying 8.5% of the area. Thus, over 90% of the parcels have an area less than 20 ha.

Data collection

The study was carried out during four irrigation seasons (from 1996/1997 to 1999/2000). In these four seasons, there were no irrigation restrictions, although the 1998/1999 season had very limited rainfall (Table 2; 150 mm between September 1998 and August 1999, as compared with 559 mm average during the 4 years of the study and the long-term average of 606 mm).

Crops on each parcel were recorded for each season and the cumulative water-meter readings of every parcel were taken four or five times during each season. Information on soil maps and characteristics was obtained from previous studies conducted before the area was developed for irrigation. The district manager provided maps with parcel information and irrigation system characteristics. Each parcel was visited at least once a year to confirm the crop information and describe the method of irrigation. Portable sprinkler systems were most common for herbaceous crops, while drip irrigation became the most common method in olive during the last irrigation season.

The frequency and duration of irrigation applications and sowing dates for the different crops were obtained from personal interviews with the scheme manager and using a questionnaire that was answered correctly by about 10% of the farmers. The questionnaire data were used to calculate the average and variance of the sowing date. A sowing date was assigned randomly every year to each field, assuming a normal distribution for cotton, sunflower, wheat and garlic, crops for which a minimum of 16 observations were available. The sowing date frequency distribution for the other crops was estimated with the advice of the scheme manager and other local experts. Daily meteorological data were obtained from an automated weather station located in the area. Attainable crop yields under irrigated and rainfed conditions were estimated from interviews with farmers and from expert opinions; and marketable prices were compiled from local technical bulletins.

Simulation model

A mass-balance model was developed to simulate water use in the GCIS. It was composed of sub-models that computed all water-balance components and quantified the effects of water stress on crop yield. Figure 1 depicts the flowchart and the computation procedure with the sequence of operation that leads to comparisons between the calculated optimum schedules for each of the 843 parcels and the actual schedules, which were also simulated based on the water-meter readings collected several times during the season. The model calculates the soil water-balance components for each computation unit (subdivision of each parcel with a unique crop and soil) on a daily basis. Based on crop water-requirement calculations, it generates optimum irrigation schedules and compares the optimum schedules for each field (subdivision of each parcel with a unique crop) against the actual irrigation schedules, which were simulated based on water-meter readings. GIS tools were used for overlaying the parcel with soil maps to characterize the soil of each parcel and generate the computation units. The simulation model was then applied to each of these computation units and the results aggregated to obtain average values for fields, parcels and the whole area.

Table 2 Annual rainfall, scheme irrigation delivery and scheme-averaged irrigation depth for each irrigation season

Irrigation season	Annual rainfall (mm)	Annual irrigation delivery ($\times 10^3$ m^3)	Annual irrigation depth (mm)
1996/1997	729	1.61	262
1997/1998	860	1.41	219
1998/1999	150	2.94	430
1999/2000	499	1.76	252

Soil water balance

A daily soil water-balance model with multiple soil layers was developed where rainfall and irrigation were inflows, but capillary rise and lateral flow were not considered. Outflows were crop transpiration, soil evaporation, surface runoff and deep percolation. The soil profile was divided in 10-cm layers up to the maximum root system depth. Surface runoff was calculated with the SCS curve number method using daily rainfall records (Soil Conservation Service 1972). Adjustments were included to express the effects on runoff of slope and soil moisture conditions (Williams 1991). Water extraction by roots was calculated for each soil layer as a function of its water content and root-length density (Coelho et al. 2003), as root water uptake is not uniform along the soil profile (Taylor 1983). The water in excess of the maximum storage for each soil layer flowed in a cascade mode and deep percolation was computed as the excess water of the last layer of the root zone. The soil water balance took into account the extraction of water by crops after the last irrigation and before crop maturity. Deep percolation due to irrigation was also caused by application non-uniformity; and, for its calculation, it was assumed that the applied water followed a uniform distribution (Mantovani et al. 1995).

