9 - SOIL HYDRAULIC PROPERTIES OF SIEROZEM SOILS AND FIELD CROP OBSERVATIONS FOR RZWQM APPLICATION IN FERGANA

G. V. Stulina[1], **M. R. Cameira**[2]

Abstract: Located in the Aral Sea Basin, Uzbekistan suffers from environmental problems related to soil salinization and water scarcity. Under conditions of limited resources, crop production must be maintained at expense of minimum inputs but aiming the achievement of maximum returns. The search of the best combination between the available resources and crop yield can be eased by the interactive use of selective field experimentation and modelling. This study relates to the experimentation phase, where field experiments were conducted under the management commonly found in the region. The objective of this research is the characterization of an irrigated Sierozem soil and the related water and plant growth relationships to parameterize the Root Zone Water Quality Model (RZWQM). In a companion paper the model is used for the simulation and analysis of different agricultural management scenarios upon crop yields. The research was conducted during the crop season of 2001, on a maize (*Zea maïs*) field irrigated with saline water, located in the Fergana Valley. Soil hydraulic properties were determined using an *in situ* monolith experiment together with laboratory methods. Soil moisture, soil water potential, salt regime, and plant development were monitored during the season. The methodologies applied showed adequate to obtain the main input parameters required by the simulation model.

Keywords: Soil hydraulic properties, Soil water, Crop growth, Maize, Fergana.

Introduction

Located in the Aral Sea basin, the Republic of Uzbekistan suffers from an environmental desertification crisis that do not favour sustainable development. The prevailing arid climate requires that cultivated crops be intensively irrigated.

[1] Central Asian Scientific Research Institute of Irrigation (SANIIRI), B.11, Karasu-4, Tashkent, 700187, Uzbekistan. Email: galina_stulina@mail.ru

[2] Agricultural Engineering Research Center, Institute of Agronomy, Technical University of Lisbon, Tapada da Ajuda, 1349-017 Lisbon, Portugal. Email: roscameira@isa.utl.pt

Population growth, development of new lands, an abrupt increase of water withdrawals from the major rivers SyrDarya and AmuDarya, the exhaustion of river's reserves, as well as a series of dry years led to distorted equilibrium and water-salt imbalance. In addition, the economical situation is under transition to market with many difficulties associated to such changes. A view on water and land management relative to these problems is presented by Dukhovny and Sokolov (1998).

Irrigated agriculture is and will be the main water user in the region, up to 90% of the total available water. The search for feasible issues leading to increase irrigation water productivity is essential to cope with the scarcity of irrigation water. Among others, modelling is an effective tool to develop new management approaches. We must ensure that models and their parameters are evaluated with as much rigor as possible. In order to collect appropriate data for evaluation, the experiments need to be properly designed. A poor sampling arrangement could lead to the rejection of a good model or the acceptance of a poor one (Addiscot *et al.*, 1995). Some parameters often cannot be measured directly or easily and the second best option is to obtain such parameters by fitting to data, independent of the type of the problem to be simulated. (Addiscot *et al.*, 1995).

The objective of this research is to apply field and laboratory methods in order to obtain the parameters necessary for the application of the Root Zone Water Quality model to simulate the influence of different agricultural management scenarios, including salinity and irrigation management, upon crop yields as analyzed in a companion paper (Stulina *et al.*, 2005).

The research was conducted on a maize field irrigated with saline water, located in the Fergana Valley, during the 2001 growing period. Soil hydraulic properties were determined using an *in situ* monolith experiment together with laboratory methods. Soil moisture, soil water potential, salt regime, and plant development were monitored during the season.

Materials and methods

Location and general characterization of the experimental site

The field research was conducted in the maize cropped field # 5 located in the farm Azizbek-1 during the 2001 crop season. The farm is located in the area of the former Niyazov state farm 2, in the Ahunbabayev rayon of Fergana province, SyrDarya river basin. This area lies within the flat smooth proluvial plain that constitutes the peripheral part of the alluvial cone of the Margilansay, Shahimardansay, and Isfaramsay rivers. This plain is slightly inclined to the modern valley of the SyrDarya river. Elevation ranges from 429 to 434.7 m. A dense network of irrigation canals supplied by the Big Fergana Canal (BFC) delivers irrigation water to the intensive agriculture that developed in the plain. Open and close drains and drainage collectors having a depth of 5 - 7 m or more constitute the drainage system. Slopes northward are low, from 0.002 to 0.005.

