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Elevation and infiltration in a level basin. I. Characterizing variability

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Abstract Spatial characterization of soil physical properties could improve the estimation of surface irrigation performance. The aim of this research was to characterize the spatial and time variability of a set of irrigation-related soil properties. The small-scale experimental level-basin (729 m^2) was located on an alluvial loam soil. A corn crop was established in the basin and irrigated five times during the season. A detailed survey of the soil properties (generally using a 3×3 m network) was performed. Classic statistical and geostatistical tools were used to characterize the variables and their interactions. Semivariograms were validated for the studied variables, except for the clay fraction, the saturated hydraulic conductivity and the infiltration parameters. The resulting geostatistical range was often in the interval of 6–10 m. For the three surveys of soil surface elevation the range was smaller, about 4 m. No correlation was found between saturated hydraulic conductivity and the other soil physical properties. Soil surface elevation showed a high correlation between surveys. After the first irrigation, the standard deviation of elevation increased from an initial 9.6 mm to 20.8 mm. The soil physical parameters were used to map the soil water management allowable depletion. In a companion paper these results are used to explain the spatial variability of corn yield and soil water recharge due to irrigation.

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Introduction

Surface irrigation systems, when properly engineered and managed, can attain levels of uniformity and efficiency similar to, or greater than, more technologically advanced irrigation systems. Hanson et al. (1995) conducted a study on 959 Californian irrigation systems and reported that the distribution uniformity (DU) for furrows and borders was 84% and 81%, respectively. The DUs corresponding to micro-irrigation systems for permanent crops and for continuous-move sprinklers were 73% and 75%, respectively. These results were obtained in an area where the technological level was high and water scarce. In many other regions of the world surface irrigation uniformity would be lower.

Once design and management are optimized, the limitations of surface irrigation uniformity are associated with the spatial variability of soil surface elevation and infiltration (Erie and Dedrick 1979; Walker and Skogerboe 1987). This hypothesis is supported by the fact that models not considering the spatial variability of these variables give predictions of irrigation uniformity well above experimentally obtained values (Playán et al. 1996a).

In recent years, several authors have reported the results of experiments exploring the relationship between the spatial variability of soil surface elevation and infiltration. Izadi and Wallender (1985) examined furrow hydraulic characteristics in space and time and related these characteristics to infiltration. They used a zero-inertia irrigation model to simulate different rates and measurement conditions and these cases were field-tested. They concluded that one-third of the variability in infiltration could be attributed to the variation in wetted perimeter along the furrow and the remaining two-thirds to soil variability and measurement errors. Oyonarte (1997), working in furrow irrigation, found that the main source of variability in the irrigation water recharge was the soil infiltration characteristics. In his experiments, infiltration variability could be successfully expressed by the variability of the basic infiltration rate. He found that this variable was randomly distributed (spacing between infiltrometers was 23 m) and he presented a procedure to introduce random infiltration into a furrow irrigation model.

Jaynes and Hunsaker (1989) monitored the spatial and seasonal variability of soil water and infiltration in a flood-irrigated field. Their results showed a coefficient of variability in the infiltration rate as high as 53%, although the stability of infiltration between irrigations was high. The spatial variability of soil surface elevation in level-basin irrigation was addressed by Hunsaker and Bucks (1991). They concluded that 51–68% of variability in infiltrated depth was explained by differences in water content before irrigation, and 23% by non-uniformity in surface elevation. Playán et al. (1996b) reported that micro-topography could account for 73% and 34% of variability in opportunity time and soil water recharge, respectively.

Almost without exception, irrigation researchers have modeled infiltration using variations of the Kostiakov equation. This approach relies on an empirically based equation without representation of the physical insight into the infiltration process. The Kostiakov equation represents the shape of the infiltration curve and often explains ring infiltrometer data satisfactorily. Nevertheless, this experimental model has an important limitation: the required parameters are empirical in nature and do not directly represent the physical process.

Physically based infiltration models such as those of Green and Ampt (1911) or Philip (1957), are based on the solution of the Richards' flow equation (1931). Haverkamp et al. (1990) derived a physically based equation that takes into account the effect of changing boundary conditions at the soil surface. Application of a fractal model to the shape similarity between the cumulative particle-size distribution and the soil water retention curve (Fuentes 1992) was a further step towards describing the behavior of water infiltration into porous media. These models currently require extensive measurement or inference of soil physical properties. This drawback could at the same time be the source of their attraction, for these infiltration models are well suited for predictive applications.

In recent decades, researchers have been focusing on variability problems as related to water application and water use. Classical statistics were often insufficient to assess and properly quantify spatial variability. Webster and Cuanalo (1976) used autocorrelograms as a means of expressing changes in field-measured soil properties over a soil transect. Warrick and Nielsen (1980) reviewed different concepts used to express variability in soil physics. In their work they discussed the applicability of coefficients of variation, scaling theories and spatial structure to different problems. The introduction of geostatistics has improved our understanding of the spatial variability of soils. In geostatistics it is implied that the spatial variation of a soil property is not random but follows a spatial structure that can be mathematically expressed by a function called semivariance. Following these theories, Vieira et al. (1981) reported a geostatistical analysis of infiltration rate. The magnitude of spatial variability has been used to validate soil water retention models (Shouse et al. 1995) by comparing the spatial variability of the model output with the spatial variability of readily measurable variables: bulk density and texture. Chien et al. (1997) reported a large-scale soil survey based on geostatistical analyses. They found a moderate scale dependence of all the tested soil properties. The authors based their choice of methodology on the belief that the spatial characterization of soil physical properties could improve the utility of soil classification systems by enabling users to anticipate levels of variability. This would in turn permit users to manage agricultural fields more effectively.