Crop water requirements and yield

Crop water requirements ($\mathrm{ET_c}$) were calculated using equations currently recommended by the FAO (Allen et al. 1998):

$$\mathrm{ET_C} = \mathrm{ET_O}(K_\mathrm{S} \times K_\mathrm{cb} + K_\mathrm{e}) \qquad (1)$$

$\mathrm{ET_o}$ is the daily reference evapotranspiration calculated with the Penman–Monteith equation, K_cb is the basal crop coefficient and K_e is the soil evaporation coefficient. K_e is obtained by calculating the amount of energy available at the soil surface (Allen et al. 1998) as follows:

$$K_\mathrm{e} = K_\mathrm{r}(K_\mathrm{c\,max} - K_\mathrm{cb}) \qquad (2)$$

K_r is a dimensionless evaporation reduction coefficient dependent on topsoil water depletion (Allen et al. 1998) and $K_\mathrm{c\,max}$ is the maximum value of K_c following rainfall or irrigation. The value of K_e cannot be above the product $f_\mathrm{ew} \times K_\mathrm{c\,max}$, where f_ew is the fraction of the soil surface that is both exposed and wetted.

A study by Allen (2000) found that his maximum ET estimates had to be lowered by about 15%, to take into account management factors that limited ET. One factor is water stress, which is addressed here by using K_s, a water-stress coefficient that reduces the maximum $\mathrm{ET_c}$ by decreasing the value of K_cb, when the average root zone water content is not sufficient to sustain full plant transpiration, using the expression (Allen et al. 1998):

$$K_\mathrm{S} = \frac{\mathrm{WHC} - D_\mathrm{r}}{(1-p)\mathrm{WHC}} \qquad (3)$$

WHC is the water-holding capacity of the root zone, D_r is the root zone depletion and p is the fraction of the WHC below which the root zone water content limits crop transpiration. When the root zone depletion is smaller than $p \times \mathrm{WHC}$, K_s is equal to 1.

