SIMULATION OF BASIN IRRIGATION SCHEDULING AS A FUNCTION OF DISCHARGE AND LEVELING

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SUMMARY

Irrigation scheduling was simulated on several case studies involving basin irrigation for two crops and two locations using a two-dimensional irrigation model. The crops were wheat and alfalfa, and the locations had reference evapotranspiration of 1,194 and 926 mm year^{-1}, respectively. Two variables were considered at the farm level: inflow discharge and quality of land leveling. Considered discharges ranged from 0.05 to 0.20 m^3 s^{-1}. The quality of land leveling was characterized by means of the standard deviation of surface elevation (SD), ranging from 0 to 30 mm. Results indicated that increasing the discharge from 0.05 to 0.20 m^3 s^{-1} reduces the number of irrigations by an average 32%. As for land leveling, if the SD was improved from 30 to 0 mm, the number of irrigations would be cut by 22%. Low discharge and poor leveling are associated with low application efficiency which results in important seasonal deep percolation losses.

KEY WORDS: Level basin
Laser
Inflow discharge
Efficiency
Deep percolation
Scheduling

INTRODUCTION

Irrigation scheduling can be effectively used as a tool to estimate the impact of modifications on the design and management of surface irrigated fields on the seasonal use of water and labor, and on the potential for non-point-source pollution. The impact of practices such as enlarging the capacity of the conveyance system or using laser guided leveling will vary according to crop water requirements.

The development of two-dimensional hydrodynamic models of basin irrigation (Playán *et al.*, 1994) has revealed some inherent limitations of one-dimensional models when applied to the design and management of basin irrigation systems. Two-dimensional models are very advantageous to explore the effect of the spatial variation of soil

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parameters on irrigation performance. Among these parameters, soil surface elevation has been identified as an important source of variability in irrigation depth (Playán *et al.*, 1996a).

A two-dimensional model has been used in this research to evaluate the effect of soil surface undulations and inflow discharge on the performance of an irrigation event on a level basin. Irrigation scheduling, using a water budget method, was applied to determine the seasonal distribution of the irrigation events, the number of irrigations and the seasonal deep percolation losses for two crops (wheat and alfalfa) and two sites differing in water requirements.

MATERIAL AND METHODS

The B2D model was presented by Playán *et al.* (1994, 1996b) as a simulation tool for basin irrigation. B2D was first used to characterize field shape effects on irrigation performance and to explore the relationship between spatial variability of infiltration and irrigation uniformity. Lately, the model has been used to characterize the effect of microtopography on irrigation performance. Surface irrigated basins have no global slope, but the undulations of the soil surface can have an important effect on the advance and recession processes of an irrigation event. In this research, the model is applied to the simulation of irrigation events on a rectangular basin 288 m long and 29 m wide. An irrigation evaluation on the experimental basin revealed that infiltration was characterized by the following Kostiakov-Lewis expression:

$$z = 0.00326\, \tau^{0.457} + 0.000088\, \tau \qquad [1]$$

where:

z = infiltrated depth (m); and
τ = opportunity time (min).

In all the simulations reported in this work, infiltration will be modeled using equation [1], which does not show dependence on space (within the basin) and time (between irrigations). This assumption represents an important simplification of the real field conditions. The spatial variability of soil physical properties induces a large variability in the infiltration parameters. Neglecting this source of spatial variability will result in an overestimation of application efficiency. The differences in soil water and compaction between irrigations produce time variability of the infiltration parameters, resulting in relevant differences in the time of advance between irrigations. As a consequence, some variability in the irrigation efficiency is also to be expected. Since these sources of variability were not considered in this research, the efficiency estimates could be higher than real. However, we believe that they reflect properly the differences in irrigation performance resulting from different conditions of irrigation discharge and soil leveling.

In the simulations, the field was irrigated from the West side (Fig. 1). According to Clemmens (1994), the irrigation time was determined by the advance process: the inflow was cut off at the time of complete advance in all cases. Differences in irrigation time among simulations resulted in different average irrigation depths.