The purpose of this paper is: (1) to characterize the spatial variability of some soil physical properties measured in a small network (with a 3 m step); (2) to study the spatial and time variability of soil surface elevation and infiltration; (3) to explore the statistical relationships between the studied variables; and (4) to map the soil water management allowable depletion. The results of this research can be used to establish efficient sampling strategies for the characterization of soil physical properties relevant to level-basin irrigation design and management. In a companion paper the values presented for infiltration and elevation are used to estimate cumulative infiltration. These estimates are compared to soil water recharge (measured with a neutron probe), crop water stress and corn yield.

Materials and methods

Statistical significance

In the correlation analyses presented in this work, the following convention has been adopted for the significance levels: * indicates $0.01 < P \leq 0.05$; ** indicates $0.001 < P \leq 0.01$; and *** indicates $P \leq 0.001$. If no stars follow a correlation coefficient, the correlation is not significant ($P > 0.05$).

Basic geostatistics

Spatial variability was analyzed using geostatistical techniques (Englund and Sparks 1988). This method is based on semivariance, a statistical function of the distance separating two observations of a variable. The experimental semivariogram is a plot of semivariance versus distance. Theoretical semivariograms are mathematical functions used to model experimental data. Three parameters are used for this purpose: nugget, sill, and range.

The nugget is the value of the semivariogram for a distance equal to zero. A non-zero nugget indicates a systematic measurement error or the existence of spatial variation at a smaller scale than measured. The final, stable value of the semivariogram equals the sum of sill and nugget. The percentage of nugget to nugget plus sill can be regarded as an index of spatial dependence (Chien et al. 1997). The lower the index the larger the spatial dependence. If the index is less than 25%, the variable has strong spatial dependence. If the index is between 25% and 75%, the variable has moderate spatial dependence. Otherwise, the variable has weak spatial dependence.

The range is the distance at which the semivariance first reaches its stable value. It indicates the distance over which measurements are correlated, thus identifying the size of the different soil units. The parameters of the theoretical semivariogram can be statistically validated using the cross-validation procedure. Kriging can be used to estimate the value of the variable at untested locations.

The experimental level basin

The experiment was a small level basin (27 × 27 m) located at the Agricultural Research Service (SIA) experimental farm in Saragossa, Spain. The soil, developed from alluvial deposits, was classified as Typic Xerofluvent, coarse loam, mixed (calcareous), mesic (Soil Survey Staff 1992). This small basin was chosen in order to represent a scaled-down commercial farm basin. Scaling was intended to allow adequate characterization of the spatial variability of the measured variables. Geostatistical analyses of irrigation-related properties have often revealed that the range is small. The sampling density required to characterize this variability would be unmanageable for a commercial level basin, the size of which ranges between 0.5 and 5 ha. Following the procedure reported in Playán et al. (1996b), the inflow discharge was adjusted to complete irrigation advance in a time representative of local level-basin systems. The basin was leveled with laser-controlled equipment, having a typical commercial accuracy represented by a standard deviation of soil surface elevation (SDe) of 10 mm. This level of accuracy was found when the field was first surveyed a few days after land leveling. When irrigating with a small discharge, this residual relief can control the shape of the advancing front, increasing the variability produced by the advance process. As a consequence, the experimental plot was potentially over-sensitive to the effect of micro-topography. Quantitatively this effect is not relevant, since most of the non-uniformity is generated during the recession phase of the irrigation event (Playán et al. 1996a).

After leveling, the experimental basin was plowed with a moldboard to prepare a seedbed for corn. Short season corn (*Zea mays* L. cv. Clarissia) was planted on 17 May 1996 in rows 0.75 m apart. The irrigation water was applied from a corner. The cut-off time was when advance was complete. Water was conducted from the irrigation ditch to the basin corner through a pipe. A propeller flow meter and a gate valve were installed in the pipe in order to measure the applied water and keep a constant discharge throughout each irrigation event. Discharge ranged between 8.7 and 14.7 L s^{-1} among irrigations, with an average value of 10.2 L s^{-1}.

A 1.5 m square grid (361 nodes) was marked in the field using flags displaying the Cartesian coordinates of each node. The origin of the coordinates was located at the inflow corner. To avoid interference between measurements, different subgrids were used for different variables. The subgrids used for each variable are presented in Fig. 1. For clarity and completeness, this figure includes information about the variables used in the companion paper.

Measurements of bulk density, hydraulic conductivity, infiltration, penetration resistance and soil texture were performed at an 81-node square subgrid with 3 m side spacing starting at the node with coordinates $x = y = 1.5$ m. The elements of this grid are indicated in Fig. 1. The soil water characteristic curves and soil depth were measured in a 100-node square grid formed by the nodes with coordinates being multiples of 3 m. Soil surface elevation and the location of the advance and recession fronts were determined at all nodes. For soil surface elevation, five 1.5 m square cells were randomly chosen to survey at an interval of 0.75 m. The purpose of this locally refined network was to improve the geostatistical analysis of soil surface elevation by adding semivariance data at small distances. All the soil physical properties based on soil wetting or auger holes were measured before leveling and seedbed preparation to avoid interference with water redistribution and the soil water balance.

Correlation analysis was used to establish relationships between different variables. Since various grids were used for data gathering, geostatistical analysis and kriging were used when needed to estimate the value of the variables at the locations used for the correlation analyses. These locations are in all cases those denoted by black squares in Fig. 1. GEO-EAS software (Englund and Sparks 1988) was used to perform all the geostatistical analyses.