Climate

The climate of the region is continental and arid. Summer is hot and dry and the winter is cold with moderate frost (Fig. 1). Soil surface temperatures have a similar regime to that of air temperatures. The average annual temperature of the soil surface is 21.2 °C.

The average annual precipitation is 169 mm. The distribution of precipitation is irregular, with most of it falling during the non-growing season (112 mm), with the maximum in March (24 mm). During the crop growth period, the maximum precipitation occurs in April-May (18-19 mm) and the minimum in July-August (2-4 mm). In 2001, the distribution of precipitation throughout the year differs from the average. Spring was dry and only 42% occurred in March. In summer, the amount of precipitation exceeded the long-term average.

The average relative humidity (RH) of the air is 52%. June is the driest month (RH = 46%) while air humidity reaches 80% in December through February. Thick fogs and ice-covered ground also characterize winter months.

Potential evaporation from free water surface is high, totalising 924 mm during April-September with a maximum of 206 mm in July. In 2001 evaporation behaved different from usual since it decreased during the mid-growing period due to precipitation.

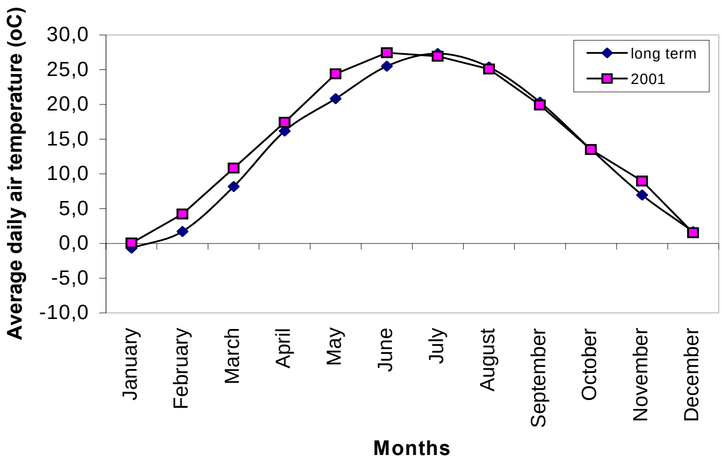

Fig. 1. Air temperatures: average values for the period 1970-2000 and 2001 values. Fergana meteorological station.

Soils and hydrogeology

The Fergana region presents a shallow groundwater that includes both free and artesian water. Artesian water is at a depth of 120-200 m. Specific yields of wells average 1 ls^{-1}. Water is fresh, with salinity of 0.55 gl^{-1}, dominated by sulphate-hydrocarbonate-calcium-magnesium. The shallow groundwater depth varies from 1.2 to 2.1 m in the sandy loam and loam zones. The groundwater salinity is between 2.9 and 4.6 gl^{-1}, dominated by sulphate-chloride and sulphate. High groundwater salinity relates to low gradient and slow outflow. The water table gradient is 0.002-0.0025, indicating low drainability. The small slopes and conductivity of the soil surface, causes a stagnant nature of the groundwater, which due to evaporation leads to salt accumulation in soils and increases groundwater salinity. Groundwater is recharged mainly through infiltration of irrigation water, seepage from the irrigation canals and the deep artesian aquifers.

Soils are Calcic Sierozems, formed on alluvial-proluvial deposits of talus train. Two soil profiles were selected for analysis on experimental fields. Sierozem soils are described by Dobrovolskiy (1979), Bogatyryev *et al.* (1988) and Umarov (1975). Field and laboratory studies were carried out to study soil parameters (supplemental information in Stulina, 2003). Table 1 shows the soil particles distribution and the bulk density for all soil layers between the soil surface and 130 cm deep.

Bulk density is similar for the depths below 20 cm, except for the 35 – 50 cm layer, which presents a lower value. Also at the surface layer the bulk density presents a small value of 1.1, probably due to tillage effects. These lower values influence the water retention properties, especially in the wet region.

Table 1. Soil particle distribution and bulk density of the different layers, Fergana, Azizbek, field # 5.

