Elevation and infiltration in a level-basin:

II. Impact on soil water and corn yield.

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Abstract

The spatial variability of irrigation water recharge and crop yield is affected by a number of factors. Soil surface elevation, infiltration and soil water management allowable depletion are the most relevant related to level basin irrigation. Measurements of soil water recharge (using a neutron probe) were compared to estimates based on ring infiltrometers and observations of the opportunity time. Estimates of cumulative infiltration were obtained separating the variability of infiltration and opportunity time (largely determined by elevation). Soil surface elevation was correlated with measured recharge, grain yield and total dry matter. A correlation was found between infiltration and the measurements of water recharge. While soil surface elevation can be regarded as a management variable, little can be done to reduce the variability of infiltration. Distribution uniformities from estimated cumulative infiltration were about 20% higher than those obtained from measurements of water recharge. Seasonal uniformity was

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only marginally higher than average uniformity, confirming the low random component of water recharge in level basin irrigation. Deep percolation resulted more intense in areas with low management allowable depletion, emphasizing the relevance of the characterization the variability of soil physical properties (mainly soil depth) in surface irrigation. Extrapolation of the results of this research to field scale irrigation basins should take into account the methodology used: in particular, the reduced scale of the experimental level basin.

Introduction

This paper takes on the results of a companion paper in which the soil of the experimental basin was physically characterized (Zapata and Playán 1999). The values of infiltration and soil surface elevation are used in this work to estimate irrigation cumulative infiltration. The purposes of this paper are: First, to include, separately and jointly, the variability of these two variables in the estimation of cumulative infiltration, creating three different variables; Second, to evaluate separately their impact on measured water recharge (irrigation water stored in the soil) and irrigation uniformity; And third, to quantify the influence of the spatial variability of estimated cumulative infiltration and soil water recharge on crop water stress and corn yield. The joint characterization of the variability of soil surface elevation and infiltration in level basin irrigation during an irrigation season has not been attempted before and constitutes a step forward in the analysis of surface irrigation performance.

The spatial variability of crop yield and water stress has been addressed in several works dealing with surface irrigation. Warrick and Gardner (1983), working on crop yield as affected by spatial variations of soil and irrigation, concluded that irrigation uniformity is the most important factor, especially for surface systems. Hunsaker and Bucks (1987) reporting on soil variability effects on irrigated wheat yields, concluded that the variability in soil texture was responsible for up to 37% of the variability in yield, depending on the irrigation treatment. Sousa et al. (1995) used irrigation and crop models to analyze the impact of the accuracy of laser controlled leveling in furrow irrigation systems. They concluded that unlevelness decreases water distribution uniformity and can result in yield decreases of up to two-thirds of the potential value.

Materials and methods

The experiment was located at the SIA experimental farm in Zaragoza, Spain. A small level-basin (27 by 27 m) constituted the experimental plot. The sampling points for all variables are presented in Fig. 1 of the companion paper (Zapata and Playán 1999). The materials and methods used in this research, as they differ from the methods presented in the companion paper, are presented in the following paragraphs.

Estimation of soil cumulative infiltration

Soil water infiltrated due to irrigation was estimated using infiltration measurements and the opportunity time. Estimated cumulative infiltration (ECI) is therefore a variable of space and time. Cumulative infiltration was estimated at the 81 points of the 3 m x 3 m network starting at the point with coordinates (1.5 m, 1.5 m).

Infiltration was measured twice during the season using 81 single infiltrometer rings. Individual infiltration curves were fitted to each ring data using a Kostiakov equation and the corresponding adjustment coefficient (Merriam and Keller 1978). This procedure was used for irrigations 2 and 5, in which an infiltration experiment was performed. For irrigations 3 and 4 ECI was computed twice at each location, first using the infiltration parameters corresponding to the first infiltration experiment, and then using the infiltration parameters corresponding to the second infiltration experiment. For a given irrigation, from the two sets ECI values, the set showing the best correlation with the neutron probe measured water recharge (MWR) was adopted.

In a given irrigation, ECI has been considered to be governed by two sources of spatial variability: the parameters of the Kostiakov equation and the opportunity time. To characterize their influence separately, two additional variables were defined: the estimated cumulative infiltration without spatial variability of infiltration, ECI-I, and the estimated cumulative infiltration without spatial variability of opportunity time, ECI-τ.

ECI-I was computed at each location using an adjusted, spatially-averaged set of Kostiakov parameters and the local opportunity times. This Kostiakov equation was obtained by regression using data from all infiltrometers simultaneously, and adjusted to match the average opportunity time with the average infiltrated depth:

$$ECI\text{-}I_i = \overline{k_{adj}}\,\tau_i^{\bar{a}} \qquad [1]$$

where $\overline{k}_{adj}$ and $\overline{a}$ are the parameters of the adjusted, spatially-averaged Kostiakov equation and *i* is an index variable for the 81 data points.

ECI-τ was computed at each location using the spatially averaged opportunity time ($\overline{\tau}$) and the local Kostiakov parameters:

$$ECI\text{-}\tau_i = k_{adj_i}\,\overline{\tau}^{a_i} \qquad [2]$$

Throughout the paper, reference to ECI-τ will be used as an estimation of cumulative infiltration without consideration of the spatial variability of soil surface elevation. This is due to the fact that opportunity time is very dependent on the surface relief : advance is strongly dictated by elevation (see the advance maps presented in the companion paper), and recession is completely governed by it.

Measurement of soil water recharge

Neutron scattering (Hanks 1992) was used to measure the volumetric water content of the soil. The principal advantages of this technique are that it is rapid, non destructive and allows for periodically repeatable measurements at the same location and depth. Among its drawbacks, one of the most relevant is the difficulty to measure accurately at the soil surface.

A total of 64 neutron probe access tubes were installed to a depth of 1.20 m (where possible). The access tubes formed a 3 m by 3 m regular network starting at the point with coordinates (3 m, 3 m) (see Fig 1 in Zapata and Playán 1999). Within each access tube the water content was measured at a depth of 0.15 m to represent the upper

0.3 m of the soil profile. The water content at subjacent layers was measured with an interval of 0.2 m. Soil water was determined the day prior to and the day immediately following each irrigation. Following harvesting, a calibration curve was developed for this soil using data from 15 randomly chosen points. This curve was used to convert all readings to volumetric water contents. A drawback of using a single calibration curve for all the experimental field is that the spatial variability of the soil water content due to the variability in bulk density was masked.