Crop water requirements

Crop water requirements were computed following standard FAO procedures (Doorenbos and Pruitt 1977). The meteorological data required to compute reference crop evapotranspiration with the Penman-Monteith method (Jensen et al. 1990) were obtained from the meteorological station at the SIA experimental farm. Crop coefficients were derived from phenological data recorded during the corn season. Daily crop evapotranspiration (ET_c) and precipitation are presented in Fig. 2.

Soil physics

Two determinations of soil texture were performed at each sampling point. Samples were collected at depths 0–0.3 and 0.3–0.6 m. The samples were air-dried and passed through a 2 mm sieve. The sand (0.05–2 mm), silt (0.002–0.05 mm) and clay (< 0.002 mm) percentages of the soil samples were determined using the pipette method (American Society of Agronomy 1965). Bulk density was determined at the same points as soil texture, taking undisturbed soil samples. A cylinder sampler (54 mm in diameter and 30 mm in length) was used for this purpose.

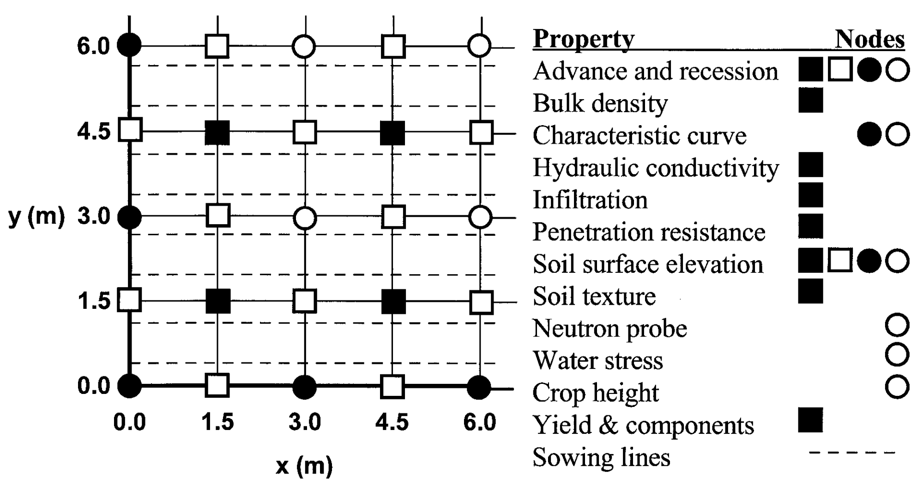

Fig. 1 Location of the field measurements

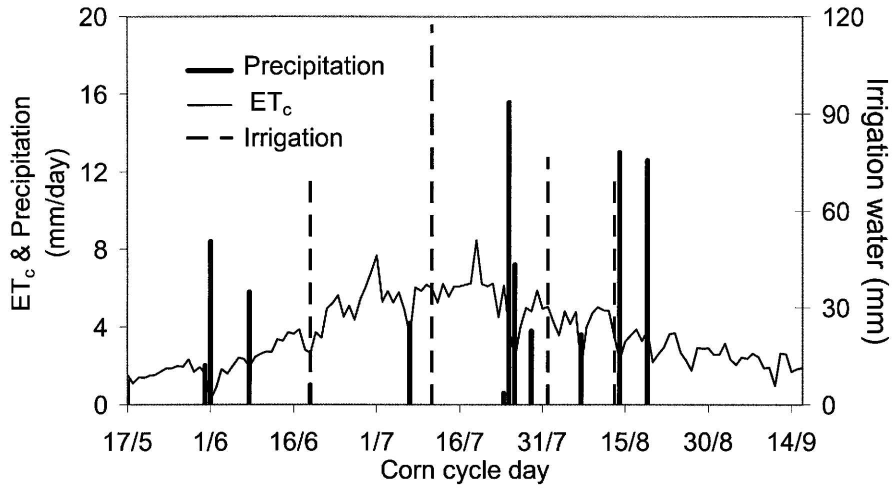

Fig. 2 Daily crop evapotranspiration (ET_c), precipitation and irrigation

Soil water characteristic curves were determined on disturbed samples using a pressure chamber (Hanks 1992). Four samples were collected at each point at 0.3 m intervals to a maximum depth of 1.20 m. Two pressure heads considered characteristic of wilting point and field capacity (−1.5 and −0.03 MPa, respectively) were used for each sample. Soil depth was measured during the sampling process for soil water retention. A subjacent undulated gravel horizon was found to limit soil depth in the level basin.

The hydraulic conductivity at the soil surface was measured in situ. A disc permeameter (Perroux and White 1988) working at zero head (saturation), was used. A disc permeameter is a constant-head infiltrometer that can operate at either a zero or a negative head. The measurements were performed before laser leveling and seedbed preparation to avoid interference with the soil water regime. This circumstance could affect the significance of the experimental data.

Penetration resistance was measured once on 6 August (in the middle of the corn growing season) using a cone penetrometer probe (O'Sullivan et al. 1987). The force required to press the cone penetrometer into a soil is related to the soil shear resistance. This force is correlated with soil penetration resistance (Nw cm^{-2}) which is measured as a function of depth. The probe was also used to determine the depth of the hard layer. This is the maximum depth to which the penetrometer could be driven.

Soil surface elevation

An automatic level was used to survey soil surface elevation on three occasions during the experiment. The first survey was performed on 1 April (a few days following laser leveling of the plot). The second was performed a few days after the corn was planted (31 May). The third survey was performed after harvest, on 16 October. For each survey, the standard deviation of elevation was computed and used to characterize the variability of soil surface elevation.

