Overland water and salt flows in a set of rice paddies

by

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Abstract

Cultivation of paddy rice in semiarid areas of the world faces problems related to water scarcity. This paper aims at characterizing water use in a set of paddies located in the central Ebro basin of Spain using experimentation and computer simulation. A commercial field with six interconnected paddies, with a total area of 5.31 ha, was instrumented to measure discharge and water quality at the inflow and at the runoff outlet. The soil was classified as a *Typic Calcixerept*, and was characterised by a mild salinity (2.5 dS m^{-1}) and an infiltration rate of 5.8 mm day^{-1}. The evolution of flow depth at all paddies was recorded. Data from the 2002 rice growing season was elaborated using a mass balance approach to estimate the infiltration rate and the evolution of discharge between paddies. Seasonal crop evapotranspiration, estimated with the surface renewal method, was 731 mm (5.1 mm day^{-1}), very similar to that of other summer cereals grown in the area, like corn. The irrigation input was 1,874 mm, deep percolation was 830 mm and surface runoff was 372 mm. Irrigation efficiency was estimated as 41%. The quality of surface runoff water was slightly degraded due to evapoconcentration and to the contact with the soil. During the period 2001-2003, the electrical conductivity of surface runoff water was 54% higher than that of irrigation water. However the runoff water was suitable for irrigation. A mechanistic mass balance model of inter-paddy water flow permitted to conclude that improvements in

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irrigation efficiency can not be easily obtained in the experimental conditions. Since deep percolation losses more than double surface runoff losses, a reduction in irrigation discharge would not have much room for efficiency improvement. Simulations also showed that rice irrigation performance was not negatively affected by the fluctuating inflow hydrograph. These hydrographs are typical of turnouts located at the tail end of tertiary irrigation ditches. In fact, these are the sites where rice has been historically cultivated in the study area, since local soils are often saline-sodic and can only grow paddy rice taking advantage of the low salinity of the irrigation water. The low infiltration rate characteristic of these saline-sodic soils (an experimental value of 3.2 mm day^{-1} was obtained) combined with a reduced irrigation discharge resulted in a simulated irrigation efficiency of 60%. Paddy rice irrigation efficiency can attain reasonable values in the local saline-sodic soils, where the infiltration rate is clearly smaller than the average daily rice evapotranspiration.

Keywords: Ebro, Aragón, Spain, efficiency, simulation, saline-sodic, salinity, infiltration, runoff, percolation

Introduction

In water-scarce regions of the world rice cultivation is often criticised for using too much water. Tuong and Bhuiyan (1999) summarised the results of a number of researchers in which rice irrigation efficiency fluctuated between 22 and 61%. These results are in reasonable agreement with those of Clemmens and Dedrick (1994), who presented a pessimistic and an optimistic estimation of paddy rice efficiency, with respective values of 40 and 60%. According to these figures, it is clear that paddy rice ranks very low in the comparison of irrigated agricultural systems based on irrigation efficiency.

A number of authors (Keller et al., 1996; Perry, 1999) have emphasized the hydrologic implications of irrigation efficiency, particularly in what refers to upscaling. A common conclusion of these works is that low values of on-farm irrigation efficiency (Burt et al., 1997) may not be harmful to regional water availability if the quality and location of the return flows permit to reuse them. In fact, water reuse is a very common feature of rice growing areas, in which water flows from paddy to paddy following intricate paths. Recently, Hafeez et al. (2007) presented data on an irrigated rice project in the Philippines. Water reuse at various levels resulted in a regional irrigation efficiency of 71%. The authors believed that achieving 80% efficiency would not require major improvements in irrigation management and structures. Similar conclusions can be drawn in the central Ebro basin of Spain when taking into account non point source water reuse in the Flumen irrigation district (Nogués and Herrero, 2003). These regional figures should alleviate social pressure on rice cultivation in areas where return flows are reused.

The reduction of on-farm water use presents advantages over return flow reuse. These are related to the conservation of water quantity (keeping irrigation water at the system source; controlling watertable rise) and quality conservation (avoiding the pollution present in runoff and percolation water). This is the reason why a number of techniques have been proposed to improve on-farm rice irrigation efficiency, such as soil puddling (Kukal and Aggarwal, 2002), intermittent ponding (Belder at al., 2004), soil suitability assessment (Beecher et al., 2002) and nonsubmerged sprinkler irrigation (McCauley, 1990).

The central Ebro Valley of Spain has an irrigated area of about half a million hectares. The area cropped to rice fluctuates every year, but rarely exceeds 20,000 ha. Rice is not particularly important in the region from a water use perspective, but it occupies its own niche: it is the only cropping alternative for saline-sodic soils. The vertical saturated hydraulic conductivity of these soils is usually very low, due to: 1) a degraded structure; 2) the frequent alternating millimetric layers of silt and sodic clay of the underlying Holocene sediments; and 3) soil tillage, puddling with the rice straw to produce an impervious soil pan. As a consequence, rice irrigation can attain reasonable efficiencies. In these crop conditions, soil salinity does not pose a limitation to rice growth and yield due to the permanent flooding with fresh water. Saline-sodic soils are often located in poorly drained, low geomorphic positions. Rice is cultivated every year in these soils. In the years when rice is particularly profitable, the crop can also be found in non saline-sodic soils occupying higher geomorphic positions. Rice farms in the area often occupy between 3 and 10 ha, and are typically divided into a number of paddies, with 0.5 to 2 ha each. The set of paddies has a canal turnout and a runoff disposal point, and water continuously flows between paddies during the crop season. Rainfall usually represents a small fraction of the seasonal water input.

The objectives of this paper are: 1) to assess water use in a set of rice paddies in the central Ebro basin, estimating all terms of the hydrologic balance as well as irrigation performance; 2) to evaluate the quality of irrigation and surface runoff waters; 3) to assess the influence of soil infiltration on irrigation performance; and 4) to identify better performing irrigation management techniques, capable of reducing surface runoff.

Material and Methods

The experimental field

A commercial rice field located in *Albero Bajo* (Huesca, Ebro valley, Spain) was evaluated in 2002 for irrigation performance and during 2001, 2002 and 2003 for irrigation and runoff water quality. The coordinates of the field are 41º 59′ 53″ N and 0º 24′ 34″ W. The total field area was 5.31 ha, divided into six paddies with areas ranging between 0.58 and 1.39 ha (Table 1, Figure 1). A topographic survey revealed that the difference in elevation between the highest and the lowest paddies was 4.26 m. The standard deviation of soil surface elevation (Playán et al., 1996) for each paddy ranged between 0.010 and 0.021 m, indicating that the field had been laser-levelled in recent years. Rice was grown annually in the field since 1996, following the attractive grain prices and Common Agricultural Policy subsidies of the end of the 20th century. Rice cultivation in the field was opportunistic, since according to the farmer other crops could be successfully cultivated in the field.

The field was equipped with an underground low-pressure concrete pipeline for surface irrigation water delivery to the six paddies. When used for rice irrigation the irrigation system was modified by the farmer so that water could continuously run from paddies 1 to 6. The concrete pipeline was only used to deliver water from the irrigation ditch to paddy 1, from 2 to 3, and from 4 to 5. The rest of the connections were performed using either the drainage system (1 to 2) or by breaching the paddy dikes (from 3 to 4 and from 5 to 6). In this last case, a plastic sheet was used to line the breach in order to prevent erosion. The connections between paddies were continuously regulated by the farmer in order to maintain flow depth in the paddies at target levels. The water levels and the regulations were performed in an empirical way.

During the 2002 season, the field was flooded on May 3. Rice sowing was performed immediately after flooding (May 6), sprinkling the seed over the flooding water with a fertilizer distributing machine. Physiological maturity was reached on September 23. The cropping period involved the 143 days separating flooding from physiological maturity.

Characteristics of the climate and experimental soils

The climate was characterized using the records of the nearby Grañén-Montesodeto weather station. Mean annual temperature was 14.3ºC, and mean annual precipitation was 525 mm. The mean annual reference evapotranspiration (ET_0) was 1,304 mm (Faci and Martínez-Cob, 1991). The soil temperature regime was classified as thermic (Soil Survey Staff, 1999), while the soil moisture regime was xeric, according to the available soil water holding capacity (Jarauta, 1989).

Mild soil salinity was evidenced by the abundant occurrence of *Tamarix sp.*, and *Atriplex halimus* L. at the field berms. Some scarce *Suaeda vera* Forsskål ex J.F. Gmelin could also be observed at the berms. The hydrophyte *Phragmites australis* (Cav.) Trin. ex Steud. invaded the drainage ditches.

Several pits 2 m deep were dug to study the soil profile and for soil sampling, following Schoenenberger et al. (2002). Electrical conductivity of the saturated paste extract (ECe) was determined in all soil samples, as well as the major ions concentration.

Mapping soil salinity at the experimental field was not considered necessary, since rice development did not show irregularities. The average soil salinity was estimated using electromagnetic induction (EMI) techniques. A hand-held EM38 sensor (Geonics Ltd., Mississauga, ON, Canada) was used at 101 points randomly distributed throughout the field, resulting in a density of 19 reading points per ha. At each point electromagnetic sensor readings were conducted in both the horizontal and vertical dipole orientations, and soil elevation was determined using a radiometric total station. The readings were corrected to the reference temperature of 25°C. After dividing them by 100 to facilitate the calibration equations, the two corrected readings were named EMh and EMv. Readings were converted to soil salinity by calibrating against ECe determined in the soil samples taken by auger at 0-25 cm and 25-50 cm depth at 16 locations immediately after each EMI reading. According to our experience in nearby locations (Herrero et al., 2003; Nogués et al., 2006) a simple linear regression was applied for calibration.