MWR was computed from neutron probe readings by subtracting the water contents after and before irrigation. Only in the first 0.5 m of the soil layer a significant change in water content due to irrigation was observed. One of the goals of this research is to compare MWR with the different ECI's using correlation analyses. When establishing these comparisons, it has to be noted that both variables represent slightly different concepts. MWR only accounts for the irrigation water retained by the soil matrix and once it has had some time to redistribute vertically and horizontally. Therefore, MWR does not account for the evapotranspiration between neutron probe readings and for the deep percolation losses. The magnitude of both effects was controlled by the short period between neutron probe readings and by the relatively light water application depths, respectively.

The networks for estimated cumulative infiltration and measured water recharge were offset by 1.5 m in each axis. This offset was intended to avoid interaction between the infiltration and soil water measurement procedures. To permit comparison between MWR and ECI, geostatistical techniques were used. Once a semivariogram was validated for MWR, kriging was used to estimate the value of MWR at the locations where a value of ECI was available. The variability in MWR was somewhat reduced by this process, and some error was introduced by the interpolation procedure. One of the advantages of using kriging among all the available interpolation techniques is that the magnitude of the error is minimized and known. The kriging obtained values of MWR were only used for correlation analysis.

Distribution Uniformity

Distribution Uniformity, DU (%), was computed for each irrigation event and for the whole season. The seasonal DU was compared with the average DU at each individual irrigation event. The definition of Distribution Uniformity used in this work is the one proposed by Burt et al. (1997). The ratio of the two average depths, one based on the extreme values (low quarter) and the other based on all values, was computed for the estimated cumulative infiltration (ECI, ECI-I and ECI-τ) and for the measured water recharge (MWR).

Crop growth, water stress and yield

A short cycle corn (*Zea mays* L. cv. “Clarissia”) was cultivated in the experimental plot. The crop was carefully monitored in order to reveal the relationships between soil water and crop yield. The measured crop parameters included crop height, grain yield, total aerial dry matter and a crop water stress index. Crop height (CH) was measured as the distance between the soil surface and the insertion of the last leaf of the plant. CH was measured at harvest, on three plants randomly chosen in the vicinity of each of the sampling points. The crop water stress index (SI) was based on leaf rolling, measured as the ratio between the projected width of the rolled leaf and the extended width. The index was determined on the third uppermost extended leave at solar midday (Begg 1980). The water stress index was determined on the same plants used for plant height measurement. The SI determinations were performed in July 25, before irrigation 4, somewhat during the grain filling stage. Irrigation 4 was slightly delayed to induce crop water stress beyond the usual limit and therefore obtain higher variability in the stress index and in the yield parameters.

The crop yield parameters studied were corn grain yield at a moisture content of 14 % (GY) and total aerial dry matter (TDM). The aerial parts of the plants of a subplot of 1.5 m by 1.5 m surrounding each sampling point were hand harvested. The ears were separated from the rest of the plants. The remaining fresh aerial matter, stalks and leaves, were weighted and a subsample of two plants per subplot was oven dried to measure moisture content. The ears were oven dried to constant weight at 60ºC. At this point moisture was measured and the resulting weight was adjusted to represent a moisture content of 14 %. The grain was separated from the corncob to obtain the grain weigh per squared meter at each sampling point. The harvest index (HI) was computed as the ratio between grain weight and total aerial dried matter weight.

Classic statistic and geostatistical analyses were applied to the characterization of the spatial variability of estimated cumulative infiltration, soil water recharge and crop yield parameters. In addition, cross-correlation analyses were used to obtain relationships between ECI, MWR and crop yield parameters. The cross-correlation function, expressing the correlation between two variables as a function of the distance separating the observations, has proven useful to find quantitative relationships between crop yield and soil properties (Stein et al. 1997).

Results and discussion

Opportunity time

Table 1 presents the descriptive statistics and the parameters of the semivariograms corresponding to the opportunity time (τ) for the five irrigation events. Irrigation 3 showed the highest average τ and its standard deviation almost doubles the rest of the irrigations. A spherical theoretical semivariogram could be successfully fitted in all cases (Fig. 1). The sill of the semivariogram of irrigation 3 had a value of 89,000 min^2, more than double of the rest of the irrigations. Except in the pre-planting irrigation ($\tau 1$, with a range of 10 m), the semivariograms are characterized by a zero nugget and ranges in the vicinity of 4-6 m. This range is very similar to the range obtained for soil surface elevation (Zapata and Playán 1999). In fact, the correlations between soil surface elevation at every survey and opportunity time at each irrigation event are high and significant (Table 2). The pre-planting irrigation ($\tau 1$) was better explained by survey 1, ($r = -0.416$***). The rest of the irrigation events, 2 to 5, had higher correlation with survey 2 (-0.540*** $> r > -0.628$***). The correlation analyses between the opportunity times corresponding to all irrigations (data not shown) reveal a high consistency in time for the spatial structure of the opportunity time. This can be explained by the dependence of τ on soil surface elevation, and by the high correlation among the three soil surface elevation surveys.

Estimated cumulative infiltration

Cumulative infiltration for irrigations 3 and 4 was estimated using infiltration experiment 1. The values of the adjustment scaling factor α (Zapata and Playán 1999) were 2.258 and 1.679, respectively. Table 3 summarizes the estimates of cumulative infiltration. The CV for ECI was very similar for irrigations 2, 3 and 4 (around 18%), while the CV for ECI in irrigation 5 was doubled, 36%. This is due to the fact that irrigation 5 was explained by infiltration experiment 2, and this experiment showed a higher spatial variability.

No spatial structure was found for estimated cumulative infiltration in any irrigation. A correlation analysis was performed to assess the time variability (for irrigations 2 to 5) of the three estimates of cumulative infiltration. Better correlation was found between irrigations explained with the same infiltration experiment, varying from 0.853*** to 0.926*** for ECI, from 0.612*** to 0.710*** for ECI-I and from 0.987*** to 0.997*** for ECI-τ. The correlation between irrigations explained by different infiltration experiments ranged from 0.350** to 0.401** for ECI, from 0.482*** to 0.739*** for ECI-I and from 0.317* to 0.321* for ECI-τ.