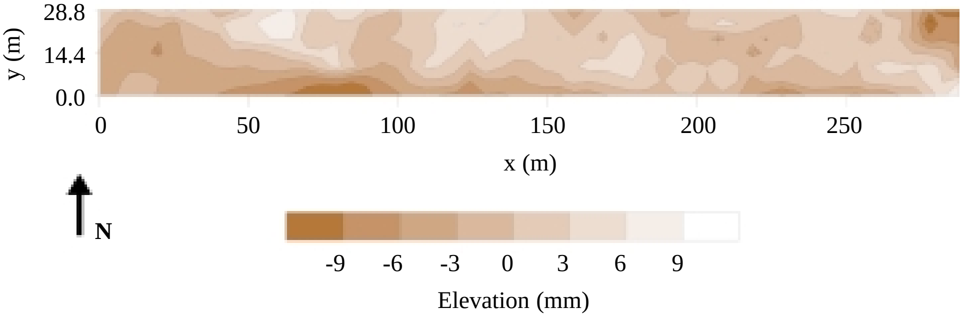

Fig. 1.–Contour level map of soil surface elevation in the experimental basin
Mapa de curvas de nivel de la elevación del terreno en el tablar experimental

Four values were used for the inflow discharge (Q): 0.05, 0.10, 0.15 and 0.20 $m^3 s^{-1}$. The quality of land leveling was measured using the standard deviation of soil surface elevation (SD). In the studied basin, elevation was characterized by a detailed survey. The field had no general slope, and showed an SD of 34 mm. The original relief of the field was modified by scaling down the elevation data to obtain four relieves with SD's of 0, 10, 20 and 30 mm. This was accomplished by multiplying the original elevation data by an *ad hoc* constant. In each case, the value of the constant that resulted in the desired SD of the elevation data set was adopted. A zero value of SD indicates a perfectly flat surface (an unreal situation). A typical value of SD for basins leveled with laser guided scrapers is 10 mm (Bucks and Hunsaker, 1987). SD's of 20 and 30 mm are characteristic of not uncommonly poorly leveled basins. The resulting relieves were used as an input to the model, and applied to the computation of the local slopes in the x and y directions at each node. More details on the simulation procedures can be found in Playán (1996).

Irrigation events for two crops (alfalfa and wheat) and two locations (Zaragoza and Daroca, NE Spain), were scheduled for the different net irrigation depths listed in Table 1 using a water budget method. In this method, crop evapotranspiration (ET_c) and net water requirements (NH_n) were computed using guidelines proposed by Doorenbos and Pruitt (1977). Thus, long-term averages of total monthly reference evapotranspiration (ET_0) were computed in the two locations by applying the FAO-USDA Blaney-Criddle method (Doorenbos and Pruitt, 1977; Allen and Pruitt, 1986). Required meteorological parameters (long-term monthly average of daily mean air temperature, daily minimum relative humidity, daily windrun at 2 m above soil level and daily bright sunshine hours) for the period 1970-1989 were recorded at the two locations (Faci and Martínez-Cob, 1991). The Zaragoza weather station was located at 1°00'23'' W (Greenwich) longitude and 41°39'43'' N latitude, while Daroca weather station was located at 1° 24'33'' W (Greenwich) longitude and 41°06'53'' N latitude. Both locations are in a semiarid climate. Ratios of annual precipitation to annual ET_0 are at the lower (Zaragoza) and the higher (Daroca) limits of the semiarid range as defined by the FAO (FAO, 1977).

TABLE 1

MAIN CHARACTERISTICS OF THE IRRIGATION EVENTS SIMULATED WITH THE TWO-DIMENSIONAL MODEL

Características principales de los riegos simulados con el modelo bidimensional

Q	SD	TA	TR	PAELQ	ZN	VG	VN	VDP
0.05	0	233	488	83	69	699	582	117
	10	245	750	82	71	735	603	132
	20	261	1,026	70	65	783	550	233
	30	—	—	—	—	—	—	—
0.10	0	124	479	91	82	744	678	66
	10	129	724	86	80	774	666	108
	20	137	1,022	76	74	822	623	199
	30	140	1,290	65	64	840	549	291
0.15	0	91	531	95	94	819	777	42
	10	94	779	88	90	846	746	100
	20	99	1,069	79	83	891	707	184
	30	103	1,363	69	76	927	638	289
0.20	0	74	584	97	103	888	863	25
	10	77	837	89	99	924	824	100
	20	80	1,130	80	92	960	770	190
	30	83	1,433	72	85	996	714	282