Inflow-outflow water quality

Water samples were collected at the inlet of paddy 1 (I1) and the outlet of paddy 6 (O6) during the three experimental seasons. In each season, between 37 and 46 samples of irrigation water and between 43 and 51 samples of surface runoff water were collected. The samples were analysed for electrical conductivity (at 25ºC, EC), pH, major anions (Cl^-, SO_4^{2-}-, HCO_3^-, CO_3^{2-}), major cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+), and nutrients (nitrate and ammonia).

Evapotranspiration estimation

An automatic agrometeorological station was installed in paddy 5 (Figure 1). This station recorded half hour averages of the following variables: air temperature and relative humidity using a Vaisala probe HMP45AC; net radiation using a NR-Lite (Kipp & Zonen) net radiometer; soil heat flux using two HFP01 (Hukseflux) plates buried at 0.08 m depth; soil temperature at 0.03-0.06 m depth just above the soil heat flux plates using a TCAV (Campbell Scientific) probe; wind speed using a cup anemometer (A100R, Vector Instruments); and wind direction using a wind vane (W200P, Vector Instruments). High-frequency air temperature was also recorded with three fine-wire (76 µm diameter) thermocouples (chromel-constantan, TCBR, Campbell Scientific). These thermocouples were installed at 0.65, 1.40 and 2.15 m above ground, but were moved up as the crop grew in order to keep the lowest measurement height about 0.5 m above crop canopy. The cup anemometer, wind vane and Vaisala probe were kept at the same height as the highest thermocouple. The net radiometer was installed on a separate mast at 1.5 m above ground.

Rice evapotranspiration for half-hour periods was determined by solving the energy balance equation:

$$LE = Rn - G - H \qquad (1)$$

where: LE, latent heat flux; Rn, net radiation; G, soil heat flux; and H, sensible heat flux. All terms in Eq. (1) are expressed in W m^{-2}. Once determined, LE values were converted to evapotranspiration by using the following equation:

$$ET = 1.8 \frac{LE}{\lambda} \qquad (2)$$

where: ET, evapotranspiration expressed in mm (30 $min)^{-1}$; λ is latent heat of vaporization (kJ kg^{-1}), computed from measured half-hour averages of air temperature as described elsewhere (Allen et al., 1998); and 1.8 is a unit conversion factor.

An additional term, the water heat storage, would have been included in Eq. (1) (Harazono et al., 1998). In this work, this term was neglected as irrigation water was permanently running over the paddy. In this situation changes in water temperature were mainly due to the convective transport heat by the running water rather than to the energy exchange between the surface and the atmosphere above it.

Soil heat flux at the soil surface was determined as follows (Allen et al., 1996):

$$G = \frac{F1 + F2}{2} + \frac{\Delta T_s}{\Delta t} \rho_b d_z (840 + 4190\Theta) \quad (3)$$

where: F1 and F2, soil heat flux measured by the two plates buried at 0.08 m depth (W m^{-2}); $\Delta T_s/\Delta t$ change in average soil temperature (°C) above the plates between two consecutive half-hour periods (thus, Δt = 1800 s); ρ_b, soil bulk density, 1,300 kg m^{-3}, as determined from soil samples; d_z, burying depth of the soil heat flux plates, 0.08 m; and Θ, volumetric soil water content.

Sensible heat flux (H) was determined by the surface renewal method. This method was selected because it has been reported as a low-cost, low-maintenance, accurate method for ET determination (Snyder et al., 1996; Spano et al., 1997). Therefore it is appropriate when measurements along the whole crop season at remote places are required. This method is based on the fact that traces of high-frequency temperature data show ramp-like structures resulting from turbulent coherent structures (Paw U et al., 1992). Two parameters characterize these temperature ramps for unstable and stable atmospheric conditions (Paw U et al., 1992, 1995): the amplitude (a) and the inverse ramp frequency (ls). The mean values of these two parameters during a time interval (for instance, half-hour) can be used to estimate H over a vegetated surface using surface renewal (SR) analysis (Paw U et al., 1995; Snyder et al., 1996):

$$H = \alpha \rho c_p \frac{a}{ls} z \quad (4)$$

where: ρ, moist air density (1.194 g m^{-3}); c_p, specific heat of air (1.013 J g^{-1} C^{-1}); z, measurement height (m); α, a factor to account the effects of uneven temporal heat distribution in the canopy air and advective effects (Paw U et al., 1995); α = 1.0 if the volume of air is heated evenly; measured values of α close to 1.0 have been reported when applying the surface renewal method over short canopies as long as measurements are taken well above crop canopy (Snyder et al., 1996; Spano et al., 1997); thus, a value of α = 1.0 was assumed in this paper. Three measurement heights were used for high-frequency air temperature readings in this work so three sets of H and corresponding ET values were computed through Eqs. (1), (2) and (4).

Snyder et al. (1996) and Spano et al. (1997) suggested use of the Van Atta (1977) approach to estimate the mean ramp characteristics used in Eq. (4). Thus, high-frequency temperature measurements were used to determine structure functions $S^n(r)$ for each half-hour period according to the expression:

$$S^n(r) = \frac{1}{m-j} \sum_{i=1+j}^{m} \left(T_i - T_{i-j}\right)^n \tag{5}$$

where: m, number of data points measured at a frequency f (Hz) within a t-minute interval; n, function exponent (n = 2, 3 and 5), see Eq. (6) below; j, sample lag between data points corresponding to a time lag r = j/f; and T_i, the ith temperature sample. In this work, t=30 min and f=0.25 s, thus m=7200; j=3; and r=0.75 s; values close to these have been reported as providing good results for short crops (Snyder et al., 1996; Spano et al., 1997; Zapata and Martínez-Cob, 2002).

The mean amplitude (a) for the 30-minute interval was estimated by solving the following equation for the real roots:

$$a^3 + \left[10S^2(r) - \frac{S^5(r)}{S^3(r)}\right] a + 10S^3(r) \quad = \quad 0 \tag{6}$$

Finally, the inverse ramp frequency ls was calculated by the expression:

$$ls = -\frac{a^3 r}{S^3(r)} \tag{7}$$

For a particular half-hour period and measurement height, the computed ls value was discarded if less than 5r (Snyder et al., 1996); in this case, H and LE estimates were not available. For a particular half-hour period, this problem rarely occurred simultaneously for the three measurement heights (only for 17 of 6,886 half-hour periods considered in this work). Because differences between LE estimates for the three measurement heights were small, as shown later, for a particular half-hour period, the average of the three LE estimates was computed in order to get a single LE estimate. The 17 unavailable data were estimated by linear interpolation between the two neighbouring half-hour periods.

Flow depth and discharge measurements

During the 2002 irrigation season, flow depth and discharge measurements were performed in a number of points of the experimental field in order to characterize the water balance. At the turnout of the irrigation ditch, a Cipolletti weir (Bos et al., 1984) was installed. Discharge measurements at this point are representative of point I1 (see Fig. 1). A V-shaped weir was installed at the field outlet, O6. Both weirs were instrumented with shaft encoder level sensors and data loggers (OTT GmbH & Co. Kempten, Germany). Both sensors produced continuous 30 min measurements of field inflow and outflow.

Flow depth was manually recorded in all six paddies with an approximate frequency of 4 days. The average of 17 soil surface elevation measurements per paddy were used to establish the average soil surface elevation of each paddy. At each paddy, a reference mark was established with an elevation equal to the average. All flow depth measurements were referenced to these marks. In addition to manual measurements, automatic measurements were performed at paddies 1 and 6. The previously reported shaft encoder level sensors were used for this purpose. Automatic flow depth measurements were taken every 30 min.

Measuring discharge between paddies was not an easy task. The critical-flow conditions required to install weirs or flumes were only satisfied in O3 and O5. Outflows O1, O2 and O4 used underground pipes, making it difficult to measure discharge in a continuous fashion. Additionally, measuring devices would interfere with the usual practices of the farmer, who continuously regulates these inter-paddy structures. As a consequence, no additional structures were built to measure discharge. A water balance method was used instead to estimate average discharge during certain time intervals.

During the 2003 season, flow depth measurements were performed at the *Albero Bajo* field and at a nearby rice field where the soil was saline-sodic. The new field was located in *Callén* (Huesca, Ebro valley, Spain). The coordinates of the *Callén* field were 42º00′04″N and 0º22′04″W. In this season, the purpose of flow depth measurements was to estimate soil infiltration. In both cases the procedure involved closing the inflow and outflow of a paddy in each field and recording the evolution of flow depth during the night time. Under the hypothesis that night evapotranspiration is negligible, the decrease in flow depth can only be attributed to infiltration. In *Albero Bajo*, the infiltration experiments were performed in the period June 9-12, and involved paddies 1, 5 and 6. The abovementioned automatic flow depth recording instruments were used as in 2002. In *Callén* the experiment was performed from July 9 to 14. Flow depth was measured using an automatic shaft encoder level sensor.

Water balance and irrigation performance

Water balance in the experimental field between times t_1 and t_2 can be expressed in terms of volume as:

$$\bar{I}(t_2 - t_1) + P\,A = ET\,A + DP\,A + \bar{O}(t_2 - t_1) + (S_2 - S_1)\,A \qquad [8]$$

Where A is the field area, $\bar{I}$ is average irrigation input discharge (determined at I1); P is precipitation; ET is evapotranspiration; DP is deep percolation rate; $\bar{O}$ is average surface runoff output discharge (determined at O6); and $S_2 - S_1$ represents the change in overland storage as determined from flow depth measurements. The equation was applied to the whole field between the manual flow depth measurements of May 13th and September 23rd, and solved for the deep percolation rate (mm d^{-1}). Since in paddy rice the soil is saturated, deep percolation is equivalent to infiltration.