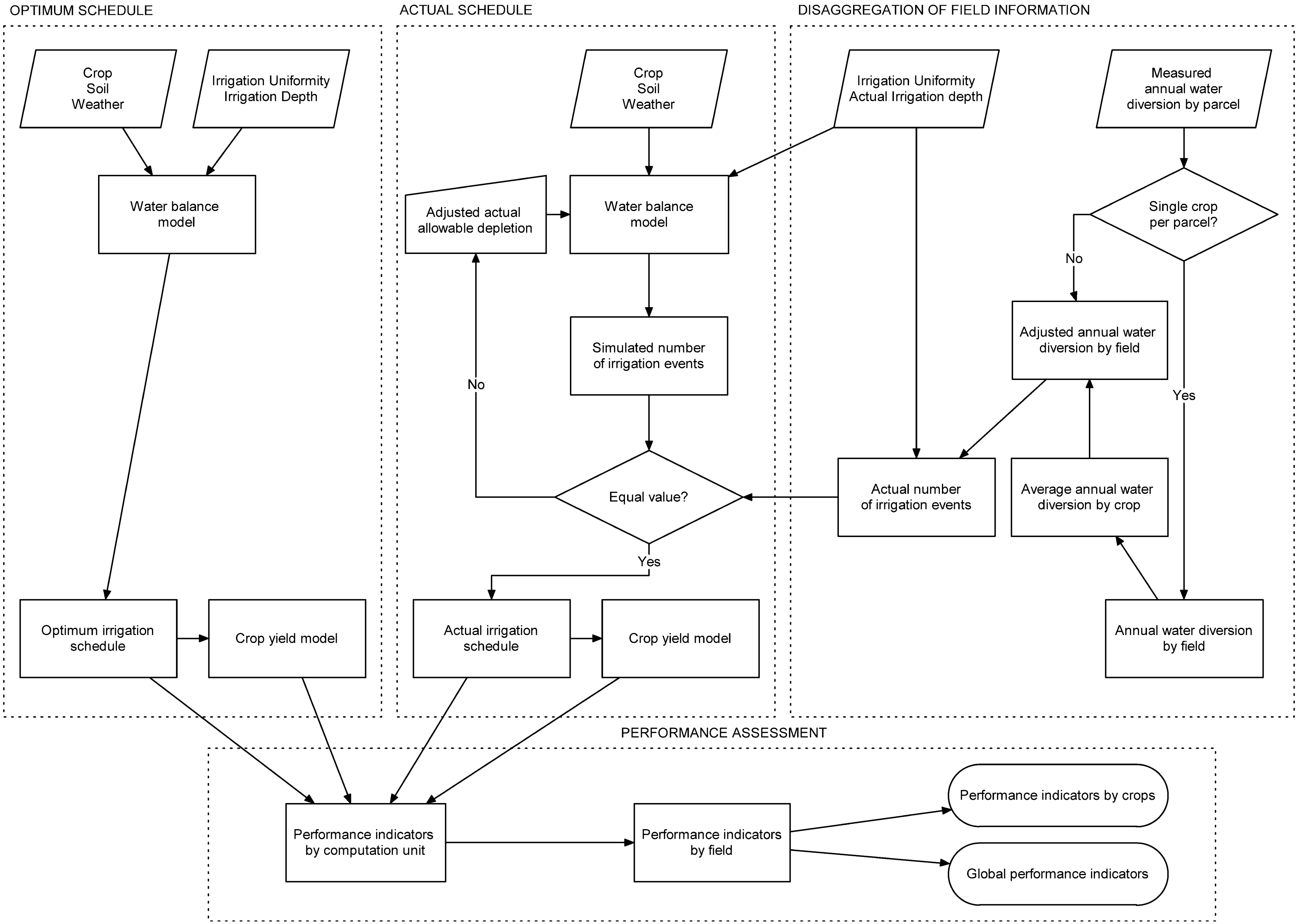

Fig. 1 Flowchart of the simulation model and the computation procedures

Seasonal maximum evapotranspiration ($ET_{c\,max}$), seasonal actual evapotranspiration (ET_c) and the crop yield response factor (K_y) are used in the model to estimate the crop yield reduction based on linear crop-water production functions, as described by Doorenbos and Kassam (1979):

$$\left(1-\frac{Y_a}{Y_m}\right)=K_y\left(1-\frac{ET_c}{ET_{c\,max}}\right) \tag{4}$$

Y_a is the actual crop yield, Y_m is the maximum expected crop yield (which we obtained from local sources) and K_y is an empirical crop response factor. Values for K_y proposed by Doorenbos and Kassam (1979) were first adjusted according to our local experience and then modified for situations of severe water deficits (Table 3). It is well known that severe ET deficits affect harvest index (and therefore yield) more negatively than biomass production (Fereres 1984). It was assumed that the production function was valid until a seasonal ET_c deficit of 40% of $ET_{c\,max}$ was reached. At that threshold point, a linear reduction in crop yield was assumed, reaching a zero yield at an ET_c deficit of 80% of $ET_{c\,max}$.

In our model, ET_c was reduced due to average water deficit and to water deficit induced by the lack of uniformity in the applied irrigation water. To account for both effects, Mantovani et al. (1995) proposed the use of a deficit coefficient (C_d), defined as the ratio between the mean deficit and the required depth (Losada et al. 1990), which depends on the seasonal gross irrigation depth, the seasonal required depth (H_R) and the Christiansen uniformity coefficient. ET_c can then be calculated as:

$$ET_c = ET_{c\,max} - (C_d \times H_R) \tag{5}$$

H_R is defined as:

$$H_R = ET_{c\,max} - \text{Rain} - \Delta S \tag{6}$$

Rain is the effective rainfall along irrigation season and ΔS is the increase or decrease in root zone water storage.

Irrigation scheduling

Two scheduling strategies were analyzed: optimum and actual. Under the optimum strategy, the model simulates the irrigation schedule using allowable depletion equal to p adjusted from the data of Allen et al. (1998). In addition, the non-uniformity of the irrigation application implies the need of an additional water depth to compensate for the lack of uniformity. To calculate such a depth, an economic optimum was defined for each crop based on yield price and water cost (Wu 1988). Thus, the optimum strategy includes additional water up to the economic optimum depth. For specific crops, certain common management practices were incorporated into the optimum schedules, such as preirrigation or irrigation cut-off at the end of the season.

Table 3 Values for the crop yield response factor, K_y, adjusted to local conditions and compared with K_y values presented by Doorenbos and Kassam (1979) when available

	K_y (Local values)	K_y (Doorenbos and Kassam 1979)
Garlic	1.00	–
Cotton	0.85	0.85
Winter wheat	1.05	1.05
Sunflower	1.20	0.95
Beans	0.85	1.15
Maize	1.25	1.25
Olive	0.85	–
Sugar beet	1.10	1.00

The actual irrigation schedule was derived from the total amount of water used in each parcel, obtained by reading the water meters periodically (four or five times throughout the season). First, we estimated the number of irrigation events carried out by each farmer, using the information on irrigation practices (rate and duration for each irrigation) for the different crops. Such a number of irrigation events could be higher or lower than that determined for the optimum schedule. To distribute the actual number of irrigation events within the season, the simulation model was run under the assumption that the farmer would distribute the water by attempting to reach the same level of allowable depletion in the root zone. A number of iterations were carried out with the simulation model on each field until the actual number of irrigation events was fitted to the irrigation period (Fig. 1). In parcels with more than one crop, the allocation of irrigation water to the different fields was made proportionally to the average consumption, as measured in parcels with a single crop.