	Particle distribution (%)			Bulk
Soil layer (cm)	sand	silt	clay	Density
0-20	33	52	15	1.10
20-35	34	52	14	1.50
35-50	45	48	7	1.32
50-90	48	42	10	1.50
90-130	47	46	7	1.52

Table 2 presents some chemical parameters of the soil, measured on the 1:5 water extract. Total salts are distributed evenly along the profile, not exceeding 1.10%. As for the ions composition, calcium and sulphates prevail and constitute 11–15 meq/100 g of soil. Others are Mg (0.986–1.726 meq/100 g), Na^+ (0.609–0.826 meq/100 g), Cl^- (0.423–0.846 meq/100 g), and CO_3H^- (less than 0.2 meq/100 g).

Table 2. Chemical content of water extract 1:5 for soils of studied field (17.03.2001).

Horizon, cm		content (%)						
		EC 1:1, dS/m	TDS	HCO'_3	Cl'	SO''_4	Ca	Mg
A n	0-25	1.34	1.05	0.012	0.015	0.671	0.260	0.015
B 1	45-66	1.49	1.03	0.012	0.025	0.654	0.250	0.012
B 2	66-83	1.25	1.02	0.009	0.020	0.647	0.250	0.018
B 3	83-94	1.33	1.06	0.012	0.020	0.714	0.270	0.018
B 4	94-120	1.39	1.07	0.012	0.025	0.708	0.275	0.015
B 5	121-143	1.43	1.01	0.009	0.020	0.728	0.275	0.018
B 6	143-173	1.44	1.08	0.015	0.030	0.747	0.280	0.021
B 7	173-200	1.38	1.01	0.012	0.025	0.715	0.275	0.018

Horizon, cm		concentration (meq/100g)						
		$Na'+K'$	HCO''_3	Cl'	SO''_4	Ca	Mg	$Na'+K'$
A n	0-25	0.019	0.197	0.423	13.956	13.000	1.233	0.826
B 1	45-66	0.018	0.197	0.705	13.603	12.500	0.986	0.783
B 2	66-83	0.016	0.147	0.564	13.457	12.500	1.479	0.696
B 3	83-94	0.016	0.197	0.564	14.860	13.500	1.479	0.696
B 4	94-120	0.015	0.197	0.705	14.735	13.750	1.233	0.652
B 5	121-143	0.016	0.147	0.564	15.146	13.750	1.479	0.696
B 6	143-173	0.017	0.246	0.846	15.465	14.000	1.726	0.739
B 7	173-200	0.015	0.197	0.705	14.880	13.750	1.479	0.652

Hypothetically, under such ion composition, salts of $Ca(HCO_3)_2$, $CaSO_4$ (soluble gypsum), $MgSO_4$, Na_2SO_4, and NaCl are present in soils. Major amount of salts are represented by the non-toxic compound of $CaSO_4$, which practically constitutes more than 80% of solid residue. However, the presence of this salt in the soil solution creates osmotic effects and reduces the water extraction by plant roots. Yield losses can be higher than 25%.

Agrochemical soil properties were studied in the top 50 cm layer. Regarding organic matter content (OM), the soils in the plough-layer were estimated as "rich", with 1.6–1.9%. This values decrease to 1.2–0.7% along the profile. $N–NH_4$ concentrations show values of 22–32 $mgkg^{-1}$ (ppm) in the upper soil horizon, which increase up to 42–51 $mgkg^{-1}$ in underlying layers. Phosphorus in PO_2 form changes with depth from low concentration (14–16 $mgkg^{-1}$) to very low (7–12 $mgkg^{-1}$). Potassium (K_2O) varies within 100–154 $mgkg^{-1}$, meaning low availability.

Crop management

The experimental field was cropped with Maize for silage, under the recommendations of the local agronomist experts (Table 3).

Table 3. Agronomic practices relative to maize cropped in the experimental plot.

Date	Practice
03.07.01	Planting
29.07.01	1st irrigation
10.08.01	Application of super phosphate 250 kg/ha + potassium chloride 50 kg/ha + urea 174 kg/ha
14.08.01	2nd irrigation
07.09.01	3rd irrigation
15.10.01	Harvesting

The crop was irrigated by furrows. Three irrigations were performed, with a total amount of approximately 300 mm, using water with and average salinity of 3.7 dS m^{-1} (Table 4). Irrigation scheduling was based on the soil and crop water status. Irrigation is described with more detail in Horst *et al.* (2005).

Table 4. Irrigation scheduling on the experimental plots.