The water balance Eq. 8 was then used to estimate discharge between paddies. For this purpose, the equation was written for paddy j between two successive manual flow depth measurements, 1 and 2. In this case, the infiltration rate was an input to the equation:

$$\overline{I_j}(t_2 - t_1) + P\,A_j = ET\,A_j + DP\,A + \overline{O_j}(t_2 - t_1) + (S_{j2} - S_{j1})\,A_j \qquad [9]$$

When equation 9 is successively applied to paddies 1 to 6 all intermediate average outflow discharges between times 1 and 2 can be estimated. The last outcome, $\overline{O_6}$, can be contrasted with the measured value of field outflow, thus resulting in an error estimate. The equation can be equally run backwards from paddy 6 to 1 to estimate all intermediate average inflow discharges. In this case, the final outcome, $\overline{I_1}$, can be compared with the field inflow and result in an error estimate. In this work the equation was solved in both directions, and the final discharge estimate for each paddy between two manual measurements was determined as the average of both forward and backward estimates.

Since there were 33 sets of flow depth recordings between May 13th and September 23rd, a series of 32 discharge estimates were obtained for each paddy. The average flow depth was determined for each paddy at each of the 32 time periods. Potential regressions were applied to each discharge - flow depth (h) data set to determine the seasonal discharge equations for each paddy:

$$Q = p_{ij}\ h^{q_{ij}} \qquad [10]$$

where p_{ij} and q_{ij} are the regression coefficients corresponding to discharge between paddies i and j. These regression equations represent the average conditions of each outflow throughout the 2002 season. It is important to stress that each of these equations do not represent the behaviour of a discharge structure at a point in time, but the "average" seasonal discharge law resulting from the frequent regulations performed by the farmer in the structure width, base elevation or opening.

Irrigation performance was estimated by the Irrigation efficiency (IE) term proposed by Burt et al. (1997), which can be expressed as:

$$IE = \frac{\text{Volume of Irrigation Water Beneficially Used}}{\text{Volume of Irrigation Water Applied - Storage of Irrigation Water}} \qquad [11]$$

The volume of irrigation water beneficially used was made equal to the volume of rice evapotranspiration.

Simulation model for paddy flow

A computer model was built to gain insight from the experimental results. The model simulates flow routing through the paddies using the previously discussed potential discharge equations. The model time step is adjustable: all required variables are linearly interpolated as needed. A time step of 30 min was used in all simulations in this work, in coincidence with the time step of variable input data. Model input includes field and paddy geometry, the time variation of irrigation inflow, ET and P, the infiltration rate and the parameters of the inter-paddy discharge equations. Model output includes the time variation of paddy flow depth and inter-paddy discharge, as well as all the terms of the water balance expressed in Eqs. 8 and 9 and the estimate of Irrigation Efficiency. The main simplifications used in the model are: a) soil surface elevation is considered constant inside each paddy, and microtopography does not affect the process of paddy filling and depleting; b) water movement in the paddies is slow, flow depth can be considered constant within a paddy, and water flow can be explained by mass conservation alone; and c) infiltration only occurs vertically and is not influenced by field boundaries.

During the simulated irrigation season, a paddy can eventually reach a zero flow depth. In such case, the model responds by maintaining evapotranspiration unchanged, and deducting this amount of water from deep percolation. It was assumed that the paddy water table was shallow enough to fulfil crop water requirements for a few days. This is not a valid hypothesis for long periods, in which the crop would suffer from water stress.

Six simulation scenarios were designed to evaluate alternative irrigation conditions. One of the simulation scenarios reproduced the experimental conditions, and served the purpose of model validation. The remaining five scenarios were based on different values of irrigation discharge and infiltration rate. Simulations were applied to the complete crop season (from flooding to physiological maturity).

Results and Discussion

Characteristics of the experimental soils

Most soil samples in the pits and auger holes had loam or silty-loam texture, with few coarse fragments of limestone. Calcium carbonate content was high in all samples, according to the strong reaction to hydrochloric acid at 10% concentration. No evidence of gypsum was found. A layer of massive structure occurred at a depth of 25 cm. This pan, about 15 cm thick, had signs of cycling between reduction and oxidation conditions, with prevalence of the first ones; few straw residues were found, however. Redoximorphic features did not occur in other layers of the studied profiles. In April 5, 2001, before the seasonal flooding, the water table was found at 190 cm in paddy 2 and at 110 cm in paddy 5. In some locations the densic pan underlied a C horizon made by land levelling works, and was lying on a buried A horizon. Our interpretation is that the densic layer results from repeated tillage of wet soil at the same depth. The addition of rice straw to the puddling seems limited, in contrast with other paddies in saline-sodic soils in depressed locations 1 km away from the experimental farm.

Sodicity and salinity must be considered to understand the soil behavior. The soils in the experimental field were moderately alkaline (pH < 8.5) and non-sodic, with SAR < 2 (Table 2), then chemical limitations to infiltration could be expected from the low salinity of the irrigation water but not from soil sodicity. The ECe determined in laboratory through the profiles was < 2 dS m^{-1}, except the Ap horizon. This upper horizon was more saline, with a median ECe value of 2.64 dS m^{-1} for 0-25 cm, and 3.72 dS m^{-1} for 25-50 cm in the samples taken at the 16 auger holes. Eleven of the 32 samples taken by auger surpassed the 4 dS m^{-1} threshold for saline soils, all these saline samples coming from the two lowest paddies. When ECe was computed for the 0-50 cm layer, the median was 3.16 dS m^{-1}. The distribution of the values of ECe determined in laboratory for the upper 50 cm of the soil along the paddies is shown with solid marks in Figure 2.

EMh and EMv were linearly correlated, with r = 0.990. Notwithstanding, the regression equations in Table 3 show that EMh (regression #1) performed better than EMv (regression #2) in predicting ECe, both in terms of R^2 and the standard error of the estimate. The parameters of the regression equations resulted very similar to those previously obtained in the conterminous area of Barbués (Nogués et al., 2006) and other close sites (Herrero et al., 2003). An exploratory data analysis of the distribution of EMh and EMv found two groups of values: one for the paddies 1 to 4 and the other for the paddies 5 and 6. These two lower paddies were much more saline than the rest, as confirmed by the laboratory measurements of ECe represented by solid marks in Figure 2.

In these circumstances, separate regressions were performed for paddies 1 to 4 (regressions #3 and #4) and for paddies 5 and 6 (regressions #5 and #6) (Table 3). EMv performed better for the upper paddies, while EMh was the best choice for the lower paddies. Therefore, we propose to use regressions #4 and #5 for the upper and lower paddies, respectively. The different performance of EMh and EMv calibration in the two groups of plots, as well as the low coefficients of determination and high standard errors in regressions #5 and #6 can be attributed to the shallower water table in the lower paddies. The ECe estimates, presented in Figure 2, showed a higher coefficient of variation (Table 1) in the most saline paddies. The high coefficient of variation for the entire experimental field (Table 1) was related with the differences in salinity between higher and lower paddies.

The 101 estimates of ECe were represented against soil elevation in Figure 2 using circles for the upper paddies and triangles for the lower paddies. These figures should not be interpreted in terms of the physiological effects of soil salinity on the rice crop because the rooting layer (about 0-25 cm) was less saline than the layer used for salinity estimation (0-50 cm), and because of the low salinity of the flood water.

The mean (4.17 dS m^{-1}) and median (3.16 dS m^{-1}) of ECe determined in laboratory for the 16 drilling points were in agreement with those calculated for the same points either by a single calibration (regression #1, with 4.17 and 3.49 dS m^{-1} respectively) or by separate calibrations (regressions #4 and #5, with 4.16 and 3.49 dS m^{-1} respectively). When the 101 EMI readings were taken into account, a mean of 2.25 dS m^{-1} and a median of 1.69 dS m^{-1} were obtained by single calibration, and a mean of 2.50 dS m^{-1} and a median of 1.96 dS m^{-1} by separate calibrations. These figures confirmed the mild salinity of the topsoil, whose mean of 2.50 dS m^{-1} is within the interval 2-4 dS m^{-1} for Very Slightly Saline soils (Schoenenberger et al. 2002), and agreed with the 1.94 dS m^{-1} measured at the water table.

Irrigation and runoff water quality

The chemical characterisation of irrigation and runoff water is presented in Table 4. Results were quite similar during the three years of study. This seems to be due to the stable, low mineral load of the irrigation water, which is transported from the Pyrenees through a network of mountain rivers and lowland canals. The years of continuous rice cultivation add stability to the chemical properties of the runoff water. Due to this time stability, average results from the three years of study will be discussed, with some references to particular years.

The irrigation water electrical conductivity averaged 0.24 dS m^{-1}, with an inter annual coefficient of variation of 22%. Runoff water averaged 0.37 dS m^{-1}. This increment in salinity (54%) was significant, and could be attributed to two processes: 1) the evapoconcentration of the irrigation water as it flows along the rice paddies; and 2) the interaction with the saline soil. The experimental data did not allow us to establish the relative importance of these processes. The salinity level of the runoff water was compatible with its reuse for irrigation according to the guidelines of FAO (Ayers and Wescot, 1984). In fact, this runoff water is currently mixed with drainage water and reused for irrigation in the same project area. During its course over the rice field, the pH of the water decreased from 8.2 to 7.5 (data from 2002), standing within the normal range of 6.5-8.4 for irrigation waters. Regarding the major water ions, important increases were seen in Cl^{-} (from 0.21 to 0.69 mmolc L^{-1}), and Na^{+} (from 0.28 to 0.88 mmolc L^{-1}). Sodium chloride could be partly responsible for the increase in electrical conductivity between irrigation and runoff water, agreeing with the presence of Na^{+} and Cl^{-} in the soil profile (Table 2). The increment in SO_4^{2-} was moderate, in coincidence with the absence of gypsum in the soil. The remaining ions did not show significant increases.