To analyze separately the influence of infiltration and opportunity time on the spatial variability of ECI, correlations between ECI, ECI-I and ECI-τ were computed. The high correlation between ECI and ECI-τ (varying from 0.731*** to 0.973***) showed that the spatial variability of infiltration was the principal variable affecting ECI. The slight and, in times not significant, correlation between ECI and ECI-I evidenced the low influence of the spatial variability of opportunity time on ECI. When the value of Kostiakov a is low (as in this case, with an average of 0.295), the long term infiltration rate is very small, and therefore τ does not control cumulative infiltration.

Measurements of soil water recharge.

Means, standard deviations and CV's of MWR are presented in table 3. The CV's are large and present a decrease in time that can be explained by seal formation and a reduction in macropore flow. Gaussian semivariograms were fitted to MWR for irrigations 2 and 3. For the rest of irrigations spherical semivariograms showed a better cross-validation. The semivariogram range for irrigations 2 and 3, around 45 m, was much longer than the corresponding to irrigations 4 and 5, around 6 m.

A correlation analysis was performed between measured water content before and after each irrigation (Table 4). The water content measured after each irrigation presented significant correlation coefficients between irrigations, varying from 0.305* to 0.895***. Correlation of the water content before the irrigation between the different irrigation events did not present the same behavior. A good correlation was found between water content before irrigations 2 and 3 (0.834***), and between water content before irrigations 4 and 5 (0.779***). No significant correlation was found in the rest of the cases. This could be due to the relevance of crop extraction after irrigation 3, when the corn reached the flowering stage and when the crop is more affected by water stress.

Correlation of MWR between irrigations was always high and strongly significant, varying from 0.691***, between irrigations 2 and 3, to 0.881***, between irrigations 4 and 5. This is in agreement with the general perception that in surface irrigation the pattern of soil water recharge is common to all irrigation events (Vachaud et al. 1985, Jaynes and Hunsaker 1989). The consistency of the spatial structure of soil water before and after the irrigation events (data not shown) indicates that its spatial variability is constant over time. This is not the case for properly designed and managed sprinkler irrigation systems, where the patterns of soil water and MWR reportedly have a strong random component, particularly in the presence of strong winds (Keller and Bliesner 1990).

Comparing MWR with ECI's

All MWR means were lower than the correspondent ECI (Table 3). The difference, averaging 24 mm per irrigation event, can be attributed to deep percolation losses, to evapotranspiration between neutron probe readings and to experimental errors while using the neutron probe at the upper layer. The management allowable depletion (MAD) determined in the companion paper was used to estimate the dependence of deep percolation losses on soil physical parameters. MAD is an estimation of the water holding capability of the soil. A seasonal difference ratio (SDR) was computed at each point as the difference between the seasonal values of ECI and MWR over ECI. Among the three above mentioned components of SDR, only deep percolation losses are spatially variable. The correlation coefficient between SDR and MAD was -0.538***. The magnitude of this correlation indicates that water losses were particularly large on soils with poor water holding capability. These results suggest that neglecting the spatial variability of soil physical properties may lead to relevant errors in the estimation of irrigation uniformity and efficiency.

Correlations between measured water recharge and estimated cumulative infiltration were low but often significant (Table 5). The correlation coefficients vary from 0.216 for irrigation 4 to 0.345** for the seasonal irrigation. MWR showed similar correlation with ECI-I and ECI. No correlation was found in any irrigation between MWR and ECI-τ. From these results, it can be concluded that introducing the spatial variability of infiltration did not improve the estimation of cumulative infiltration. It is possible that a more accurate determination of infiltration and/or soil water recharge changed this conclusion. A higher sampling density in infiltration would require a great effort that could not make up for the possible better results.

Soil water recharge measured by neutron probe showed a negative, generally significant correlation with the three surveys of soil surface elevation (Table 6) reported in the companion paper. The negative sign implies that high spots receive less irrigation water. These high spots are consistently drier and therefore offer more resistance to the penetrometer. The correlation coefficient between the maximum penetration resistance and survey 3, with a value of 0.274*, confirms this conclusion (Zapata and Playán 1999). The correlation between soil surface elevation and MWR was better when the first survey was considered. Installation of the neutron probe access tubes (just after the first leveling) and their presence while performing the sowing operation could result in small scale leveling disruptions introducing errors in the two surveys performed thereafter.

Regarding the relationship between estimated cumulative infiltration and soil surface elevation, the correlation analysis (table 6) shows that there is not a significant correlation between them. Nevertheless, correlation between soil surface elevation and ECI-I was negative, high and strongly significant. The highest correlation coefficients corresponded to survey 3. One more time, the conclusion is that the measured spatial variability of the infiltration parameters masked the influence of soil surface elevation in ECI.

A positive, small but still significant correlation was found between ECI-τ and soil surface elevation. This positive correlation implies that high spots infiltrate more water than low spots. Since the opportunity time is not considered, what this correlation reveals is that high spots had larger infiltration rates. This finding is in agreement with the negative correlations found between soil water before irrigation and soil surface elevation (data not shown). This fact would have been evidenced if a physically based infiltration equation had been used to model field data.

Distribution Uniformities

The lowest values of DU (Table 7) were obtained for the infiltrated depths measured by the neutron probe (MWR). The DU based on MWR increased in time: from 45.95 % for irrigation 2, to 66.64 % for irrigation 5. Computing the DU with ECI, the values are higher and they remain practically constant for irrigations 2, 3 and 4. The decrement of DU for irrigation 5 was due to the higher variability of infiltration at this irrigation event (infiltration experiment 2). The same trend can be observed for ECI-τ. The highest DU’s were obtained for ECI-I: the values showed and increase in time (from 84.15 to 91.54 %), just like the DU for MWR.

The differences found between the DU's for ECI and MWR (17.94% on the average) could be due to the spatial representativeness of the variables used in each case. While ECI is determined on a somehow large area (due to the estimation of the advance and recession times, and to the diameter of the infiltration ring), the determination of MWR typically involves no more than a few centimeters surrounding the access tube. The evaluation procedure tends to yield spatially averaged variables, and therefore the DU based on these variables is high. Nevertheless, DU's based on MWR consider all the possible sources of spatial variability in soil water recharge, while ECI only considers infiltration and opportunity time. This point of view explains the larger DU for ECI than for MWR.