Q, inflow discharge. SD, standard deviation of surface elevation. TA, time of advance. TR, time of recession. PAELQ, potential application efficiency of the low quarter. ZN, net irrigation depth. VG, gross irrigation volume. VN, net irrigation volume. VDP, deep percolation volume.

Q, caudal de riego. SD, desviación estándar de la elevación del terreno. TA, tiempo de avance. TR, tiempo de receso. PAELQ, eficiencia potencial del cuarto bajo. ZN, lámina neta de riego. VG, volumen bruto de riego. VN, volumen neto de riego. VDP, volumen de percolación profunda.

Next, crop coefficients (K_c) were required to compute ET_c values from estimates of ET_0 and derived from tabulated values as a function of crop development stages and general local climatic conditions (Doorenbos and Pruitt, 1977). Alfalfa was considered a perennial crop and a uniform K_c value (representative of the average crop conditions) was used for all months of the year in a particular location ($K_c = 0.89$). For wheat, it was assumed that sowing and physiological maturity dates were December 15 and July 10, respectively, in Zaragoza, and December 5 and July 20, in Daroca, and crop seasons were divided in four stages as indicated by Doorenbos and Pruitt (1977).

Subsequently, monthly net crop water requirements (NH_n) were obtained subtracting effective precipitation from estimated ET_c values. Effective precipitation was computed from long-term averages of total monthly precipitation recorded at the two weather stations and the estimated ET_c values, using the U.S. Soil Conservation Service method (Cuenca, 1989). Thus, computed NH_n values represent the average water requirements of alfalfa and wheat in Zaragoza and Daroca for an average year.

Finally, the number of irrigations during the crop season was computed for the different net irrigation depths resulting from the simulation experiments. For each case, a given monthly NH_n value, expressed in mm day^{-1}, was assigned to the central day of a month. Daily NH_n values for other days were obtained by linear interpolation between two consecutive monthly NH_n values. Then, a daily soil water balance was performed subtracting the daily NH_n estimate for day *i* from the soil water content at day *i-1*. The initial soil water content was arbitrary. An irrigation was scheduled when soil water depletion attained the chosen net irrigation depth. Potential application efficiency of the low quarter (PAELQ) was used as an adequacy criterion (Walker and Skogerboe, 1987). Deep percolation losses can be computed in basin irrigation as 100 - PAELQ. The seasonal volume of deep percolation depends on the application efficiency and the number of irrigations.

RESULTS AND DISCUSSION

Figure 1 presents a map of soil surface elevation in the experimental basin. The map reveals the existence of localized high and low spots. These spots can have a relevant effect on overland water flow during the irrigation event. Figure 2 presents five contour line maps of flow depth during the simulation of the case study characterized by a discharge of 0.15 m^3 s^{-1} and a SD of 20 mm. During the advance phase (times 40 and 80 min) water flows towards the East. Advance is faster in the South side, due to the lower soil surface elevation in this area (Fig. 1). In the depletion phase (time 300 min) the water surface is parallel to the soil surface, and water depth becomes a negative image of soil surface elevation. During the recession phase (times 500 and 700 min) water accumulates on the low spots, increasing their opportunity time.