Irrigation evaluation

The experimental plot was irrigated five times during the crop season. The first irrigation was pre-planting (a common practice in the area) and was not fully characterized. During the crop season irrigation was applied when approximately 25% of the plants suffered from rolled leaves. The dates and amounts of the irrigation events are presented in Fig. 2. Only irrigations 2 (19 June) and 5 (13 August) were studied in this paper, as they coincided with the infiltration experiments. In the companion paper, this analysis is extended to irrigations 3 and 4.

In the measurements of the advance and recession processes, the Cartesian coordinates marked in the field were used. Every 10 min during the advance phase or 30 min during the recession phase, the water front location was registered. At each 1.5 × 1.5 m grid node, the advance and recession times were thus obtained, and the opportunity time computed.

Infiltration characteristics

Infiltration was characterized using 81 single infiltrometer rings (Merriam and Keller 1978). The 0.23 m-diameter rings were 0.3 m high and were driven 0.1 m into the soil to ensure good contact between the rings and the soil. Cumulative infiltration curves were measured during the second and the fifth irrigation events. When the irrigation front reached each ring, a volume of water was carefully added to each infiltrometer and the decrease in the water level was measured over time. The infiltrometer rings were removed after each experiment.

An attempt was made to describe the infiltration process with a physically based equation. The parameterized Philip model was fitted to the data obtained in each infiltrometer ring. When physically based infiltration models are applied, the model parameters can be used to estimate soil hydraulic properties. Prediction uncertainty is caused by errors due to violation of the assumptions implicit in the model and by uncertainty in the model parameters (Clausnitzer et al. 1998). Philip (1957) solved Richards' equation using a time series and neglecting the higher order terms. The resulting equation uses two parameters that have a physical meaning:

$$Z = S\tau^{1/2} + K\tau \quad (1)$$

where Z is the cumulative infiltration (m), τ is the time (min), S is the sorptivity (m $min^{-0.5}$) and K is the long-term gravity-driven flow or hydraulic conductivity (m min^{-1}). Individual infiltration adjustments were performed for each ring and for each infiltration experiment using the Philip equation. The parameter K was found to be negative for over 95% of the measured points. This could be due to the fact that the water levels inside and outside the rings showed relevant fluctuations, thus violating the assumptions that led to Eq. 1. Therefore, it was decided to use an empirical equation to model infiltration in this experiment.

In an irrigation context the empirical Kostiakov equation has been satisfactorily used to describe the infiltration process. Individual infiltration curves were fitted to the data from each ring using the Kostiakov equation:

$$Z = k\tau^a \quad (2)$$

where k and a are regression coefficients. The estimated cumulative infiltration (ECI) can be computed at each location and for each irrigation using the adjusted corresponding Kostiakov parameters and the local opportunity time. The adjustment process is based on the general procedure described by Merriam and Keller (1978). In this case, a scale factor α was applied to the 81 infiltration equations to ensure that:

$$\frac{\alpha \sum_{i=1}^{81} k_i \tau_i^{a_i}}{81} = \frac{\sum_{i=1}^{81} k_{\mathrm{adj}_i} \tau_i^{a_i}}{81} = \overline{Z} \quad (3)$$

where α is the adjusting coefficient, $\bar{Z}$ is the observed average irrigation depth (inflow volume divided by basin area), and $k_{\mathrm{adj}i}$ is the set of adjusted k coefficients. This procedure was used for irrigations 2 and 5, in which an infiltration experiment was performed.

In order to compare the infiltration characteristics at different points of the basin, a new variable was defined as the infiltrated depth computed with the locally fitted parameters and the average opportunity time for each irrigation event. This variable represents the ECI without consideration of the spatial variability of the opportunity time, and will be denoted as ECI-τ. Reference to this variable will be made in the companion paper, in a context of soil water recharge due to irrigation.

Results and discussion

Spatial variability of soil physical properties

The upper and lower soil layers showed very similar average values of the three textural classes (Table 1), denoting similarity of the soil materials. In both layers the average texture can be typified as loam, according to the USDA classification. The upper soil layer shows higher variability in texture than the lower layer (higher CV for the three textural classes). The percentage clay is the variable which presents the weakest spatial dependence: a theoretical semivariogram could not be fitted at the upper layer (Table 1). Bulk density did not vary much with depth, with averages of 1.46 and 1.44 Mg m^{-3} for the upper and lower layer, respectively. Warrick and Nielsen (1980) summarized previous works showing that this property is not very variable in depth. They reported a spatial average CV of 7%, which supports the results of the present work (Table 1). A theoretical semivariogram could be validated for each layer, with ranges similar to those obtained for soil texture (Table 1). The gravimetric water contents at field capacity (w_{FC}) and wilting point (w_{WP}), show higher variability in the lower layer (Table 1). At both sampling depths w_{FC} is more uniform than w_{WP}, a result in agreement with the findings of Nielsen et al. (1973).

The spatial dependence is larger for the upper layer than for the lower layer for all the variables analyzed, except for w_{WP}. The strong spatial dependence of soil properties has often been attributed to soil formation factors, and weak spatial dependence to soil and crop management practices (Chien et al. 1997). The results reported in this research indicate that the layer most affected by crop production practices (upper layer) presents the highest spatial dependence. The alluvial nature of the soil could be responsible for this behavior. All the studied variables show a spherical pattern with ranges in the vicinity of 8 m (between 4 and 10 m). The ranges in the upper and lower layers do not show consistent differences.