Both irrigation and runoff water are of good quality in terms of crop use (Ayers and Westcot, 1984). The load in nutrients is reasonable, in spite of the increase in both ammonia and nitrates. Their respective levels do not raise environmental concerns but contribute to the fertilization requirements of the crops that could be irrigated with this water.

Regarding infiltration, according to the EC and SAR of the irrigation water, slight to moderate use restrictions are expected. The runoff water falls in the class of no restrictions, due to its increase in EC. The expected decrease in soil infiltration rate produced by the irrigation water is not a problem, but an advantage for paddy rice.

Evapotranspiration estimation

The three sets of H values (one for each measurement height) provided slightly different estimates of half-hour sensible heat. However, the average differences between each other set of H values were low, -0.1 W m^{-2} between measurement heights 1 and 2, 1.1 W m^{-2} between measurement heights 1 and 3, and 1.2 W m^{-2} between measurement heights 2 and 3. The corresponding root mean square errors were 29.1, 40.1 and 29.1 W m^{-2}, respectively. Regarding LE estimates, the differences between measurement heights were similar, since the three sets of LE values were obtained from Eq. (1) using the same Rn and G values. In terms of water depth, those root mean square errors are equivalent to less than 0.03 mm (30 min)$^{-1}$. Therefore, the differences in LE between the three measurement heights could be assumed to be negligible (Figure 3).

Average rice evapotranspiration (ET) was 4.6 mm day^{-1} during May, and increased to 5.6 (June) and 6.4 mm day^{-1} (July) when the crop reached its maximum development; the average rice ET then decreased to 5.3 in August and 3.5 mm day^{-1} in September (Figure 4). The sharp decrease in ET during September was due to crop senescence, which substantially reduced crop water requirements. Considering the period from May 3 to September 23, total rice ET was 731 mm, a value similar to that of other summer cereal crops grown in the area. This is the case of corn, a crop with sowing and harvest dates similar to those of rice. Direct evaporation from the flooding water, particularly at the early crop stages, is partly responsible for the similarity between rice and corn seasonal ET.

Seasonal and daily rice ET values observed in this work were in general within the lower limits of the ET rates reported in previous works (Shih et al., 1982; Mikkelsen and DeDatta, 1991; Mohan and Arumugam, 1994; Harazono et al., 1998; Shah and Edling, 2000). Rice ET has been reported to have great variability due to different climatic conditions, management systems, rice varieties, etc. During the 2002 rice season air temperatures were lower and precipitation was higher than long-term averages (Figure 4). This was particularly true for July and August, so the atmospheric evaporative demand was lower than in average years.

Irrigation inflow and outflow

Inflow to the field was very variable, as presented in Figure 5. This is not a rare finding for a rice crop in the area. Water delivery in the irrigation district is based on an arranged demand schedule, in which the flow rate is limited by the capacity of the irrigation ditch, the irrigation duration is set to multiples of 24 hours, and the frequency is negotiated between the farmer and the district personnel. Very often a farmer completes irrigation before the end of the day and leaves the unused water in the irrigation ditch. As previously discussed, rice is grown at low geomorphic positions, which are also located at the end of the irrigation tertiary ditches. As a consequence, rice farmers are the last water users in their tertiary, and receive very fluctuating discharges. Rice farmers are useful to the irrigation districts, for it would not be easy to use these uneven flows in other crops.

Figure 5 presents a reconstruction of the flooding period inflow based on the water order filed by the farmer to the irrigation district. Two full days of water at a rate of 46.3 L s^{-1} (or 4,000 m^3 d^{-1}, in the local farmers' units) were applied. This discharge was out of the measuring range of the inflow weir. Therefore, water order data were used in the Figure instead of flow measurements. During the cropping season the inflow discharge equalled zero in a number of occasions. However, only one of these cases was planned by the farmer: between June 11 and 16 the inflow was cut and the field was completely emptied to apply herbicides. This is a common local practice known as *"la seca"* (the dryout).

The field outflow was much smaller than the inflow, showed smooth patterns, and responded to the peaks in inflow with a delay of 2-3 days. While the average post-flooding inflow was 7.5 L s^{-1}, the average post-flooding outflow was 1.5 L s^{-1}.

Flow levels in the paddies

The time evolution of flow depth in all six paddies is presented in Figure 6. Continuous data is presented for paddies 1 and 6 since the installation of the data loggers in May 24. Previous manual observations for these paddies are presented in dashed lines. The flow level in paddy 1 reflected the variability of inflow discharge, and was much more variable than flow level in paddy 6. Both paddies dried out during *la seca*: paddy 1 between June 16 and 17, and paddy 6 between June 16 and 19. It took five days for the paddies to dry out after shutting off inflow. During the rest of the season, flow depth in all paddies usually fluctuated between 0.06 and 0.14 m. This flow depth bracketed the optimum value of 0.09 m, which was identified by Anbumozhi et al. (1998) for the conditions of Japan in terms of paddy growth, production and water productivity. The *Albero Bajo* farmer expressed that his target was 0.10 m. This target was successfully obtained by a continuous regulation of the internal discharge structures. The farmer's expertise and the large flooded area resulted in a relatively stable water regime in the paddies despite the highly variable irrigation water supply flow rate.

Water balance, irrigation performance and infiltration estimation

Table 5 presents a seasonal field water balance. Input was dominated by irrigation: 1,874 mm. Seasonal precipitation was high for the location and period, but only represented 8% of the irrigation input. As for the output, evapotranspiration was second to deep percolation (731 and 830 mm, respectively). Surface runoff amounted to 372 mm, and finally storage resulted in 91 mm, which was the average final water depth in the paddies. Deep percolation, obtained by balance closure, resulted in an average infiltration rate of 5.8 mm d^{-1}.

Seasonal irrigation efficiency amounted to 41%. This figure compares well with the values reported by Tuong and Bhuiyan (1999), and is on the low side of the estimates provided by Clemmens and Dedrick (1994). A study performed by Lecina et al. (2007) on the 125,000 ha of the *Riegos del Alto Aragón* irrigation project, where the experimental field is located, concluded that the project wide irrigation efficiency for 2004 and 2004 averaged 78%. These results are similar to the findings by Hafeez et al. (2007) for rice in the Philippines.

The infiltration experiments performed in 2003 using isolated paddies are based on the hypothesis of negligible night time ET. The surface renewal night time ET estimations performed in June and July 2002 in *Albero Bajo* yielded an average of -0.19 mm d^{-1}. Since this estimated value was negative and small, it was considered negligible in the context of infiltration estimation. The infiltration experiments yielded the following results: 5.3 mm d^{-1} in *Albero Bajo* and 3.2 mm d^{-1} in *Callén*. Both sources of infiltration data for *Albero Bajo* were quite coincident. The figure obtained from the field water balance was retained because it was more time and space representative. Infiltration in the saline-sodic soil of *Callén* was much lower than in *Albero Bajo*, owing to its degraded structure and the underlying microlaminated sedimentary material. Both infiltration rates are on the low range of the values reported by Bouman et al. (1994) for a variety of rice soils and cultural practices. However, the infiltration rate of *Albero Bajo* constituted the largest sink of irrigation water, and effectively controlled irrigation performance.

Estimation of inter-paddy discharge equations

Figure 7 presents the derivation of parameters p and q in Eq. 10 for inter-paddy discharge. While in some cases potential fit was adequate (O1 and O6, with respective R^2 of 0.85 and 0.74), in other cases, such as O3 and O5, the regression model could not explain 25% of the variability in discharge. In the case of parameter q, the estimated values ranged from 0.94 to 3.2. As previously mentioned, outflow from paddy 6 was recorded using a V-shaped weir. However, the farmer used his own structure upstream from the weir to control outflow. Therefore, the equation for O6 corresponds to the farmer's structure. The low coefficients of determination of the discharge regressions can be attributed to the hydrological procedure used to derive pairs of observations of head and discharge, and particularly, to the frequent structure operations performed by the farmer to adjust paddy flow depth to his personal target.

Scenario definition and simulation results

The experimental results were used to build six simulation scenarios, characterized by their discharge (Q) and infiltration (Z). Regarding discharge, all scenarios implemented the flooding phase as designed by the farmer (8,000 m^3 applied in two days). For the post-flooding discharge, two variables were used: the discharge can either be high ("+", the experimental 7.5 L s^{-1}) or low ("-", 5.0 L s^{-1}); additionally, the discharge can be variable ("v", proportional to the experimental variability) or uniform ("u"). For infiltration there are two scenarios: high ("+", corresponding to *Albero Bajo*) and low ("-", corresponding to *Callén*).

Scenario QhvZh reproduces the experimental conditions, and was used to verify the model. This scenario yielded adequate predictions of all hydrological seasonal variables (Table 6). The simulated average flow depth in the experimental paddies was 0.094 m, which is compatible with flow depth measurements (Figure 6). Figure 8 presents scatter plots of observed and simulated semi hourly flow depth in paddies 1 and 6. The model successfully predicted flow depth in paddy 1, where most observations are grouped along the 1:1 line. Regarding paddy 6, the situation was very different. In fact, the observed flow depth in paddy 6 was usually in the narrow range of 0.10 and 0.15 m (Fig. 5). Flow depth surpassed this range in two occasions, and went down to zero during the dry out period (between June 17 and 20, in paddy 6). The simulated values for flow depth in paddy 6 showed similar features to field observations, but with significant time lags. For instance, the simulated dry out period in paddy 6 lasted from June 21 to 29 (data not presented). This difference resulted in a lack-of-fit to the 1:1 line in the low range of flow depth. Apparently, the farmer opened the inter paddy structures to accelerate dry out, weed control treatment and refilling. The procedure used in this work to estimate inter paddy discharge was not robust enough to derive time-dependent discharge coefficients for each paddy outflow. In any case, a large proportion of paddy 6 flow depth observations followed the 1:1 line.