The seasonal DU is slightly larger than the average DU for all irrigations (5.19% for ECI and 4.68% for MWR). The magnitude of the difference is small because the time correlation of ECI and MWR is very important. Actually, the difference between seasonal and average DU's is induced by the random variability of the estimations and measurements of soil water recharge. This is an important drawback of surface irrigation when compared to sprinkler irrigation, since irrigation uniformity does not increase substantially when the whole irrigation season is considered (Keller and Bliesner 1990).

The average DU's computed from the estimated cumulative infiltrations (ECI, ECI-I and ECI-τ), ranging from 72.44 to 87.95%, are comparable to those reported by Hanson et al. (1995), who obtained an average value of 81% for border irrigation. The extreme differences in the values of DU's considered in this work amount to 34%. Such variation suggests that each determination of irrigation uniformity should be accompanied by a detailed report on the methodology, so that fair comparisons can be established between irrigation systems and within each irrigation system.

Crop growth, crop water stress and yield

Crop yield is affected by a large number of processes, being soil water availability one of the most relevant. The influence of soil physical properties on soil water availability and at the same time on crop yield was evaluated in this work. Among the sources of yield variability not controlled in this experiment are natural soil fertility and other environmental factors, some of which are probably random (Bresler and Dagan 1988). Average values for GY and TDM were 1,011 g m^{-2} and 2,419 g m^{-2}, with respective CV's of 20.0% and 21.6%. All yield parameters were strongly inter correlated, with P values usually less than 0.001. The SI was also heavily correlated with yield and its components. The correlation coefficients were -0.666***, -0.622***, -0.511*** and -0.208 for CH, GY, TDM and HI, respectively.

Spherical theoretical semivariograms were cross-validated for all yield and stress parameters, except HI. These semivariograms show ranges of 22 m for CH, 24 m for TDM, 25 m for GY and 16 m for SI.

A correlation analysis between crop yield and the four indexes of water recharge was performed (Table 8). For MWR the highest correlation was found with total dry matter. Correlation between TDM and the seasonal MWR amounted to 0.629***. High and significant correlations, excluding irrigation 5, were also found between MWR and GY (varying from 0.381*** to 0.505***) and between MWR and SI (varying from

-0.410*** to -0.571***). Correlations between crop yield parameters and all the estimated cumulative infiltrations (ECI, ECI-I and ECI-τ) were in general lower than those obtained for the corresponding MWR, although most of them showed statistical significance. Considering all the estimations of cumulative infiltration, the best correlations were found for total dry matter. The coefficients for TDM and seasonal irrigation were 0.433*** for ECI, 0.311** for ECI-I and 0.261* for ECI-τ. Considering GY the correlation was more relevant for ECI (0.283* for the seasonal irrigation) than for the rest of the estimated recharges (0.201 for ECI-I and 0.244 for ECI-τ). The relationship between crop yield and water recharge is illustrated by Figure 1. In this figure contour line maps are presented for seasonal estimated cumulative infiltration, measured water recharge, grain yield and total dry matter.

Considering MWR and the ECI's, the highest correlations were found for TDM. Correlations with GY were less significant. This finding can be explained by the low significance of the correlations with HI. The harvest index is determined, among other factors, by the intensity and timing of crop stress. The approach used in this research, based on the study of irrigation events, was not adequate to relate water application and harvest index.

Although the correlations between MWR and ECI were slight, the correlation between them and TDM are highly significant, the best correlation corresponding to MWR. It must be taken into account that each observation of a crop yield parameter involves integration on an area of about 2.25 m^2. The spatial significance of yield observations seems to be responsible for the high correlations between ECI and the yield parameters: both variables are obtained from areas of similar extent.

Correlation between seasonal TDM and ECI had a high level of significance, 0.433***. When ECI-I and ECI-τ were analyzed, the coefficient was reduced to 0.311** and 0.261*, respectively. Most of the significance was associated to soil surface elevation, although a relevant part was due to the variability of infiltration. In fact, yield parameters showed significant correlations with soil surface elevation, particularly with survey 2 (the corresponding correlations for GY and TDM were -0.419*** and -0.509***, respectively). This finding stresses the relevance of land leveling, not only as a way to conserve water, but as a way to reduce the extent of water stressed areas (high spots) where yield is effectively reduced by localized drought. In other combinations of crops and soils, these correlations could result positive, indicating that in low spots yield was reduced by water logging. It is interesting to note that the spatial variability of infiltration (ECI-τ) had a larger effect on TDM (r = 0.261*) than on MWR (r = 0.108).

To explore the influence of distance on the value and significance of the correlation coefficients, a cross-correlation analysis was performed. Cross-correlograms between crop yield parameters and SI on one side, and MWR and ECI on the other, are presented in figure 2. Except for CH (which presents a random behavior), the rest of cross-correlograms show similar patterns. In distance, correlation coefficients approach zero and therefore lose significance. MWR always presents better correlation than ECI for similar distances. It can be concluded that for distances smaller than 11 m MWR is significantly correlated with GY, TDM and SI. In the case of ECI the maximum correlation distance varies for the different parameters (5 m for GY, 10 m for TDM and no correlation with SI). These analyses confirm the superiority of MWR over ECI when explaining the variability of crop yield related parameters.

Summary and conclusions

Geostatistical analyses established a spatial structure for the opportunity time, the measured irrigation water recharge, the crop water stress index, and the variables describing crop yield. Correlation analyses also evidenced a consistency of this spatial structure from irrigation to irrigation in the case of opportunity time and MWR. No spatial structure could be found for ECI. Measured water recharge was better explained by ECI-I than by ECI, indicating that the spatial variability of infiltration did not improve the estimation of soil water recharge and that soil surface elevation is very well suited to explain water recharge. Soil surface elevation strongly influenced the soil water regime and crop yield (significant correlations were found for MWR, ECI-I, GY and TDM). Fortunately, this variable can be regarded now a days as a management variable, due to the advent of Laser controlled leveling. This technique has proven potential to conserve irrigation water and increase crop yield

Distribution Uniformity was computed for each of the four variables expressing soil water recharge. The seasonal values of DU computed from ECI and MWR were 78.88 % and 58.63 %, respectively. The difference between these indexes confirms the need to accompany each uniformity value with a description of the methodology used. This would be particularly important when the values of DU are used to establish comparisons between irrigation systems and within each irrigation system. The seasonal DU resulted slightly larger than the average DU (58.63 % and 53.95 % for MWR, respectively). This small difference suggests that there is a certain random component on soil water recharge, but most of the variability in MWR is due to soil surface elevation. This feature constitutes a drawback of level basin irrigation: the lack of uniformity in an irrigation event is not compensated by the succeeding irrigations.