Soil depth presents a pattern of variability dominated by a gradient along the y axis, with the deep soils located at the areas with low y coordinates. The average soil depth is 1.01 m, with a CV of 25.6% (Table 1). The extreme values are 0.68 and 1.70 m. The geostatistical analysis shows that this variable is subjected to a Gaussian pattern of spatial variability with a range of 28 m (Table 1). The saturated hydraulic conductivity shows the largest variability (CV = 57%) among the measured soil properties. This figure is 50% greater than the values summarized by Warrick and Nielsen (1980). The fact that no spatial structure could be attributed to this variable indicates that either the method used is not very repeatable or that, more probably, a finer sampling mesh should have been used. The depth of the hard layer shows an average value of 0.17 m, with a CV of 34%, while the maximum penetration resistance has an average value of 0.0171 N m^{-2}, with a CV of 23% (Table 1).

Table 1 Descriptive statistics and semivariogram parameters of soil physical properties. The semivariogram type, nugget, sill, range and spatial dependence values are supplied for the variables for which a theoretical semivariogram could be cross-validated

Variables	Depth (m)	Mean	SD	CV (%)	Semivariogram type	Nugget	Sill	Range (m)	Spatial dependence (%)
Sand (%)	0.0–0.3	41.9	13.3	31.6	Spherical	35.0	185.0	5.5	15.9
Clay (%)	0.0–0.3	13.4	4.6	34.6	–	–	–	–	–
Silt (%)	0.0–0.3	44.7	11.3	25.3	Spherical	50.0	142.0	9.0	26.0
Bulk density (Mg m^{-3})	0.0–0.3	1.5	0.04	2.7	Spherical	0.0	1500.0	4.5	0.0
w_{FC} (%)	0.0–0.3	20.3	1.4	7.0	Spherical	0.0	2.1	10.0	0.0
w_{WP} (%)	0.0–0.3	7.9	0.8	10.5	Spherical	0.2	0.8	8.0	20.0
Sand (%)	0.3–0.6	42.4	7.2	17.1	Spherical	25.0	58.0	9.0	30.1
Clay (%)	0.3–0.6	14.8	2.1	14.4	Spherical	1.5	4.7	4.0	24.2
Silt (%)	0.3–0.6	42.7	6.5	15.2	Spherical	20.0	45.0	9.0	30.8
Bulk density (mg m^{-3})	0.3–0.6	1.4	0.05	3.47	Spherical	500.0	1800.0	7.0	21.7
w_{FC} (%)	0.3–0.6	20.0	2.6	13.0	Spherical	2.0	4.5	7.5	30.8
w_{WP} (%)	0.3–0.6	6.8	1.6	23.7	Spherical	0.5	2.1	8.0	19.2
Soil depth (m)	–	0.1	25.7	25.6	Gaussian	50.0	1650.0	28.0	2.9
Hydraulic conduct (m day^{-1})	–	0.2	0.1	57.1	–	–	–	–	–
Hard layer depth (mm)	–	168.0	57.0	34.0	Spherical	0.0	3200.0	8.0	0.0
Maximum penetration resistance (N cm^{-2})	–	170.7	38.8	22.7	Spherical	0.0	1400.0	4.0	0.0

Both variables show a spherical spatial pattern with a zero nugget and ranges of 8 m and 4 m, respectively. These range values are similar to those found for the rest of the variables.

A correlation analysis was performed for the textural classes, bulk density, water-holding capacity and the hydraulic conductivity for the upper and lower layers. The correlation matrix for the soil physical parameters of the lower layer is presented in Table 2. The rest of the correlation coefficients are not presented because of their non-significance.

One of the most relevant findings is that no correlation could be established between the saturated hydraulic conductivity and the soil physical parameters of the upper layer (soil textural classes and bulk density). Also, at the upper layer, water contents at field capacity and wilting point did not show any correlation with texture or bulk density (data not shown). Many authors have reported such relationships and expressed them in the form of pedotransfer functions. Some researchers used regression analyses (Van de Genachte et al. 1996), while others focused on the physical processes involved (Haverkamp et al. 1990). The use of disturbed samples for measuring water content at field capacity and wilting point could explain the low, non-significant correlation with the other soil physical properties measured. The random behavior of hydraulic conductivity at the survey scale and using the reported survey methods can explain the poor correlation with the other physical properties. At the same time, the difference in the sampling depths for hydraulic conductivity and the rest of the parameters could be partly responsible for the lack of correlation, particularly considering that textural classes did not show correlation in depth.

At the lower layer, significant correlations were found between the water contents at field capacity and wilting point, and soil texture (Table 2). Bulk density was also significantly correlated with w_{FC} and w_{WP}. Although the methodology used to determine gravimetrical soil water at field capacity and wilting point uses disturbed samples, these significant correlations for the lower layer indicate that textural effects on water retention are strong enough to reveal significant correlations. No correlation could be established between bulk density and soil texture, although the correlation coefficients border the threshold level for 5% significance.

The soil management allowable depletion (MAD) was estimated from w_{FC}, w_{WP}, bulk density and soil depth (Merriam and Keller 1978). A maximum soil depth of 1.20 m was considered, and a soil water depletion factor of 2/3 was used. Both values give results appropriate for corn. An average value of 129 mm was found for the experimental basin, with extreme values of 61 and 185 mm (Fig. 3). The map identifies two areas with relevant differences in MAD, separated by a sharp transition. The pattern of spatial variability for MAD is very similar to that of soil depth (data not presented). This detailed analysis of the MAD is used in the companion paper to analyze the fate of irrigation water.