The different simulation scenarios provided answers to irrigation management questions. The comparison between simulation results for Q+vZ+ and Q+vZ+ indicated that if the farm was located in a saline-sodic soil (low infiltration) and the rest of conditions was kept constant, the reduction in deep percolation would be compensated by an increase in surface runoff losses. In order to convey more overland flow, depth would increase from an average 0.094 m to 0.113 m (Table 6). As a result, efficiency would remain basically unchanged. Scenarios Q+cZ+ and Q+cZ- can be compared to their variable discharge parallels, to conclude that the use of highly variable irrigation water supply has very little impact on irrigation performance and on the hydrological balance. As a consequence, it can be stated that in this particular case rice irrigation does not pay a price for using a typical tail-end hydrograph. Of course this last sentence only considers the irrigation water use perspective. A number of agronomic traits could be affected by a strong variability in irrigation water input. The last two scenarios explored the reduction in post-flooding irrigation discharge. Simulation of Q-cZ+ resulted in extended dry periods for the downstream paddies. For instance, paddies 5 and 6 remained dry after mid June. As a consequence, reducing irrigation discharge was not a viable procedure to increase efficiency in the experimental farm. The water balance sinks were dominated by deep percolation, and reducing the moderate surface runoff losses induced risks of crop failure. Finally, scenario Q-cZ- showed that in saline-sodic soils (low infiltration), a low post-flooding irrigation discharge can be successfully used to boost irrigation efficiency to 60%. Even in these low-infiltration conditions, deep percolation losses constitute a major loss of water.

Conclusions

- In the experimental conditions surface runoff amounted to 18.3% of the seasonal water input (irrigation plus precipitation). The quality of surface runoff water was slightly deteriorated by rice cultivation, with a 0.13 dS m^{-1} (53%) increase in electrical conductivity. This could be explained by two processes: the evapoconcentration of the irrigation water and the uptake of soil sodium chloride during water flow along the paddies. The overall quality of surface runoff water was good enough for its reuse for irrigation without restrictions.
- A significant part of the irrigation input (41.0%) was lost to deep percolation. The complex interaction between the percolating water and the seasonal shallow water table typical of rice cultivated areas prevented us from evaluating the quality of deep percolation water in this work. The reported water balance indicates that the environmental sustainability of rice cultivation heavily depends on this issue.
- Current irrigation efficiency in the experimental field, 41%, is in line with previous findings for paddy rice. The seasonal consumptive water use (ET), 731 mm, was similar to that of other summer cereals grown in the area, like corn.
- Rice cultivation at the experimental farm does not allow substantial improvements in irrigation efficiency through the adjustment of discharge, as most losses are due to infiltration. Using a lower irrigation discharge would result in reduced runoff. However, flow depths would be smaller, and —besides possible agronomic effects— accurate land levelling and intense surveillance would be required to ensure that all parts of the fields were covered with water throughout the season. The improvement of irrigation efficiency in the experimental farm could be obtained by irrigation management techniques such as intermittent ponding or soil puddling.
- Simulations showed that irrigation performance did not substantially improve for a uniform post-flooding irrigation discharge (irrigation efficiency of 42%). Paddy rice cultivation was not affected by the variability of the inflow hydrograph. In the experimental area, where rice is generally cultivated in saline-sodic soils located at the low, downstream end of irrigation tertiary ditches, this is the only feasible crop. Its irrigation performance is not affected by the fluctuating irrigation discharge typical of a canal tail end.

- Simulated irrigation efficiency increased from 41% to 60% when infiltration was decreased from 5.8 to 3.2 mm day^{-1} and the post flooding irrigation discharge was reduced from 7.5 to 5.0 L s^{-1}. Saline-sodic soils can provide increased irrigation efficiency through the control of deep percolation losses. This control is achieved through saline-sodic soils inherent low infiltration, which is accentuated by soil puddling. Soil infiltration therefore is a major control variable to assess the suitability of a soil for paddy rice cultivation. A decrease in percolation losses from 832 to 459 mm, as shown here, will result in reduced water losses and a reduction in deep percolation pollutant loads, thus contributing to the sustainability of paddy rice cultivation in the conditions of the central Ebro valley of Spain.

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List of Tables

Table 1. *Main characteristics of the paddies: area (m²), average soil surface elevation (m, referenced to paddy 6), standard deviation of soil surface elevation (SDe, m), number of EMI readings, and statistics of the ECe 0-50 cm estimates.*

Paddy #	Area (m^2)	Elevation (m)	SDe (m)	EMI readings	ECe 0-50 cm estimates				
					Mean (dS m^{-1})	Median (dS m^{-1})	Min. (dS m^{-1})	Max. (dS m^{-1})	C.V. (%)
1	7,973	4.26	0.021	17	1.53	1.43	1.07	2.09	22.2
2	10,004	2.57	0.010	20	1.32	1.26	0.92	2.05	24.2
3	5,844	1.62	0.019	10	1.44	1.43	1.05	1.71	16.0
4	7,188	0.99	0.020	15	1.86	1.69	1.15	3.40	37.1
5	8,240	0.26	0.019	21	4.68	4.31	2.49	9.86	46.2
6	13,866	0.00	0.014	18	3.31	2.69	2.10	8.56	48.6
All	53,115	-	0.017	101	2.50	1.96	0.92	9.86	71.6

Table 2. *Saturation percentage (SP) and chemical characterization of the saturation extract from soil samples obtained from pit "Albero Bajo 4", described in 29/4/2001 in paddy 2. The soil was classified as a fine-loamy, mixed, calcareous, thermic, Typic Calcixerept (Soil Survey Staff, 1999).*

Depth (cm)	SP (%)	pH (-)	ECe (dSm^{-1})	Ca^{2+} ($mmolc\ L^{-1}$)	Mg^{2+} ($mmolc\ L^{-1}$)	Na^{+} ($mmolc\ L^{-1}$)	SAR ($(mmolc\ L^{-1})^{0,5}$)	CO_3H^- ($mmolc\ L^{-1}$)	SO_4^{2-} ($mmolc\ L^{-1}$)	Cl^- ($mmolc\ L^{-1}$)	NO_3^- ($mmolc\ L^{-1}$)
0-20	36	8.27	1.20	9.10	1.77	1.47	0.6	3.0	7.96	1.90	0.04
20-40	33	8.38	0.60	3.32	1.15	1.23	0.8	2.2	1.41	0.92	1.41
40-60	34	8.35	0.47	1.85	1.00	1.21	1.0	1.6	1.41	0.92	1.41
60-80	30	8.43	0.53	2.41	1.16	1.43	1.1	1.6	2.43	1.01	0.04
80-100	29	8.37	0.58	2.22	1.18	1.73	1.3	1.8	2.75	1.17	0.26
100-120	31	8.24	0.65	4.55	2.76	3.49	1.8	1.4	3.28	1.25	2.63
120-140	31	8.27	0.66	1.81	1.17	2.19	1.8	1.6	3.20	1.44	0.41
140-160	32	8.33	0.65	1.72	1.21	2.29	1.9	1.8	3.04	1.47	0,47

Table 3. Simple linear regressions of ECe (dS m^{-1}) determined in the laboratory in soil samples from 0 to 50 cm depth taken at 16 drilling points, on the EMI readings (EMh or EMv) in these points. Regression parameters are accompanied by the coefficient of determination, R^2 (%), and the standard error of the estimate, S.

Paddies	EMI reading	Regression #	ECe = a + b EMI *a (dS m^{-1})	**b (-)	R^2 (%)	S (dS m^{-1})
All	EMh	1	-0.043	3.67 (0.53)	77.6	1.50
	EMv	2	-0.121	3.01 (0.54)	68.7	1.78
1 to 4	EMh	3	0.602	2.15 (0.44)	79.9	0.46
	EMv	4	0.632	1.59 (0.31)	81.3	0.44
5 and 6	EMh	5	0.933	3.31 (1.07)	61.6	2.03
	EMv	6	1.113	2.65 (1.13)	47.9	2.37

(*) these values do not differ from 0 significantly (P = 0.05);
(**) the standard error of b is in parenthesis.

Table 4. *Chemical characterization of the irrigation and runoff water in the set of rice paddies for the years 2001, 2002 and 2003, and for the average of the three years. Number of samples (n), mean and coefficient of variation (CV, %) are provided for electrical conductivity, pH and for the concentration of ions and nutrients. The table also includes the Na^{+}/ Ca^{2+} ratio and the Sodium Adsorption Ratio (SAR).*