Among water recharges, MWR showed the highest correlation with crop yield parameters, although ECI was also able to explain the yield pattern. ECI-I resulted better correlated with TDM than ECI-τ. Since little can be done to reduce the variability of infiltration in commercial level basins, management efforts should be concentrated on reducing SDe. Infiltration variability (represented by ECI-τ) was more related to total dry matter than to MWR. A possible explanation is that infiltration could affect yield through variables other than measured water recharge. However, the differences in the spatial representativeness of the soil water recharge measurements and estimations seem to be a better explanation for these results. Cross-correlation analyses confirmed that MWR is better suited than ECI when trying to explain the variability of crop yield related parameters. The influence of soil physical properties on crop yield and its components could not be established in this research.

Wisdom should be used when analyzing the results of this work. The methodology applied did not permit complete separation between the effects of infiltration and elevation. In fact, ECI-I includes the influence of elevation plus the time of advance. This does not seem to be a limitation, since advance was strongly determined by soil surface elevation and recession was completely governed by it. On the other hand, the experiments were performed on a small scale basin, and differences should be expected if a large scale basin had been analyzed using the same procedure.

In particular, the variability of infiltration could be larger, and its effects on water recharge and yield more important.

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Tables

Table 1. Descriptive statistics and semivariogram analysis of the opportunity time for the five irrigations.

	Mean (min)	Std. Dev. (min)	Semivariogram type	Nugget (min^2)	Sill (min^2)	Range (m)
$\tau1$	359.7	147.8	Spherical	0	28000	10.0
$\tau2$	417.1	173.8	Spherical	0	32200	5.3
$\tau3$	551.4	284.6	Spherical	0	89000	4.5
$\tau4$	324.8	142.2	Spherical	0	24500	6.0
$\tau5$	448.0	148.1	Spherical	0	21000	4.5

Table 2. Correlation coefficients between opportunity time and soil surface elevation.

	τ1 (min)	τ2 (min)	τ3 (min)	τ4 (min)	τ5 (min)
Survey 1	-0.416 **	-0.338 **	-0.337 **	-0.359 **	-0.440 **
Survey 2	-0.261 **	-0.600 **	-0.540 **	-0.600 **	-0.628 **
Survey 3	-0.267 **	-0.502 **	-0.460 **	-0.489 **	-0.494 **

Table 3. Mean, standard deviation and CV for the estimated water recharge (ECI, ECI-I and ECI-τ), and for the measured water recharge, (MWR).

	ECI			ECI-I			ECI-τ			MWR		
	Mean (mm)	Std. Dev. (mm)	CV (%)	Mean (mm)	Std. Dev. (mm)	CV (%)	Mean (mm)	Std. Dev. (mm)	CV (%)	Mean (mm)	Std. Dev. (mm)	CV (%)
Irrigation 2	66.06	12.03	18.20	72.03	6.57	9.12	64.90	13.02	20.06	37.30	18.00	48.25
Irrigation 3	114.37	21.77	19.04	121.25	14.65	12.08	112.54	23.02	20.45	73.20	29.48	40.28
Irrigation 4	74.28	13.68	18.42	79.64	6.62	8.31	72.30	14.32	19.81	50.31	17.65	35.08
Irrigation 5	70.86	25.61	36.14	72.56	5.24	7.22	68.29	23.68	34.68	59.44	15.78	26.55
Seasonal	317.88	59.19	18.62	345.20	27.95	8.10	310.35	58.76	18.94	220.26	73.34	33.30

Table 4 . Correlation matrix between water measurements before and after the irrigations and soil water recharge.

	Irrigation 2			Irrigation 3			Irrigation 4			Irrigation 5		
	Before 2	After 2	MWR 2	Before 3	After 3	MWR 3	Before 4	After 4	MWR 4	Before 5	After 5	MWR 5
Before 2		0.736 ***		0.834 ***			0.084			-0.242		
After 2					0.777 ***			0.349 **			0.305 *	
MWR 2						0.691 ***			0.711 ***			0.692 ***
Before 3					0.746 ***		0.447 ***			0.197		
After 3								0.755 ***			0.669 ***	
MWR 3									0.866 ***			0.703 ***
Before 4								0.771 ***		0.779 ***		
After 4											0.895 ***	
MWR 4												0.881 ***
Before 5											0.792 ***	
After 5												
MWR 5												

Table 5. Correlation analisys between measured water recharge (MWR), on one hand, and estimated water recharge (ECI), estimated water recharge without infiltration (ECI-I) and estimated water recharge without opportunity time (ECI-τ), on the other.

	Irrigation number	ECI	ECI-I	ECI-τ
	2	0.297 *	0.245 *	0.075
	3	0.260 *	0.119	0.109
MWR	4	0.216	0.364 **	0.002
	5	0.238 *	0.424 ***	0.142
	Seasonal	0.345 **	0.364 **	0.108

Table 6. Correlation analysis between soil surface elevation and water recharge (MWR, ECI, ECI-I and ECI-τ).