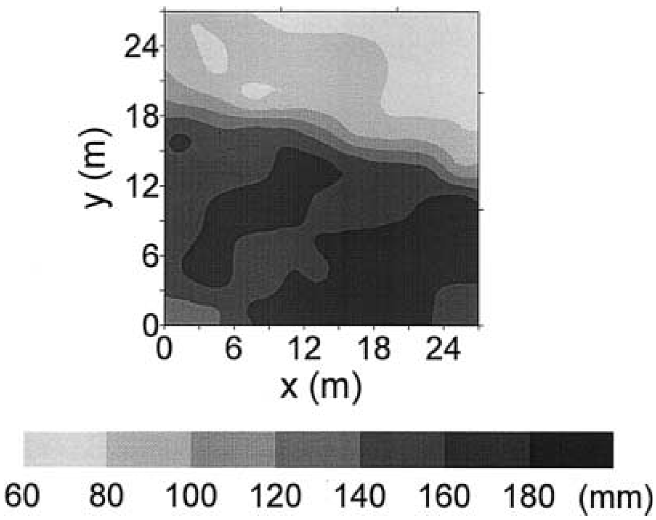

Fig. 3 Contour line map of soil water management allowable depletion (*MAD*)

Variability of soil surface elevation

Table 3 summarizes the descriptive statistics for the three soil elevation surveys, and for the reduced network used for correlation analyses, represented by black squares in Fig. 1. Just after the soil was laser-leveled (survey 1), the standard deviation of soil surface elevation (SDe) was 9.6 mm. This result agrees with previous findings by Bucks and Hunsaker (1987) and Playán et al. (1996b). The customary tillage operations resulted in differential soil compaction and incremented SDe. Survey 2 (after irrigation 1 and sowing), and survey 3 (after harvesting) show similar values of SDe, of approximately 20.8 mm. The geostatistical analysis evidenced the spatial structure of soil surface elevation in all three surveys. The corresponding semivariograms show a range approximately equal for the three surveys, around 4 m (Table 3). This range is smaller than those reported

Table 2 Correlation matrix of soil physical properties at the lower layer (0.3–0.6 m)

	Sand (%)	Clay (%)	Silt (%)	ρ_b (Mg m^{-3})	w_{FC} (%)	w_{WP} (%)
Sand (%)	1.000	−0.471 ***	−0.958 ***	−0.213	−0.295 **	−0.354 **
Clay (%)		1.000	0.198	0.211	0.274 *	0.500 ***
Silt (%)			1.000	0.1673	0.239 *	0.230 *
ρ_b (Mg m^{-3})				1.000	0.293 **	0.323 **
w_{FC} (%)					1.000	0.649 ***
w_{WP} (%)						1.000

Table 3 Descriptive statistics and semivariogram analysis of the original data for the three surveys. The standard deviation of the 81-node network formed by kriging estimates and used for correlation analysis is also presented

	Original survey data							81-node network for correlation analysis SD (mm)
	Dates of survey	Sampling points	SDe (mm)	Semivariogram type	Nugget (mm^2)	Sill (mm^2)	Range (m)	
Survey 1	April 1	375	9.6	Spherical	0.0	105	3.9	6.6
Survey 2	May 31	381	20.8	Spherical	0.0	425	4.0	9.7
Survey 3	October 16	381	20.8	Spherical	0.0	400	4.5	8.8

by Playán et al. (1996a), ranging from 6 to 27 m. Correlations between survey 1 and surveys 2 and 3 are 0.267*** and 0.275***, respectively. The correlation between surveys 2 and 3 was the highest (0.614***), revealing the time stability of soil surface elevation attained shortly after crop establishment.

Figure 4 shows contour line maps of soil surface elevation for the three surveys and reveals its evolution in time. The tillage operations related to seedbed preparation created a pattern based on horizontal lines of low and high spots. Surveys 2 and 3 are a combination of the original soil surface elevation pattern (survey 1) and the tillage induced pattern.

A correlation analysis was performed between the three surveys of soil surface elevation and the characterized soil physical properties. Significant correlations were found between penetration resistance and surveys 1 and 3 (0.244* and 0.275*, respectively). It can be concluded that high spots are harder, presumably because they are drier.

Advance and recession

Figure 5 presents contour line maps for the advance, recession and opportunity times for irrigations 2 and 5. The configuration of the advancing front shows important similarities between irrigations 2 and 5, although the effect of soil surface elevation was more relevant to irrigation 5. As for the recession and opportunity times, the effect of soil surface elevation is clear in both irrigations. Wheel-compacted paths were rapidly reached by the advancing front and slowly uncovered by the recession front.

Variability of infiltration

Table 4 summarizes the measured values of the infiltration parameters (irrigations 2 and 5). Their spatial variability is expressed by their CV, which is fairly constant between the two experiments. The CV for k, together with the CV for the saturated hydraulic conductivity (57%) is the largest among the soil physical properties analyzed in this work.

Geostatistical analyses of the Kostiakov-adjusted parameters were performed for both infiltration experiments. No spatial structure was found in any case. Consideration was given to the fact that, as infiltration was characterized by two parameters, interactions between them could obscure its spatial distribution. To explore this possibility, a semivariogram analysis was performed on ECI-τ. The result was equally discouraging: no spatial distribution was found in either of the two infiltration experiments.