Performance indicators

To assess the quality of irrigation in the area, the following six performance indicators were chosen: annual relative irrigation supply (ARIS), annual relative water supply (ARWS), drainage ratio (DR), crop yield ratio (CYR), water productivity (WP) and irrigation water productivity (IWP), as defined below. Other indicators such as those used for evaluating equity or dependability (Molden and Gates 1990) were not considered as important for this area, because water delivery is on demand and there are no supply problems.

Performance indicators related to water use

Malano and Burton (2001) defined a set of indicators for irrigation and drainage benchmarking. Included in this set are ARIS and ARWS. We defined these two indicators as:

$$\text{ARIS} = \frac{\text{Annual volume of irrigation water inflow}}{\text{Annual volume of crop irrigation demand}} \tag{7}$$

and:

$$\text{ARWS} = \frac{\text{Annual volume of total water supply}}{\text{Annual volume of crop water demand}} \tag{8}$$

ARIS relates the volume of irrigation water delivered to the volume of irrigation water needed to avoid undesirable water stress (gross irrigation requirements). The numerator depends on the reliability of the irrigation service and the farmer's knowledge, whereas the denominator is determined by the crop, the climate, the interval between water applications and the application efficiency.

ARWS relates the total volume of water applied (irrigation plus rainfall) to the volume of water required by the crop (computed as gross irrigation requirements plus rainfall).

The system drainage ratio determines the ratio between the total drained volume of water and the total flow into the system. A similar index, DR, is used here but refers exclusively to the irrigation water, which is computed only for the irrigation events:

$$\text{DR} = \frac{\text{Drained volume of water from irrigation}}{\text{Annual volume of irrigation water inflow}} \tag{9}$$

Another indicator computed here is CYR (Bos et al. 1994) defined as:

$$\text{CYR} = \frac{\text{Actual crop yield}}{\text{Intended crop yield}} \tag{10}$$

CYR relates the actual crop yield to the intended yield, defined as the attainable crop yield with optimum economic irrigation (Wu 1988).

Performance indicators related to economics

Two indicators were defined to evaluate the productivity of the water used for irrigation in this area. The first indicator is the economic output per unit irrigation supply: WP (Malano and Burton 2001). WP is defined as:

$$\mathrm{WP}\ (\mathrm{Euros/m^3}) = \frac{\text{Annual value of agricultural production}}{\text{Annual volume of irrigation water inflow}} \tag{11}$$

The decrease in agricultural production due to inefficient water management may be calculated using a crop yield reduction specific for each field caused by water stress. Also, the maximum production without water limitations and the marketable crop prices in the local markets are required to compute potential economic losses for a given irrigation schedule. In this work, we calculated WP for the scheme as the area-weighed WP per individual crop.

The last indicator considered evaluates the IWP. Bos (1997) defined a similar indicator as the yield:water supply ratio and analyzed its profitability in terms of water delivered.

$$\mathrm{IWP}\ (\mathrm{Euros/m^3}) = \frac{\text{Increase in annual value of agricultural production due to irrigation}}{\text{Annual volume of irrigation water inflow}} \tag{12}$$

In this indicator, the numerator is computed as the difference between actual crop yields under irrigation minus rainfed yields. It is assumed that management does not change much as the grower shifts from rainfed to irrigated conditions, which is probably the case for the GCIS.

Results and discussion

Table 4 summarizes the results obtained during four irrigation seasons for the six performance indicators assessed for the whole irrigation area. The major features of the assessment indicate that the GCIS is characterized by a low ARIS and a relatively high WP. Following is the analysis of the results for each indicator.