	MWR					ECI				
Irrigation number	2	3	4	5	Seasonal	2	3	4	5	Seasonal
Survey 1	-0.367***	-0.363***	-0.308**	-0.289**	-0.365***	0.005	0.004	0.021	0.006	0.027
Survey 2	-0.289**	-0.248*	-0.222*	-0.204	-0.264*	-0.079	-0.109	-0.081	-0.091	-0.100
Survey 3	-0.158	-0.248*	-0.237*	-0.319**	-0.259*	0.027	-0.118	0.067	-0.055	-0.072

	ECI-I					ECI-τ				
Irrigation number	2	3	4	5	Seasonal	2	3	4	5	Seasonal
Survey 1	-0.481***	-0.381***	-0.511***	-0.640***	-0.503***	0.290*	0.292*	0.287*	0.159	0.303*
Survey 2	-0.432***	-0.435***	-0.524***	-0.522***	-0.482***	0.174	0.179	0.168	0.037	0.142
Survey 3	-0.690***	-0.684***	-0.689***	-0.649***	-0.818***	0.329**	0.305**	0.350**	0.091	0.295*

Table 7. Distribution Uniformities computed from estimated and measured water recharge for each irrigation.

	Distribution Uniformity (%)			
	81 node network			64 node network
	ECI	ECI-I	ECI-τ	MWR
Irrigation 2	77.16	86.85	75.04	45.95
Irrigation 3	76.05	84.15	74.92	49.67
Irrigation 4	77.55	89.27	75.12	53.53
Irrigation 5	64.00	91.54	64.67	66.64
Average	73.69	87.95	72.44	53.95
Seasonal	78.88	89.34	77.65	58.63

Table 8. Correlation analysis between crop yield parameters, water stress index and water recharge (MWR, ECI, ECI-I and ECI-τ).

	MWR					ECI				
Irrigation number	2	3	4	5	Seasonal	2	3	4	5	Seasonal
GY	0.467 ***	0.505 ***	0.381 ***	0.148	0.429 ***	0.285 *	0.246 *	0.349 **	0.179	0.283 *
TDM	0.688 ***	0.637 ***	0.554 ***	0.388 ***	0.629 ***	0.355 **	0.340 **	0.406 ***	0.325 **	0.433 ***
HI	-0.314 **	-0.170	-0.214	-0.324 **	-0.267 *	-0.042	-0.084	-0.028	-0.155	-0.144
CH	-0.042	0.137	0.047	-0.089	0.030	0.237 *	0.239 *	0.246 *	0.152	0.215
SI	-0.410 ***	-0.571 ***	-0.463 ***	-0.083	-0.439 ***	-0.066	-0.076	-0.149	-0.174	-0.109

	ECI-I					ECI-τ				
Irrigation number	2	3	4	5	Seasonal	2	3	4	5	Seasonal
GY	0.145	0.031	0.290 *	0.444 ***	0.201	0.266 *	0.275 *	0.255 *	0.075	0.244
TDM	0.267 *	0.177	0.418 ***	0.502 ***	0.311 **	0.201	0.203	0.197	0.208	0.261 *
HI	-0.180	-0.219	-0.201	-0.076	-0.158	0.147	0.155	0.138	-0.146	0.052
CH	0.161	0.074	0.200	0.140	0.225	0.303 *	0.328 **	0.277 *	0.101	0.231
SI	-0.068	-0.005	-0.281 *	-0.380 ***	-0.187	-0.113	-0.132	-0.094	-0.080	-0.095

FIGURES

Figure 1.Experimental (symbols) and theoretical (lines) semivariograms of opportunity time for the five irrigations evaluated.

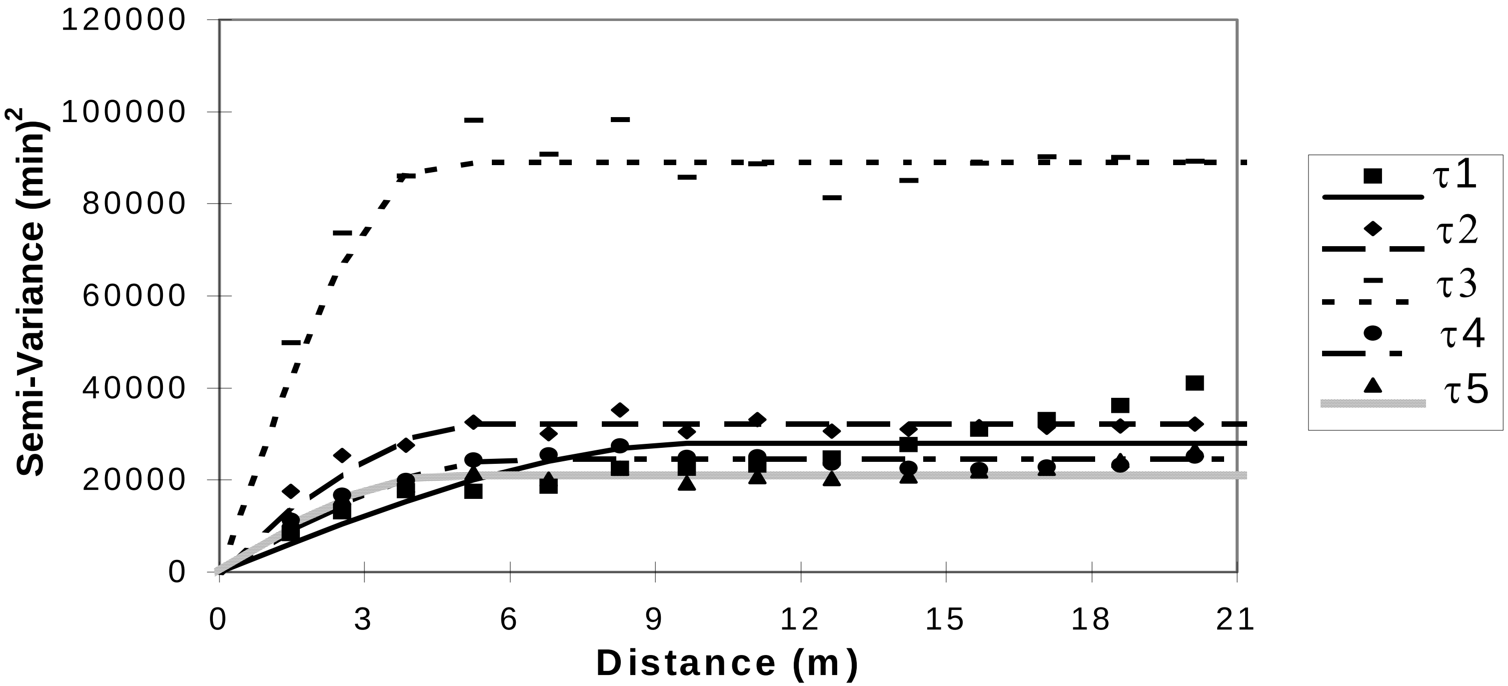

Figure 2. Semivariograms for irrigation water recharge measured by the neutron probe (MWR).