Year			2001		2002		2003		2001-2003	
Kind of water			Irrigation	Runoff	Irrigation	Runoff	Irrigation	Runoff	Irrigation	Runoff
Electrical conductivity (EC, $dS\ m^{-1}$)		n	8	14	11	12	18	17	37	43
		Mean	0.26	0.33	0.27	0.5	0.18	0.29	0.24	0.37
		CV	13	16	9	26	43	50	22	31
pH		n	0	0	11	12	0	0	11	12
		Mean	-	-	8.2	7.5	-	-	8.2	7.5
		CV	-	-	2	2	-	-	2	2
Major anions* ($mmolc\ L^{-1}$)	Cl^{-}	n	8	14	20	20	18	17	46	51
		Mean	0.26	0.61	0.12	0.67	0.24	0.78	0.21	0.69
		CV	40	39	71	114	73	76	61	76
	SO_4^{2-}	n	8	14	20	20	18	17	46	51
		Mean	0.57	0.61	0.31	0.41	0.46	0.56	0.45	0.53
		CV	11	40	63	123	42	79	39	81
	HCO_3^{-}	n	8	14	20	20	18	17	18	17
		Mean	ip	ip	ip	ip	1.27	1.63	1.27	1.63
		CV	-	-	-	-	58	78	58	78
Major cations ($mmolc\ L^{-1}$)	Ca^{2+}	n	8	14	16	17	18	17	42	48
		Mean	1.16	1.09	0.75	0.99	0.83	1.03	0.91	1.04
		CV	7	31	64	74	77	96	49	67
	Mg^{2+}	n	8	14	14	18	18	17	40	49
		Mean	0.58	0.78	0.39	0.61	0.67	0.78	0.55	0.72
		CV	14	15	36	65	42	41	31	40
	Na^{+}	n	8	14	16	19	18	17	42	50
		Mean	0.30	0.72	0.18	0.96	0.35	0.97	0.28	0.88
		CV	40	39	34	88	65	59	46	62
	K^{+}	n	8	14	20	20	18	17	46	51
		Mean	0.06	0.06	0.03	0.03	0.06	0.13	0.05	0.07
		CV	37	47	55	72	70	81	54	67
Na^{+}/ Ca^{2+} ratio			0.26	0.66	0.24	0.97	0.43	0.93	0.30	0.85
SAR from the above means of Na^{+}, Ca^{2+} and Mg^{2+}			0.3	0.7	0.2	1.1	0.4	1.0	0.3	0.9
Nutrients ($mg\ L^{-1}$)	NO_3^{-}	n	5	3	5	1	5	0	15	4
		Mean	0.3	3.6	0.1	1.1	3.4	-	1.27	2.35
		CV	46	131	51	0	55	-	51	66
	NH_4^{+}	n	0	2	15	6	7	6	22	14
		Mean	-	3.1	0.2	0.5	0.4	0.9	0.3	1.5
		CV	-	6	45	79	35	95	40	60

(*) CO_3^{2-} was inappreciable (concentration below the detection threshold of the laboratory equipment) in all samples.

(ip) Inappreciable.

Table 5. *Elements of crop water balance in the set of paddies as measured in 2002. Water balances were established from flooding to physiological maturity (from May 3 to September 23).*

		Volume (m^3)	Depth (mm)	Volume or Depth (%)
Input	Irrigation	99,516	1,874	92.6
	Precipitation	7,973	150	7.4
	Total input	107,488	2,024	100.0
Output	Evapotranspiration	38,820	731	36.1
	Deep percolation	44,080	830	41.0
	Overland storage	4,818	91	4.5
	Runoff	19,771	372	18.4
	Total output	107,488	2,024	100.0

Table 6. *Hydrologic characterisation and irrigation performance observed in 2002 and simulated with the model. The flooding volume, applied during two days before sowing, was the same in all cases (8,000 m^3). Simulations were performed between flooding and physiological maturity. Simulated and observed post-flooding average discharges refer to the period May 5 to September 23. The post-flooding simulated discharge may be constant or variable. Variable discharge was equal to the observed discharge. Uniform discharge was kept constant after flooding.*

	Variable	Observed	Simulation Scenario					
			Q+vZ+	Q+vZ-	Q+cZ+	Q+cZ-	Q-cZ+	Q-cZ-
Scenario definition	Post-flooding average Irrigation discharge (L s^{-1})	7.5	7.5	7.5	7.5	7.5	5.0	5.0
	Infiltration rate (mm d^{-1})	5.8	5.8	3.2	5.8	3.2	5.8	3.2
Hydrological balance	Irrigation (mm)	1,874	1,874	1,874	1,877	1,877	1,301	1,301
	Deep percolation (mm)	830	832	459	832	459	624	459
	Final overland storage (mm)	91	101	117	115	131	0	82
	Runoff (mm)	372	360	717	349	705	97	179
Irrigation efficiency (%)		41	41	42	41	42	56	60
Average simulated flow depth (m)		-	0.094	0.113	0.096	0.115	0.050	0.062

List of Figures

Figure 1. *Set up of the field experiment, showing the location of the six paddies, the irrigation ditch and the open drain, the irrigation water course, the agrometeorological station and the inflows and outflows of each paddy (for paddy i, Ii and Oi, respectively).*

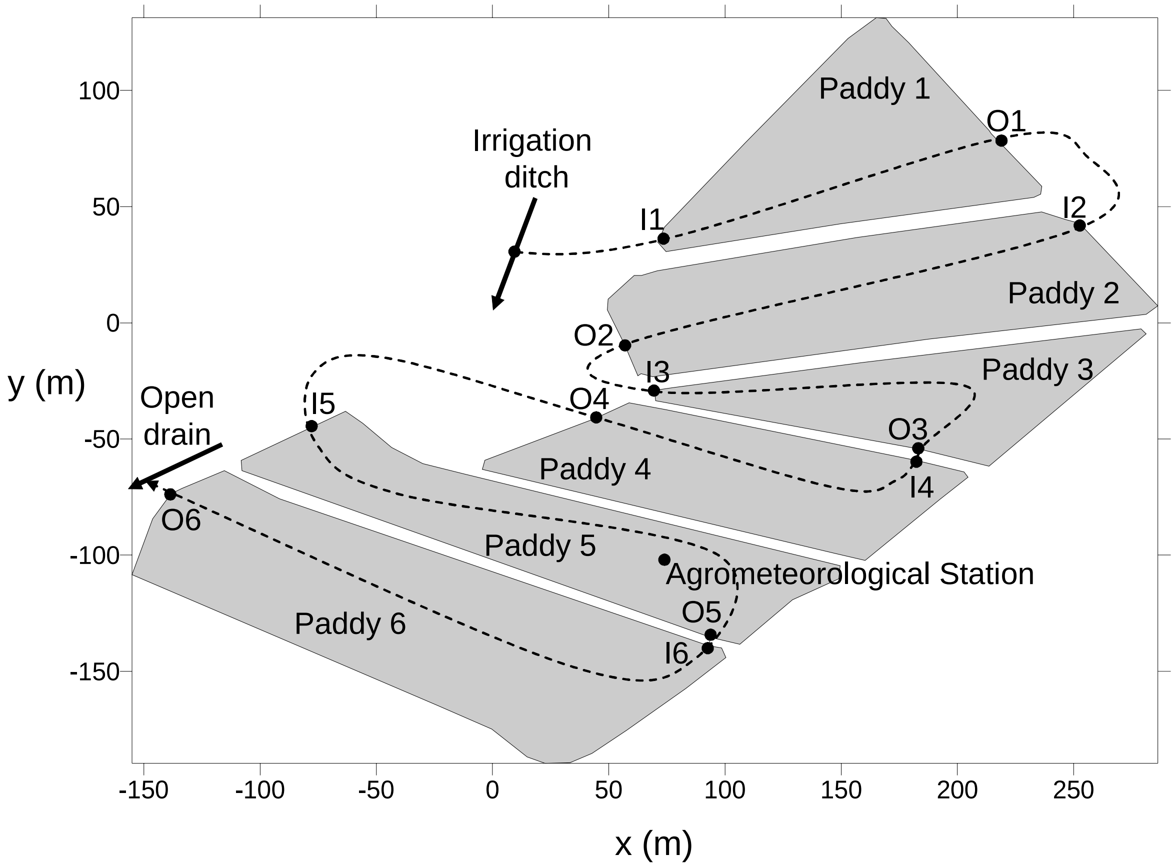


Figure 2. *Estimates of ECe from 0 to 50 cm in the 101 EMI reading points (open marks) and laboratory measured ECe up to the same depth in 16 of these points (solid marks), against their relative elevation. Calibration in paddies 1 to 4 (circles) was performed with regression #4, and in paddies 5 and 6 (triangles) with regression #5 (see Table 2).*

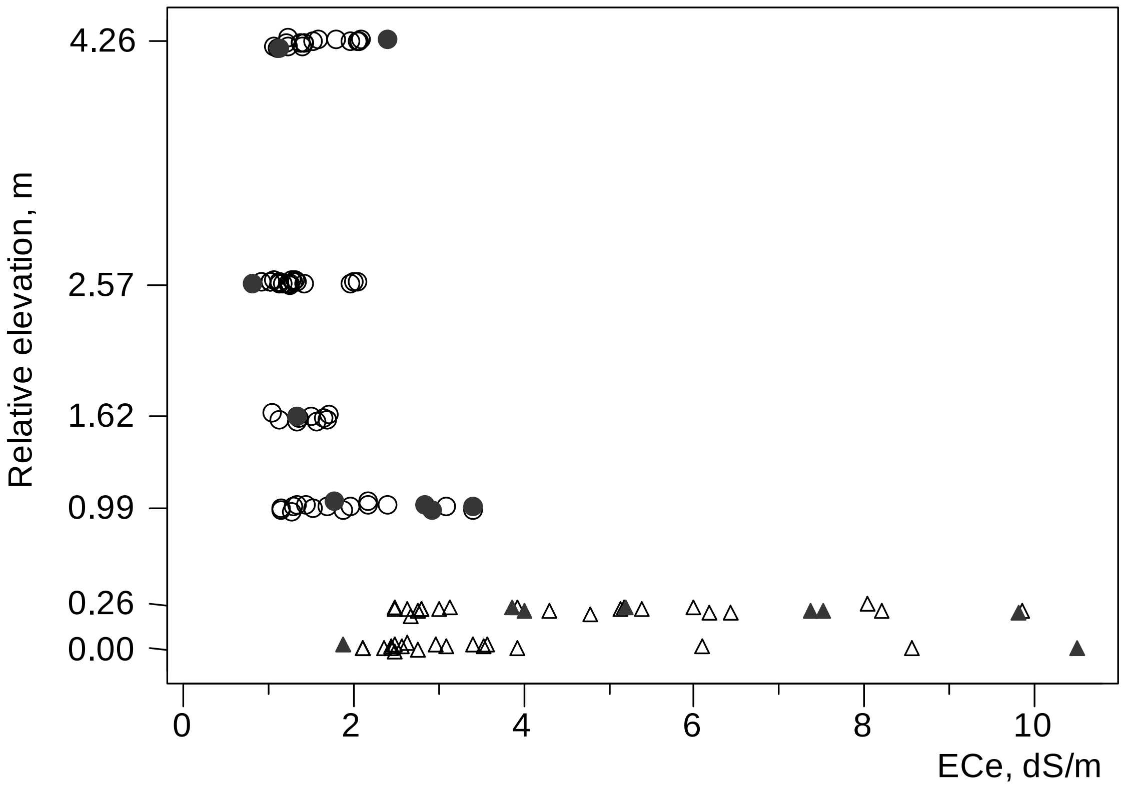


Figure 3. *Half-hour LE estimates obtained for measurement height 1 (0.5 m above crop canopy, x-axis) versus half-hour LE estimates obtained for measurement heights 2 and 3 (0.75 and 1.5 m above measurement height 1, respectively) (y-axis).*