Irrigation	Date	Applied depth (mm)	Water salinity (dS/m)
1	07.29.01	89	3.7
2	08.14.01	100	3.7
3	09.07.01	107	3.8

Characterization of the soil hydraulic properties

The unsaturated hydraulic conductivity, K(h), and the water retention curve, θ(h), were determined *in situ* in a soil monolith (2 x 2 x 2 m) located in the experimental plot, according to the methodology described by Cameira *et al.* (2003). The internal drainage flux method (Green *et al.*, 1986) was used to determine K(h). The monolith was isolated laterally by a plastic film (Fig. 2). It was equipped with a neutron probe access tube to measure volumetric soil moisture (θ) at the depths of 12.5, 27.5, 42.5, 67.5, 112.5 and 137.5 cm, and two sets of tensiometers to measure hydraulic heads (H) at the same depths (Fig. 3). Initially the monolith was saturated with water. The first measurement of θ and H was performed after infiltration. The monolith surface was then covered with a plastic film and a layer of straw to prevent evaporation and temperature fluctuations, and the internal drainage experiment was started. During the first day measurements were taken every two hours, then once a day for a week, and then every four days and finally once a week for one month. After this period the surface was uncovered allowing evaporation to occur. During this part of the experiment measurements were taken once a day for a week and then once a week for one month.

Fig. 2. Preparation of the soil monolith to avoid lateral water fluxes.

Fig. 3. Two sets of tensiometers and neutron access tubes in a monolith, Fergana.

Hydraulic conductivity was determined based upon the soil water data and the matric suction data by using the Darcy's generalized equation:

$$\varphi_w(z,t) = -K(\theta)\frac{\partial H}{\partial z} \quad [1]$$

where $\varphi_w(z,t)$ is the soil hydraulic flux, $K(\theta)$ is the hydraulic conductivity function of soil at a moisture θ at the depth z and H is the hydraulic head measured in the tensiometers.

Applying the continuity equation to the monodimensional flow and integrating it between the depths z_i and z_{i+1}, we obtain:

$$\int_{z_i}^{z_{i+1}} \frac{\partial \theta}{\partial t} \partial z = -\left[\varphi_w(z_{i+1},t) - \varphi(z_i,t)\right] \quad [2]$$

where $\varphi(z_i,t)$ and $\varphi(z_{i+1},t)$ are the hydraulic fluxes at the depths z_i and z_{i+1}.

Knowing the soil water contents function $\theta(z,t)$, the first side of the equation can be determined, and knowing one of the fluxes the right side of the equation can be determined. Then, once the hydraulic head function H(z,t) is known, the hydraulic gradient can be calculated for each time and depth. Then the hydraulic conductivity is obtained by applying the Darcy's equation. The calculation procedure is described in Fig. 4.

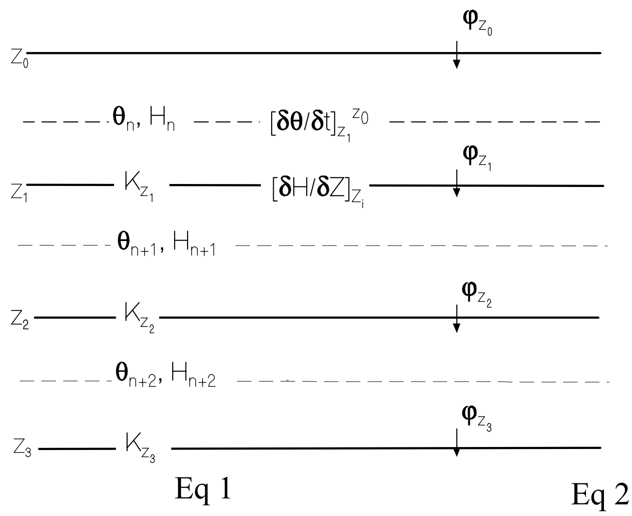

Fig. 4. Calculation procedure for the hydraulic conductivity using data from the monolith experiment.

The matric suction curve determined *in situ* was complemented by laboratory values obtained from two different methods: the pressure membrane method (pF >2, where pF = log (h) in cm) (Klute, 1986) and the desorption method (Vadunina and Korchagina, 1973) used in the University of Moscow (at pF 6.466, 5.955, 5.742, 5.512, 5.318 and 4.445). For these methods, undisturbed soil samples (100 cm^3) were collected in the experimental plot.