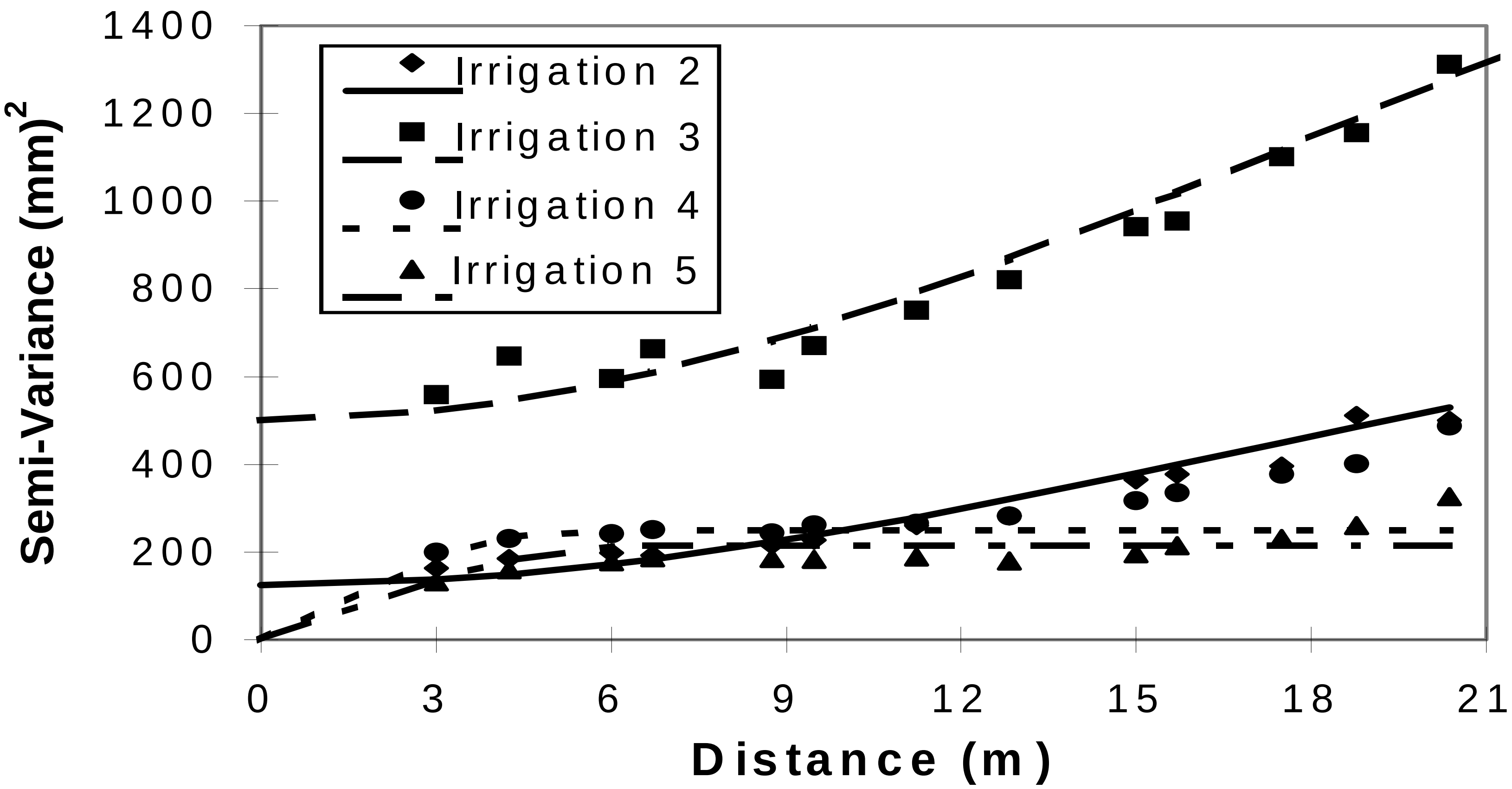

Figure 3. Experimental (symbols) and theoretical (lines) semivariograms of crop yield and its components and the stress index.