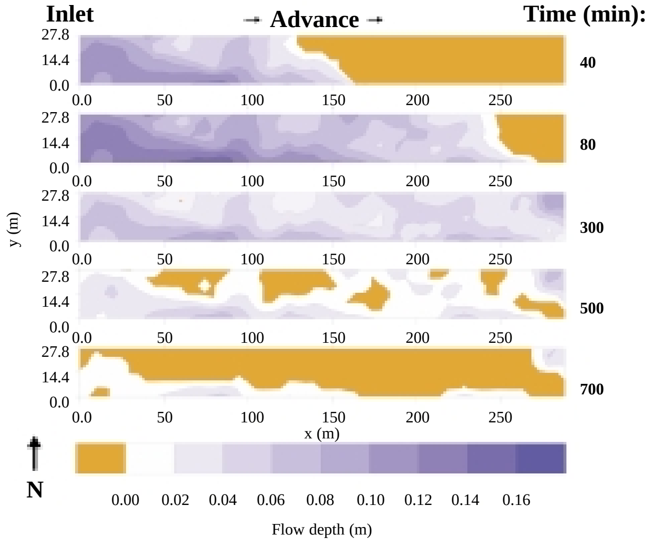

Fig. 2.–Contour line map of simulated flow depth at selected times during the irrigation with discharge of 0.15 m^3 s^{-1} and SD of 20 mm. Times 40 and 80 min correspond to the advance phase. Time 300 min corresponds to the depletion phase. Times 500 and 700 min correspond to the recession phase

Mapas de curvas de nivel del calado del agua simulado a distintos tiempos durante el riego con un caudal de 0,15 m^3 s^{-1} y SD de 20 mm. Los tiempos de 40 y 80 min se corresponden con la fase de avance. El tiempo de 300 min se corresponde con la fase de vaciado. Los tiempos de 500 y 700 min se corresponden con la fase de receso

Results of the irrigation simulation experiments are summarized in Table 1. The combination of SD = 30 mm and Q = 0.05 m^3 s^{-1} produced large numerical errors (larger than 2 %), and therefore the results were discarded from the study. The variables presented in Table 1 are: 1) time of advance (TA, min); 2) time of recession (TR, min); 3) potential application efficiency of the low quarter (PAELQ, %); 4) net irrigation depth (ZN, mm); 5) gross irrigation volume (VG, m^3); 6) net irrigation volume (VN, m^3); and 7) deep percolation volume (VDP, m^3).

Table 2 lists the long-term averages of monthly ET_0 and precipitation in the two locations, Zaragoza and Daroca. The table also includes the calculated monthly net crop water requirements for alfalfa and wheat in the two locations. In Zaragoza, ET_0 was higher and precipitation was lower than in Daroca. Thus, computed total annual net crop water requirements were about 50 % higher in Zaragoza than in Daroca for both alfalfa and wheat.

TABLE 2

LONG-TERM AVERAGES OF TOTAL MONTHLY REFERENCE EVAPOTRANSPIRATION (ET_0), PRECIPITATION (P), AND NET WATER REQUIREMENTS (NH_n) FOR TWO CROPS, ALFALFA AND WHEAT, IN TWO LOCATIONS, ZARAGOZA AND DAROCA

Evapotranspiración de referencia (ET_0), precipitación (P) y necesidades hídricas netas (NH_n) del año medio para dos cultivos, alfalfa y trigo, en dos localidades, Zaragoza y Daroca

	Zaragoza				**Daroca**			
	ET_0 (mm)	**P (mm)**	**NH_n (mm)**		**ET_0 (mm)**	**P (mm)**	**NH_n (mm)**	
			Alfalfa	**Wheat**			**Alfalfa**	**Wheat**
Jan	24	24	12	8	13	25	4	3
Feb	45	21	27	21	27	27	10	7
Mar	83	22	60	63	56	34	30	31
Apr	112	32	77	99	77	48	38	49
May	145	41	99	127	106	67	52	71
Jun	172	40	122	90	135	56	82	80
Jul	188	17	153	16	159	29	119	30
Aug	161	18	130		136	37	94	
Sep	115	23	88		102	31	71	
Oct	88	26	61		74	29	47	
Nov	39	32	17		27	33	7	
Dec	22	24	9	4	14	28	3	2
Annual	1,194	320	855	428	926	444	557	273