The Brooks and Corey (1964) functions modified as described by Ahuja *et al.* (1999) were fitted to both θ(h) and K(h) experimental data. These functions consist of the following:

- The soil water content, θ (cm^3 cm^{-3}) vs. soil water pressure head, h (cm), relation is expressed by

$$\theta(h) = \theta_s - A|h| \qquad 0 \leq |h| \leq |h_b| \qquad [3a]$$

$$\theta(h) = \theta_r + B|h|^{-\lambda} \qquad |h| \leq |h_b| \qquad [3b]$$

where θ_s is the saturated water content, θ_r is the residual content, h_b, A, B and λ are parameters derived from best fitting of experimental data.

- The hydraulic conductivity, K (cm h^{-1}), vs. soil water pressure head, h (cm), relation is given by

$$K(h) = K_s|h|^{-N_1} \qquad 0 \leq |h| \leq |h_2| \qquad [4a]$$

$$K(h) = C|h|^{-N_2} \qquad |h| \leq |h_b| \qquad [4b]$$

where K_s is the field saturated hydraulic conductivity and h_2, N_1, N_2, and C are parameters derived from experimental data.

Field monitoring

In order to collect data to control the model simulations over the 2001 crop season, some variables were monitored in the field throughout this period. Field monitoring consisted in measuring soil water data (soil moisture and water table depths) and crop data (phenological stages, plant height and biomass).

Three experimental plots with the dimensions 5 m x 6 m were established on Field # 5, cultivated with maize for silage. The experimental plots were equipped with two sets of tensiometers, access tubes for neutron probe measurements and a piezometer for monitoring the water table to a maximum depth of 2.5 m. Measurements of the soil water potential and soil moisture were made every day at the depths of 37.5 cm, 52.5 cm, 87.5 cm, 107.5 cm and 132.5 cm. At the depth of 12.5 cm soil moisture was determined by the gravimetric method.

Two crop rows were selected for the crop measurements, which were performed twice a month (at the beginning and in the middle of a month). The measurements included phenological observations to determine the beginning of each crop stage. At the beginning of each stage, six plants were collected in each row, to measure plant height, above ground biomass and rooting depth using the methodology described by Dospekhov (1985). Yield was measured at harvest.

Results and discussion

Soil water retention and hydraulic conductivity functions

Fig. 5 shows the temporal evolution of hydraulic head profiles H (z, t) during the period of observation on monolith. Field data reveal the expected evolution of the hydraulic head and reflect clearly the influence of evaporation. In the first part of the experience, when the surface was covered, a downward flux in the soil profile was observed. During the second part, when the monolith was uncovered, there was an upward flux due to evaporation. Fig. 6 shows the evolution of soil moisture at five depths during the monolith experiment (between day 174 – 23rd June and day 246 – 3rd September).

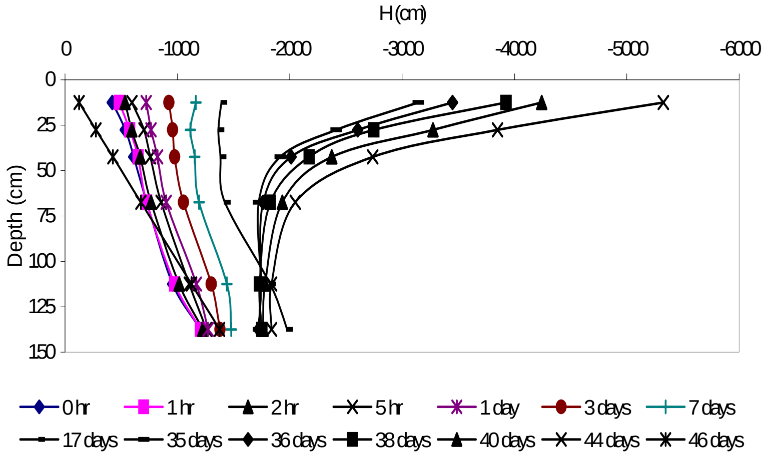

Fig. 5. Temporal evolution of the hydraulic head profiles during the drainage test on the monolith.

Equations [1] and [2] were applied to the data presented above, according to the procedure presented in Fig. 4, for the determination of K(h) and h(θ) values. For the latter, the values were completed by laboratory results.

Fig. 7 shows the soil water retention curves determined by the two lab methods referred previously as compared with the field values. Further information is given by Stulina (2003).

The method used in the Moscow lab produced results very different from the field observations. In the wet region, until pF 3, the moisture values are much higher than the values produced by the lab method described by Klute (1986) or the field values.