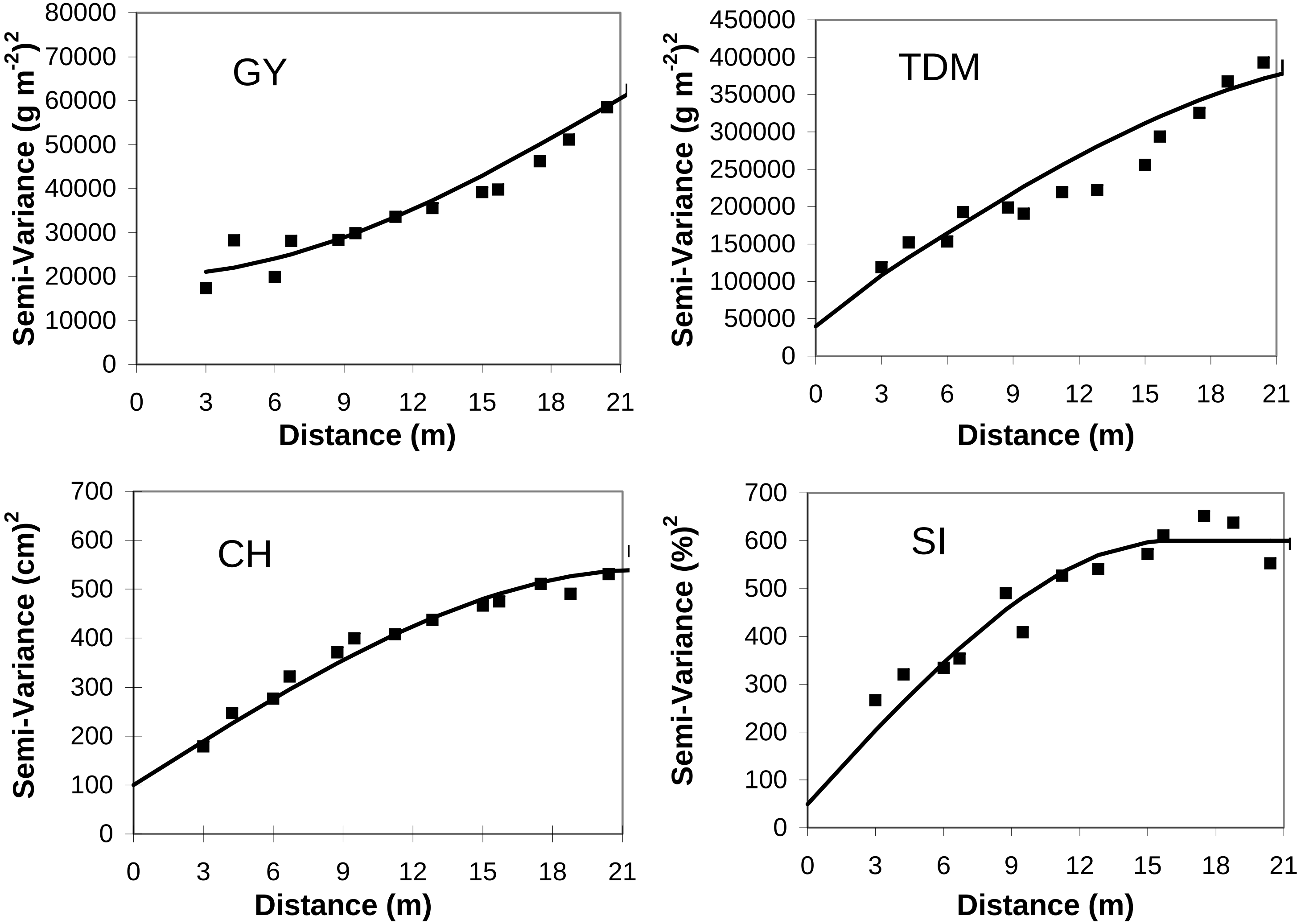

Figure 4. Contour line maps for seasonal water recharge (estimated and measured) and crop yield patterns (GY and TDM).

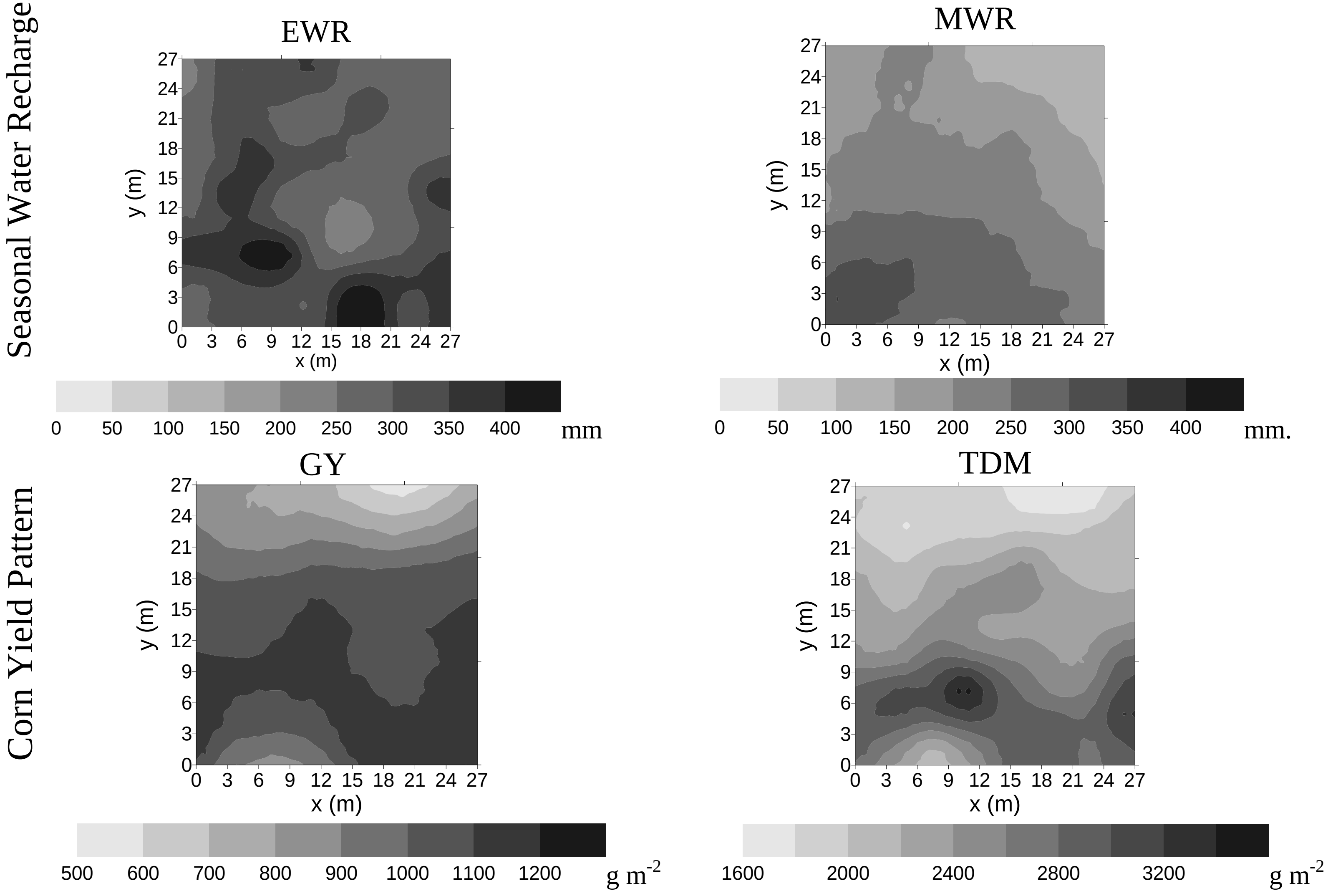

Figure 5. Cross-Correlograms between grain yield (GY), total aerial dry matter (TDM), crop height (CH), stress index (SI) and the seasonal water recharge, measured (MWR) and estimated (EWR). Continuous lines correspond to MWR and dashed lines to EWR. White symbols represent significant correlation coefficients, while solid symbols not significant correlations (at the 0.05 level of significance).