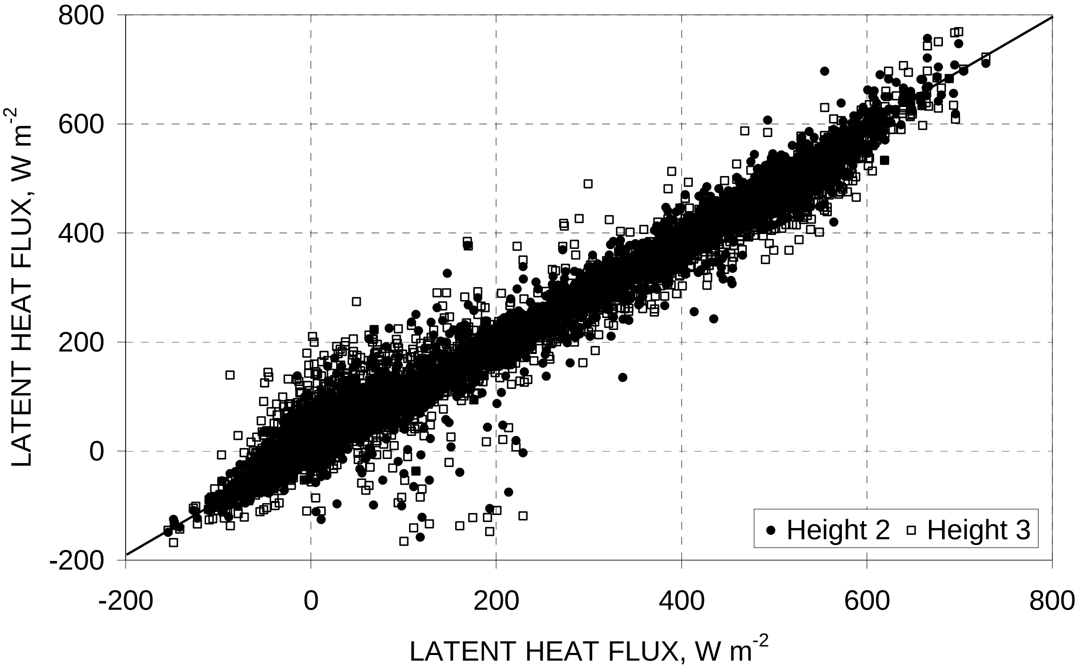


Figure 4. *Seasonal evolution of crop evapotranspiration estimates and precipitation measurements.*

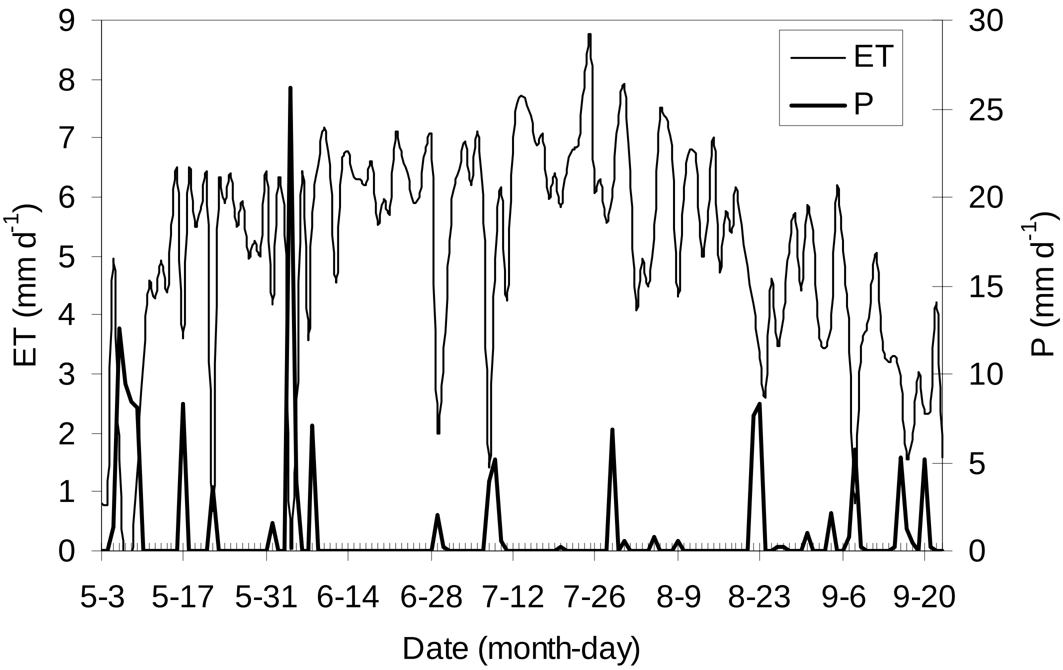


Figure 5. *Seasonal evolution of field irrigation inflow (I1) and runoff (O6). The inflow during May 5 and 6 served the purpose of flooding the field. Since the discharge was out of the range of the measuring device, its value was taken from the farmer water order to the irrigation district.*

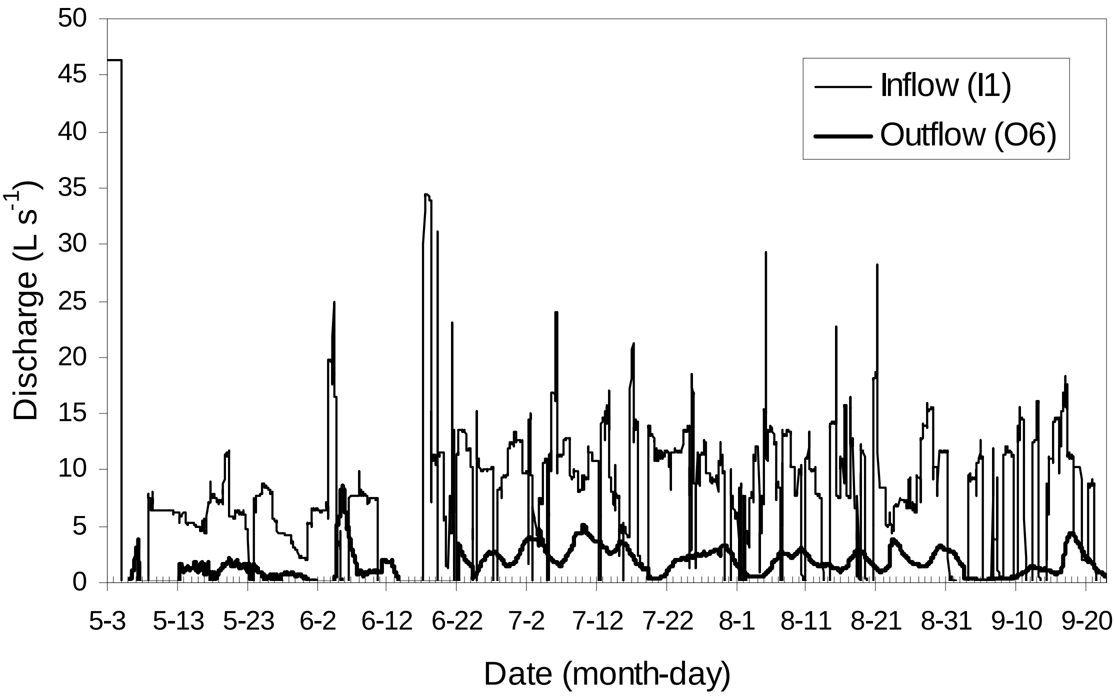


Figure 6. *Seasonal evolution of measured flow depth in the paddies. Flow depth was automatically measured every 30 min in paddies 1 and 6 and manually measured in paddies 2, 3, 4 and 5. Automatic recording started in May 24. Previous values for paddies 1 and 6 were manually measured (dashed line).*