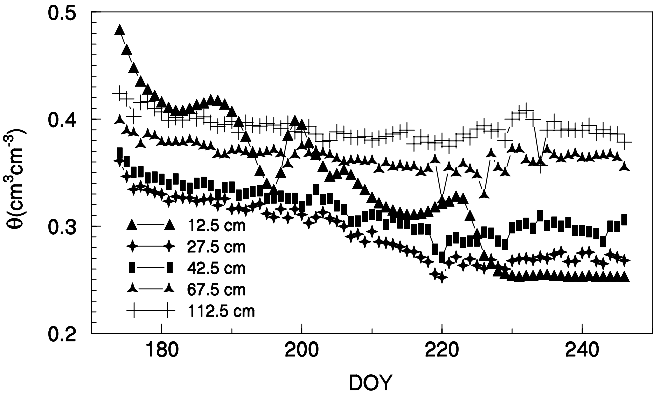

Fig. 6. Temporal evolution of soil moisture at five depths during the monolith experiment.

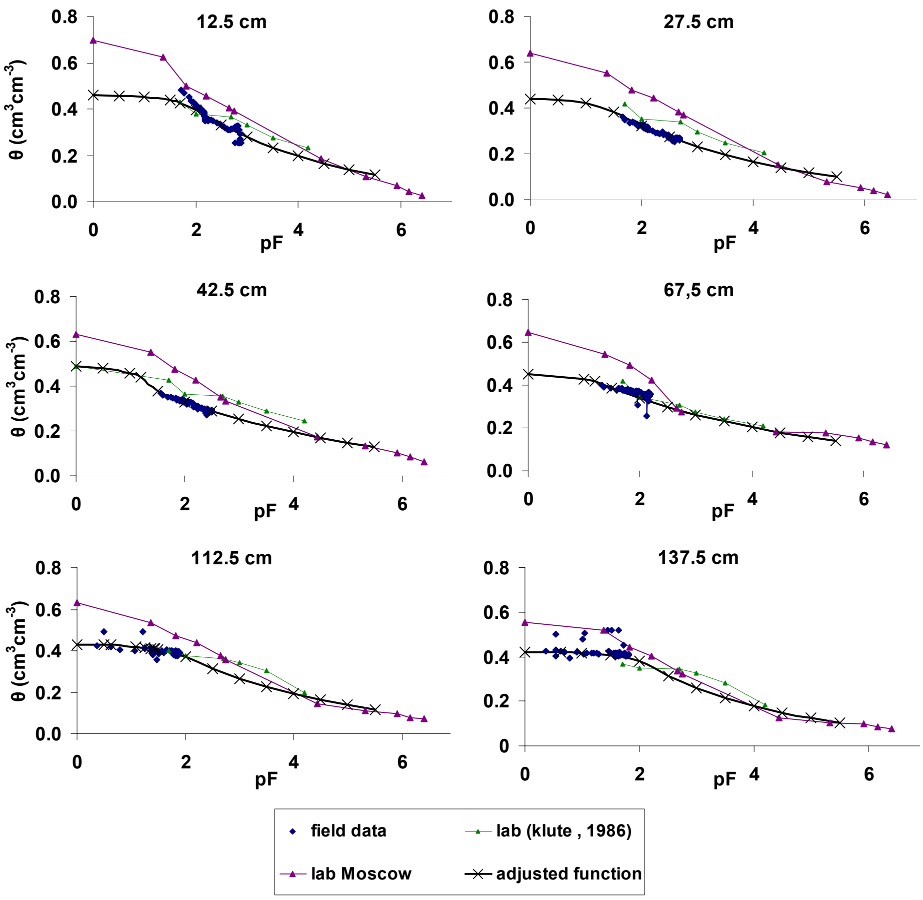

Fig. 7. Water retention curves obtained from the different applied methods.

Due to the facts referred above, the final retention curve for each layer was obtained based upon the Klute method and the field data from the monolith (Fig. 8). For all soil layers and the whole soil moisture range, the modified Brooks and Corey relationships were fitted to the experimental curves using the CoPlot program.