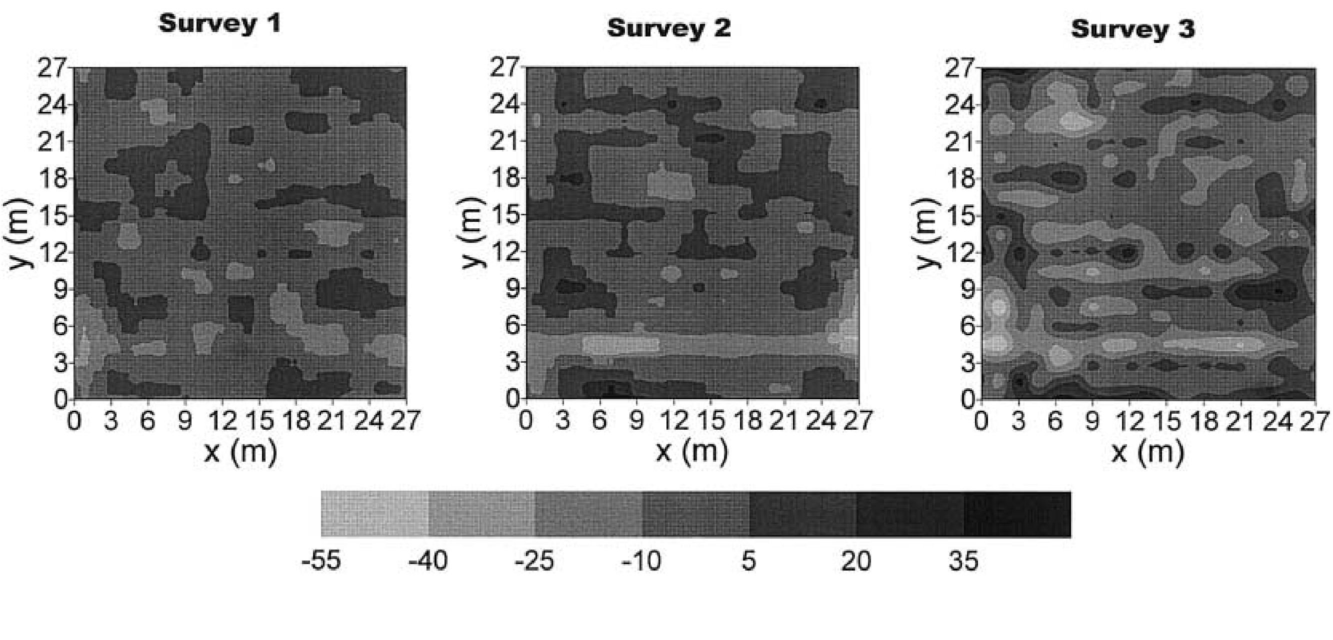

Fig. 4 Contour line maps of soil surface elevation deviation (mm) for the three surveys

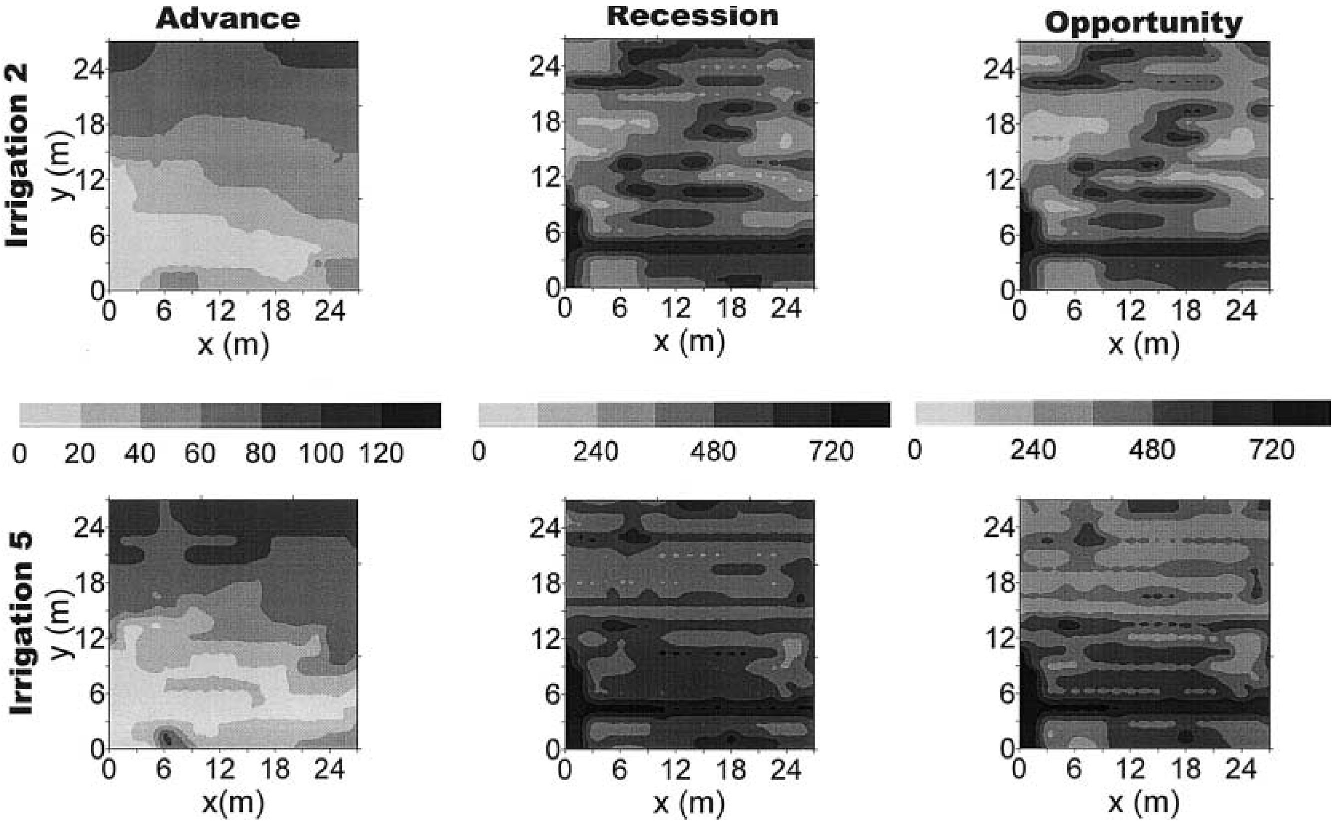

Fig. 5 Contour line maps of advance, recession and opportunity time fronts (min), for irrigations 2 and 5