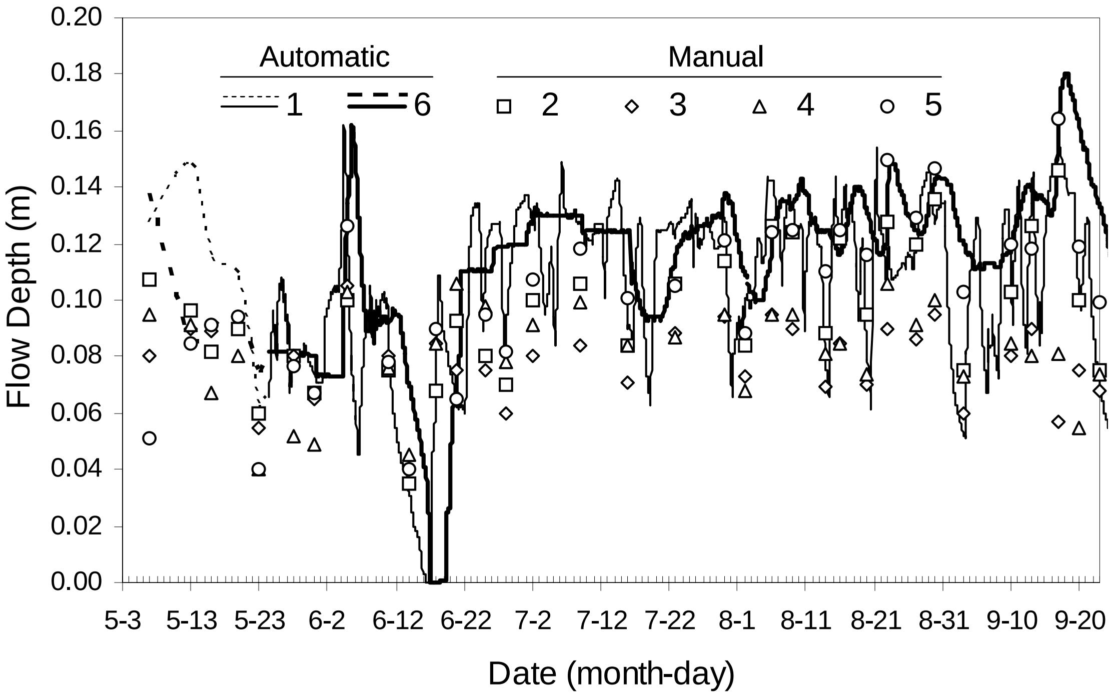


Figure 7. *Inter-paddy seasonal flow depth-discharge relationships. Scatter plots, potential regression lines, regression equations and coefficients of determination are presented for outflows from paddies 1 to 6.*

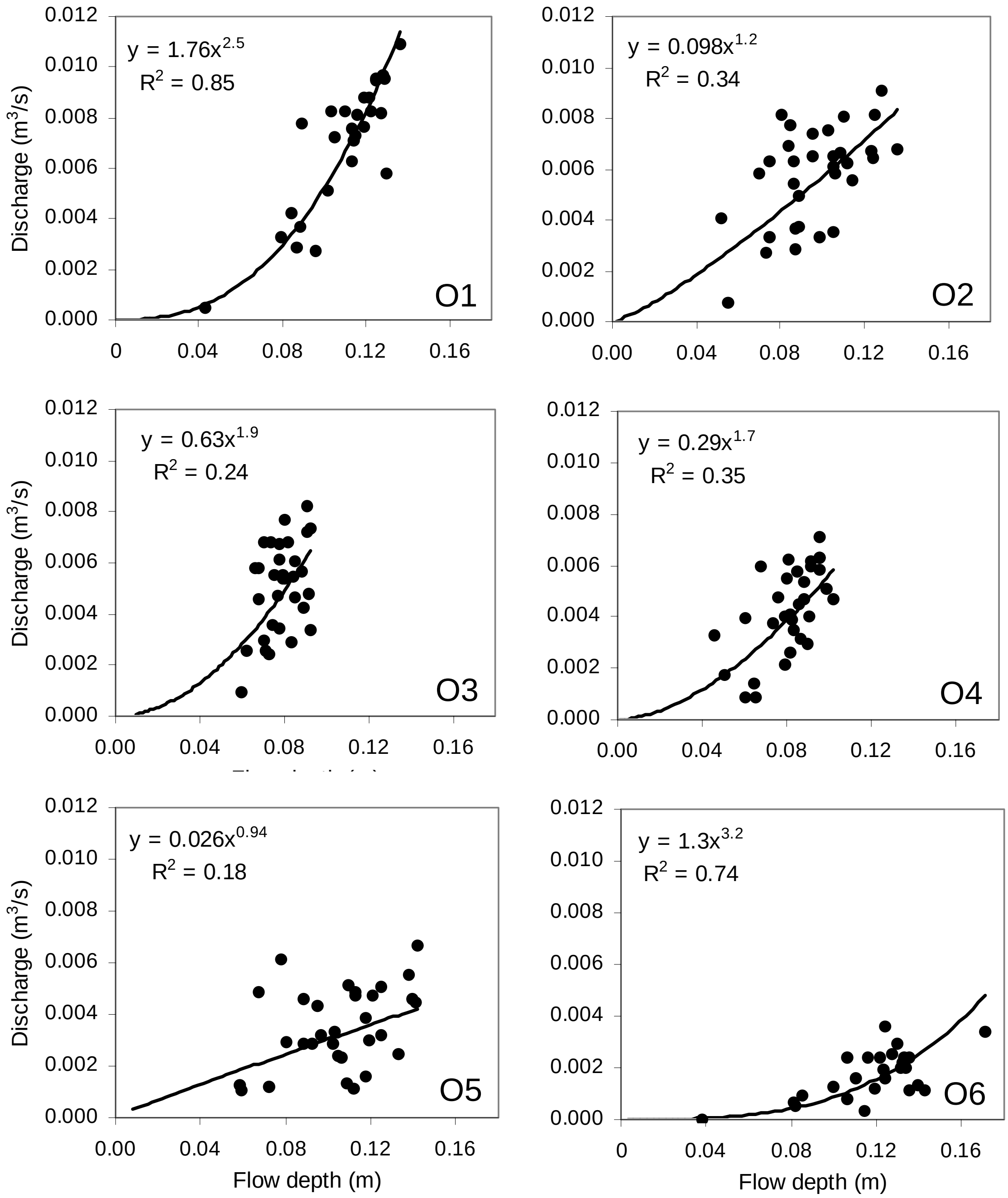
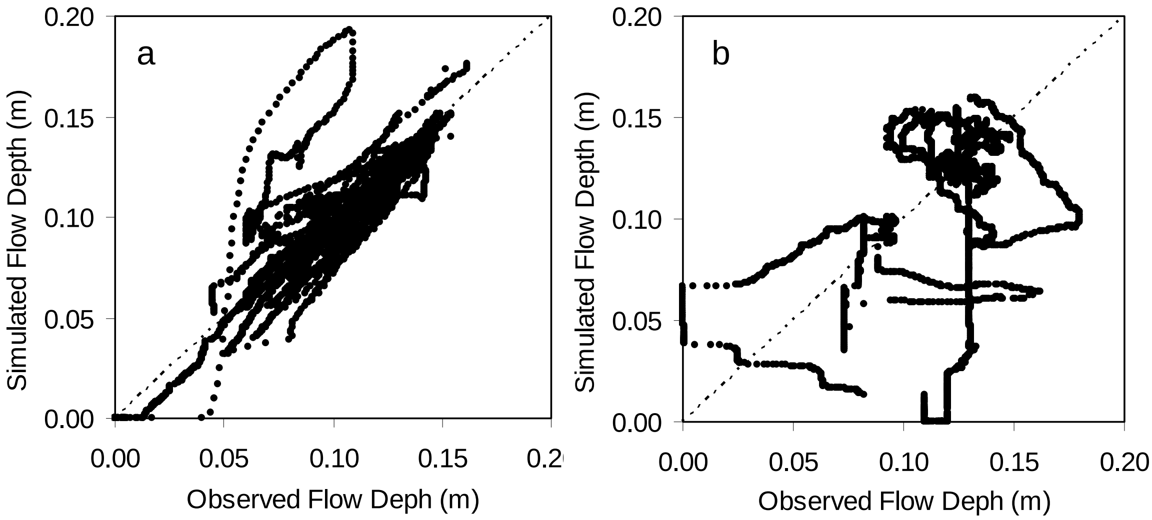


Figure 8. *Observed vs. simulated values of flow depth in paddies 1 (a) and 6 (b).*



890 **Figure 9**. *Time evolution of flow depth in Paddy 3 as observed and as simulated for scenarios*
891 *Q+vZ+,Q+vZ-, Q+cZ+ and Q-cZ-.*

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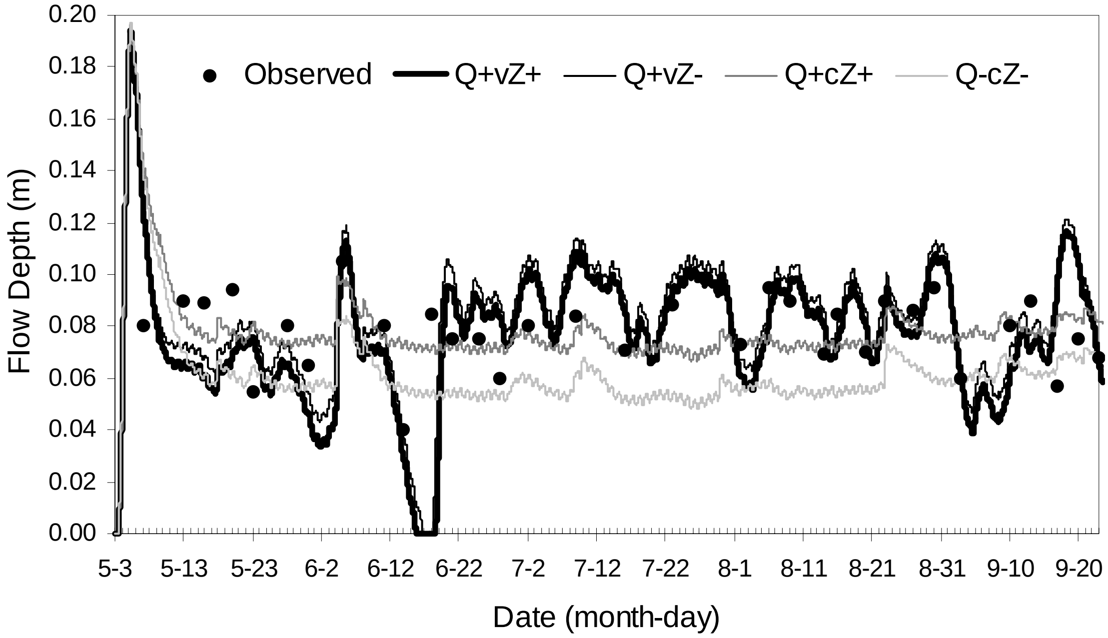

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