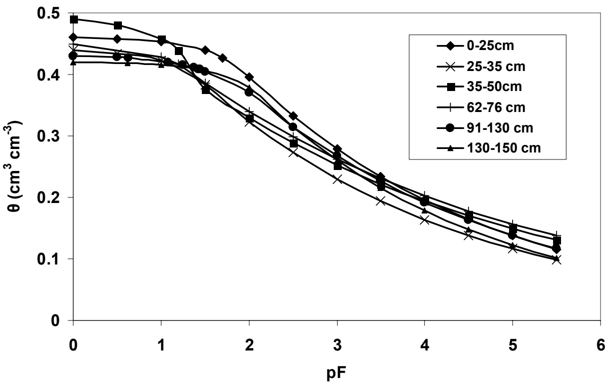

Fig. 8. Final water retention curves described by the Brooks & Corey functions.

Fig. 9 shows the Brooks & Corey hydraulic conductivity functions adjusted to field data. Due to the lack of values for pF>3, the functions were adjusted based only upon the measurements on the wet region, which is the most important for irrigation studies.

In the wet zone, near saturation, the layers presenting lower bulk density values differ from the rest, showing higher moisture content at saturation, related with the larger pores. For pF higher than the bubbling pressure, the curves are very similar for al the depths, showing a low drainable porosity and a high holding capacity for water.

The hydraulic conductivity functions are similar for the entire profile. Exceptions are found in the saturated hydraulic conductivity that shows important variations throughout the profile. The values are 1.8, 0.42, 1.8, 0.25 and 0.42 cmh^{-1} for the layers 0-20, 20-35, 35-55, 55-90 and 90-130 respectively.

Soil water dynamics in the root zone

Fig. 10 shows the evolution of the soil water content at various depths. Fig. 11 shows the water table depths during the 2001 crop growing period. The irrigations caused an increase in the moisture content for all the depths, especially above 52.5 cm. The irrigation water reaches the water table, causing it to rise until 0.75 m after the first two irrigations and to 0.3 m after the third irrigation. Below the depth of 37.5 cm, the soil moisture is always above field capacity due to the excessive irrigation amounts and the strong influence of the water table.

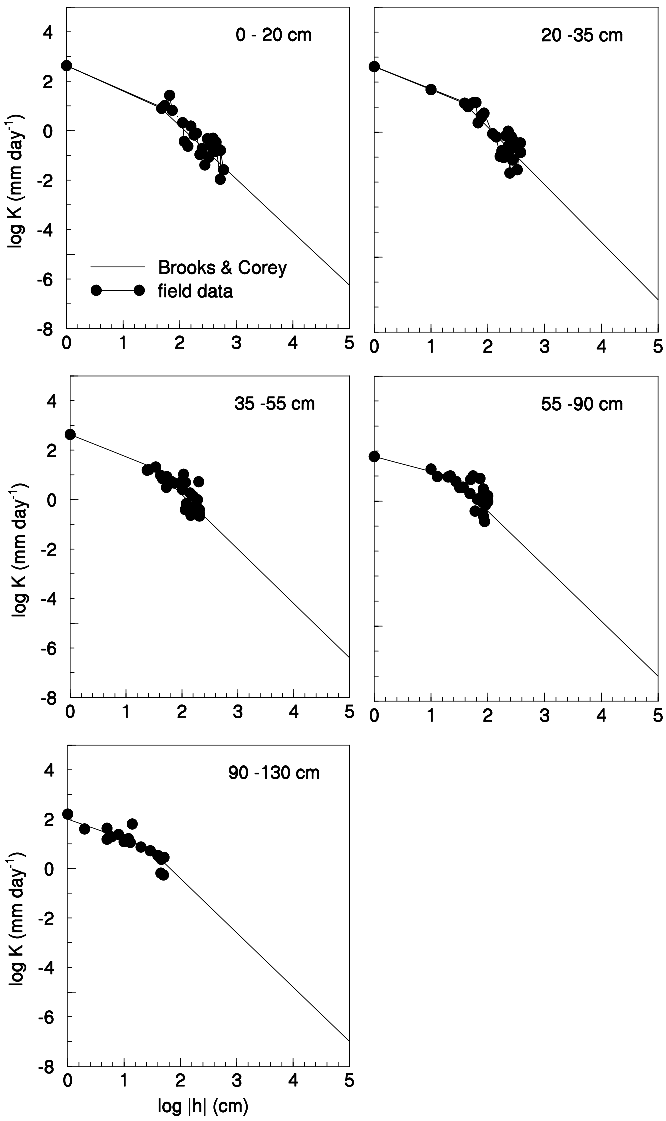

Fig. 9. Brooks and Corey functions adjusted to hydraulic conductivity field data.