Two theories were considered in order to explain the random structure of infiltration. First, a finer sampling network should have been used to reveal a spatial pattern whose range is probably smaller than 3 m (the spacing between observations) and, second, the ring infiltrometers did not provide quality measurements. The relatively low values of the scaling factor α in the irrigations coincident with infiltration measurements seem to indicate that the problem lies in the sampling network. In fact, previous works have reported that the geostatistical range depends on the particular field and on how infiltration was measured (Grah et al. 1983). In this sense, Vieira et al. (1981) found a semivariogram for 1280 field-measured infiltration rates with a range of 50 m, while Achouri and Gifford (1984) found a correlation distance lower than 2 m. The results obtained in the experiments reported in this work are similar to this last reference. The relevance of the infiltration range must be evaluated in conjunction with the area explored by the crop roots. A root system exploring a large area can effectively eliminate the effect of the variability of the infiltrated depth on crop water availability. Under these circumstances, an effort to characterize the infiltrated depth variability in detail (with a measurement spacing smaller than the diameter of the root system) would not be justified.

A correlation analysis of the infiltration parameters revealed a high correlation between parameters a and k for a given infiltration experiment. The magnitude of this correlation remains very stable in time, with values of −0.753*** and −0.738*** for the first and the second infiltration experiment, respectively. No correlation was found between the a parameters corresponding to the two experiments, while for the k parameter a high and significant correlation in time was found (0.418***). To analyze the time stability of the spatial variability of cumulative infiltration, a correlation analysis was

Table 4 Descriptive statistics of the Kostiakov equation parameters for the two experiments

Irrigation	Infiltration experiment	Infiltration parameter	Adjusted local equations (n = 81)				
			α, adjustment coefficient	Mean	SD	CV (%)	Adjusted, spatially-averaged equations
2	1	a		0.2699	0.0739	27.38	0.2563
		k (m min^{-a})	1.399	0.0143	0.0079	55.11	0.0147
5	2	a		0.3203	0.0772	24.09	0.2954
		k (m min^{-a})	1.030	0.0111	0.0090	81.17	0.0115

performed between the ECI-τ values corresponding to the two infiltration experiments. The resulting correlation coefficient was 0.315*. The time stability of the Kostiakov k parameter and the cumulative infiltration suggest that, even with random spatial distribution of infiltration, the infiltration characteristic shows some time stability.

No correlation was found between ECI-τ from either of the two experiments and the hydraulic conductivity. This is in agreement with the previous findings of no correlation between saturated hydraulic conductivity and soil physical parameters in the experimental conditions of this work. Measurements of hydraulic conductivity and infiltration were performed at different times during the season and affected different soil depths. These should be regarded as the causes for the observed lack of correlation. The only agreement between observations in the two properties is the coefficient of variation, which is the largest of the variables studied in this research.

Summary and conclusions

The magnitude of the variability of the soil physical properties characterized in this work changed with depth. Soil texture showed greater variability in the upper layer than in the lower. On the other hand, bulk density, gravimetric water content at field capacity and wilting point showed greater variability at the lower layer. The spatial dependence of the variables (textural classes, bulk density and gravimetric water content) was higher in the upper layer. Most of the studied properties showed a spatial structure with ranges in the vicinity of 6 m, although hydraulic conductivity and the clay fraction in the upper layer were randomly distributed at the experimental sampling density. Theoretical semivariograms could be fitted successfully for the rest of the variables. Correlations between soil physical properties were found only in the lower layer, where significant correlations were established between soil water content at field capacity and wilting point on one hand, and texture and bulk density, on the other. No correlation was found between saturated hydraulic conductivity and the rest of the soil physical properties. The detailed survey of soil physics allowed estimation of MAD at a number of points within the experimental basin. This variable showed a CV of 30.61%, denoting a strong variability for a property that has traditionally been considered uniform in surface irrigation analyses.

The standard deviation of soil surface elevation was in the order of 10 mm just after the laser-guided leveling operation. After seedbed preparation, sowing and a few irrigations, the SDe doubled its value, reaching 21 mm. A significant part of the benefits resulting from laser leveling could be lost in just a few months due to tillage and differential compaction. Preserving the quality of soil leveling seems to be just as important as improving it using laser equipment.

An effort was made to use the physically based Philip equation in this research, leading to unrealistic parameter estimations (negative hydraulic conductivities). Reporting similar findings, Cahoon and Quimby (1998) concluded that relying on named but evasive soil physical properties can lead to poor parameter estimations in extensive field applications. The empirical Kostiakov infiltration equation was finally used in this research. The Kostiakov parameters showed no spatial structure at the surveyed scale. A finer sampling density would not be justified in this irrigation-oriented research because of the homogenizing effect of the crop root system.

Surface irrigation performance is very sensitive to the spatial variability of soil surface elevation, infiltration and soil water-holding capability. Even in the small level basin used in this research, these three properties have been shown to have large variability. In a companion paper, these variables will be used to explain the spatial variability of soil water recharge in four irrigation events. Furthermore, the dependence of yield and its components on the sources of spatial variability will be addressed.

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