Table 4 Average values and coefficients of variation (in parentheses) for irrigation performance indicators in the Genil–Cabra irrigation scheme: annual relative irrigation supply (*ARIS*), annual relative water supply (*ARWS*), drainage ratio (*DR*), crop yield ratio (*CYR*), water productivity (*WP*) and irrigation water productivity (*IWP*). *Letters* across years indicate differences statistically significant at the 95% probability level (LSD test)

	1996/1997	1997/1998	1998/1999	1999/2000
ARIS	0.45a	0.49a	0.64b	0.57c
	(0.87)	(0.83)	(0.61)	(0.73)
ARWS	0.80a	0.87b	0.72c	0.82a
	(0.17)	(0.13)	(0.43)	(0.23)
DR	0.017a	0.020a	0.024a	0.018a
	(3.94)	(3.15)	(3.17)	(4.11)
CYR	0.74a	0.82b	0.72c	0.83a,b
	(0.28)	(0.18)	(0.44)	(0.29)
WP (€/m^3)	1.36a	1.99b	0.72c	1.62a
	(1.01)	(1.20)	(1.17)	(0.91)
IWP (€/m^3)	0.67a	0.56b	0.72a	0.58b
	(1.15)	(1.21)	(1.17)	(1.41)

Annual relative irrigation supply

The average parcel ARIS for the whole area was always less than 1.0 (from 0.45 in 1996/1997 to 0.64 in 1998/1999), indicating that irrigation application in the GCIS was insufficient to meet the crops' maximum evapotranspiration demand. There were significant differences among the ARIS values between years: the ARIS for the first 2 years (the two wettest years) were lower than those for the last 2 years (differences statistically significant at the 95% level of confidence). The standard deviations of the parcel ARIS values were quite large, leading to coefficients of variation between 0.61 (in 1998/1999, the driest season) and 0.87, indicative of large variations among irrigators, as discussed in our companion paper (Lorite et al. 2004). ARIS average values published for different irrigation areas around the world (Kloezen and Garcés-Restrepo 1998; Molden et al. 1998; Burt and Styles 1999) are generally higher than those presented in Table 4, although such areas differ from the GCIS in their crops, irrigation methods and socioeconomic conditions; and our definition of ARIS was slightly different from that of the cited authors. Within irrigated areas in Spain, Faci et al. (2000) found for an area under traditional surface irrigation in the Ebro Basin an average net irrigation requirement/diverted irrigation water ratio of 0.70, indicative of over-irrigation. In contrast, Dechmi et al. (2003) found in another area of the same basin (where sprinkle was predominant irrigation method) that the average net irrigation requirement/diverted irrigation water ratio was 1.27 (indicative of under-irrigation) and that the results were variable along the different irrigation seasons analyzed.

Other performance indicators based on water balance

The ARWS and the CYR showed similar behavior, because both indexes were correlated. Average values for the four irrigation seasons showed less variation than did ARIS, but there were statistically significant differences (Table 4). ARWS varied from 0.72 (in 1998/1999) to 0.87 (in 1997/1998). Variation in this indicator is directly related to the amount of rainfall, showing a greater coefficient of variation as rainfall decreases (varying from 0.13 in the rainiest year to 0.43 in the driest year), due to the spatial homogenization made by the rainfall. CYR varied from 0.72 (in 1998/1999) to 0.83 (in 1999/2000) and, similar to ARWS, had the highest coefficient of variation in the driest year (0.44).

Judging by the values of the ARWS indicator, it appears that the total water supply to crops in the GCIS was closer to the optimum.

Comparing the ARWS values obtained in previous works (Kloezen and Garcés-Restrepo 1998; Molden et al. 1998; Burt and Styles 1999), only one area had lower ARWS values than the GCIS. The lowest ARWS value found in the analyzed areas occurred in Muda, Malaysia (Molden et al. 1998; ARWS about 0.5), where irrigation application was limited.

Table 4 presents the DR index, which varied very little in the four irrigation seasons, although it was higher in the years when irrigation amounts were higher (1998/1999, 1999/2000). The reasons for the low DR include shallow depths of application in relation to the root-zone water deficits and the high distribution-uniformity observed under field conditions. Most of the drainage occurred with preirrigation, because the soil water content is normally high prior to planting. The large coefficients of variation found (Table 4) were caused by the very low values of DR.