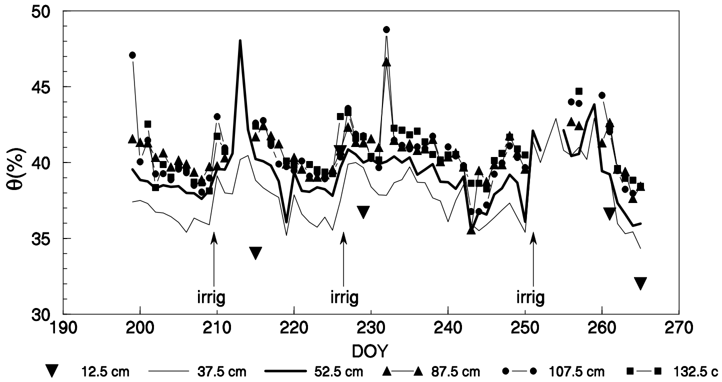

Fig. 10. Measured soil water content for the period between 18th July (DOY 199) and 22nd September (DOY 265).

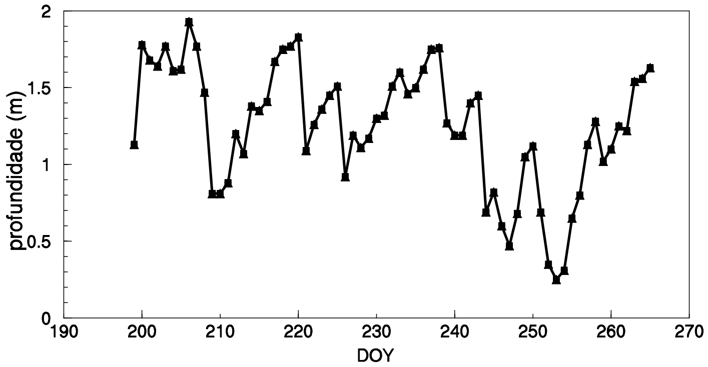

Fig. 11. Water table depths (m) during the crop growing period.

Crop growth and development

The starting dates for each crop development stage and its duration were determined by phenological observations. These stages are: 3 - 4 leaves (DOY 212); beginning of reproductive stage – 12 leaves (DOY 247); beginning of maturation (DOY 269).

Plant height, rooting depth and above ground biomass are shown if Fig. 12. The yield measured at harvest was 15 ton/ha.

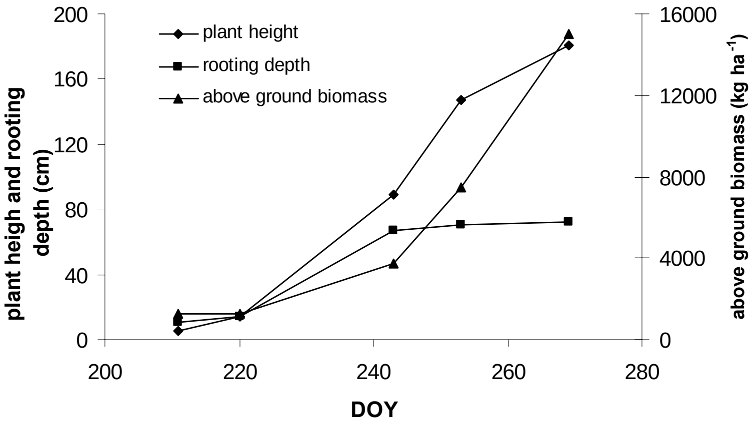

Fig. 12. Maize development.

Conclusions

The characterization of the soil hydraulic properties was performed in order to produce input parameters for the simulation model RZWQM.

The field monolith allowed the collection of a good data set for the calculation of the hydraulic conductivity.

The Moscow lab method applied for the determination of the water retention curve did not produced good results. The moisture values for the tensions in the wet range were very high when compared with the field data. Because of this only the data produced by the lab method described by Klute (1986) were used.

The Brooks & Corey functions show good adjustments to the field and lab methods, for the retention curve and for the hydraulic conductivity, providing a good description of the hydraulic properties.

The monitoring performed during the crop growth season showed that the soil moisture content was always above field capacity, except for the surface layer. After each of the three irrigations performed the water reached the water table causing it rise near to the surface. It can be concluded that the irrigation amounts were excessive.

The monitoring of the crop development allowed the collection of data to evaluate the crop growth module of the RZWQM (performed in a companion paper by Stulina *et al.*, 2005).

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