Economic performance indicators

Table 4 shows that the two indicators used, WP and IWP, differed in their response to the annual changes in seasonal rainfall and irrigation. WP was influenced by weather conditions and by irrigation management. Average WP values varied from 1.99 €/m^3 (1997/1998, rainy year) to 0.72 €/m^3 (1998/1999, dry year). The lowest WP value corresponded to the year of lowest rainfall, when farmers did not fully compensate for the lack of rainfall (that year had the lowest ARWS; see Table 4) and yields were negatively affected (see CYR values in Table 4), even though the applied irrigation volumes were greater than in the other 3 years (Table 2). The other indicator, IWP, varied less and was highest in the dry year, due to the very low rainfed yields estimated for that dry year. The expected yield increase from rainfed to irrigation in that year was much higher than in the other years and more than compensated for the greater irrigation volumes of the dry year, leading to higher IWP values (Table 4).

A recent study of WP in the irrigated areas of southern Spain (Corominas 2000) provides gross estimates of the range of WP values for the region where the GCIS is located. Only 10% of the 82 irrigated areas analyzed in this study showed WP values that were higher than those of the GCIS; and most of them were located near the coast and were devoted to off-season horticultural crops under plastic greenhouses. The high WP of the GCIS is probably due to the presence of high WP crops, such as olive and garlic, and the low water consumption in the GCIS. In a recent study of two irrigation areas in Turkey (Droogers et al. 2000; Droogers and Kite 2001), WP values were slightly lower than the GCIS values. Similarly, their lowest WP occurred in the seasons of highest irrigation depths.

Global surveys of WP in selected irrigated areas (Molden et al. 1998; Burt and Styles 1999) give WP values which are substantially lower than those in the GCIS. There are many reasons for the low WP values around the world, e.g., the cultivation of high-water-use crops (such as rice), the lack or very low level of rainfall in arid areas (leading to high irrigation depths), the low market values of many crops, the absence of subsidies in many areas in the developing world (in contrast to the subsidies received for certain crops by the GCIS farmers, contributing to higher incomes) and the widespread existence of irrigation delivery systems with high losses.

IWP did not show important variations between the 4 years, varying from 0.56 €/m^3 (1997/1998) to 0.72 €/m^3 (1998/1999). Increments in crop yield from rainfed to irrigated conditions were paralleled by increased irrigation applications, making this index relatively insensitive to seasonal variations (in fact, the IWP values for 1996/1997, a wet year, and 1998/1999, the driest year, were not statistically different). For instance, if the season was rainy, the increase in yield from rainfed to irrigated conditions was small, but the depth of water applied was also low. The variable cost of irrigation water in the GCIS was relatively low (0.02 €/m^3) and close to the average cost in the region (Corominas 2000), although it may be considered high when compared with other regions around the world. Burt and Styles (1999) indicated that water costs in several irrigation districts in Asia, South America and Africa was less than 0.02 €/m^3 and, in general terms, did not exceed 0.01 €/m^3. When water costs in the GCIS are combined with the fixed irrigation costs, the profitability threshold of irrigation water is about 0.05 €/m^3. The values of IWP are about an order of magnitude greater than this threshold for all 4 years (Table 4), indicating that, if additional irrigation water is supplied to the GCIS, it should lead to increased net returns.

For all performance indicators studied, the variability among fields was substantial, as indicated by large coefficients of variation from the average values (Table 4). It appears that an in-depth analysis of the nature and causes of the variability encountered would be desirable; and this is presented in a companion paper (Lorite et al. 2004).

Conclusions

The traditional cliché of a wasteful use of water for irrigation clearly does not apply to the GCIS. The assessment of irrigation performance in this scheme using detailed water use records for each parcel and a simulation model indicates that the scheme is in a deficit-irrigation situation, as shown by the average ARIS value, which vary from 0.45 to 0.64 in the four irrigation seasons studied. However, when other performance indicators are considered, such as the ARWS, our analysis indicates that the conjunctive use of rainfall and irrigation makes efficient use of the total water available and that yields are not limited by the deficit irrigation. The estimated average CYR varies from 0.72 to 0.83 and is lowest in the driest season, when additional irrigation applications are insufficient to compensate for the lack of rainfall in that year. The relatively high water productivity found in the GCIS (1.42 €/m^3) is due to a combination of deficit irrigation and the widespread use of herbaceous winter crops (such as garlic and sugar beet) and evergreen tree crops (such as olive) which efficiently use a substantial proportion of the annual rainfall in Mediterranean climates, thus lowering their irrigation requirements.

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