Table 3 lists the number of irrigation events scheduled for both alfalfa and wheat in the two locations for the different net irrigation depths. These results indicate that both the irrigation discharge and the quality of land leveling have an important effect on the seasonal number of irrigations. This effect is largely due to the low PAELQ associated with low inflow discharges and poor leveling status. Considering all sites, crops and leveling conditions, increasing the discharge from 0.05 to 0.20 m^3 s^{-1} reduced the number of irrigations by an average 32%. The effect of land leveling on the total number of irrigations resulted slightly smaller: if the SD was improved from 30 to 0 mm, the number of irrigations would be cut by 22%. The number of irrigations for Zaragoza ranged from 8 to 13 for alfalfa and from 3 to 6 for wheat. In Daroca, the ranges were 5 to 8 for alfalfa and 2 to 3 for wheat. Note that the combination of SD = 30 mm and Q = 0.05 m^3 s^{-1}, which was discarded due to its large numerical error, would have enlarged the range in the number of irrigations, since it would presumably have the poorest on-farm performance.

TABLE 3

NUMBER OF IRRIGATIONS SCHEDULED FOR DIFFERENT NET IRRIGATION DEPTHS FOR ALFALFA AND WHEAT IN TWO LOCATIONS, ZARAGOZA AND DAROCA. NET IRRIGATION DEPTHS WERE ESTABLISHED AS A FUNCTION OF INFLOW DISCHARGE (Q) AND STANDARD DEVIATION OF SOIL SURFACE ELEVATION (SD)

Número de riegos programados para diferentes láminas netas de riego en alfalfa y trigo y para dos localidades, Zaragoza y Daroca. Las láminas netas de riego se establecieron en función del caudal de riego (Q) y de la desviación estándar de la elevación del terreno (SD)

Alfalfa in Zaragoza					**Wheat in Zaragoza**				
SD (mm)	**Q (m^3 s^{-1})**				**SD (mm)**	**Q (m^3 s^{-1})**			
	0.05	**0.10**	**0.15**	**0.20**		**0.05**	**0.10**	**0.15**	**0.20**
0	12	10	9	8	0	5	4	4	3
10	12	10	9	8	10	5	5	4	4
20	13	11	10	9	20	6	5	4	4
30	—	13	11	10	30	—	6	5	4
Alfalfa in Daroca					**Wheat in Daroca**				
SD (mm)	**Q (m^3 s^{-1})**				**SD (mm)**	**Q (m^3 s^{-1})**			
	0.05	**0.10**	**0.15**	**0.20**		**0.05**	**0.10**	**0.15**	**0.20**
0	8	6	5	5	0	3	3	2	2
10	7	6	6	5	10	3	3	2	2
20	8	7	6	6	20	3	3	3	2
30	—	8	7	6	30	—	3	3	2

Cases with high SD and low Q required a large number of irrigation events of small PAELQ, resulting in large water losses. Table 4 presents the seasonal deep percolation losses (m^3 ha^{-1}) associated with each combination of variables. The effect of on-farm variables (Q and SD) on total deep percolation losses was quantitatively larger than the effect on number of irrigations. Losses were reduced by an average 54 % by increasing the discharge in the considered range and by 87 % by improving quality of land leveling. The combined effect of both variables was very important, as evidenced by the ranges of losses for each crop and location. In Zaragoza, losses ranged from 240 to 4,568 m^3 ha^{-1} for alfalfa, and from 90 to 2,109 m^3 ha^{-1} for wheat. In Daroca, losses ranged from 150 to 2,811 m^3 ha^{-1} for alfalfa and 60 to 1,054 m^3 ha^{-1} for wheat. Results suggest that inflow discharge and land leveling are key values determining the amount of deep percolation losses and, therefore, irrigation return flows. Some environmental problems linked to irrigation systems (i.e., salinization and nitrification of surface waters) could be amended by proper management of these variables.

TABLE 4

SEASONAL DEEP PERCOLATION LOSSES (m^3 ha^{-1}) FOR ALL COMBINATIONS OF SITES, CROPS, INFLOW DISCHARGE (Q) AND STANDARD DEVIATION OF SOIL SURFACE ELEVATION (SD)

Pérdidas estacionales por percolación profunda (m^3 ha^{-1}) para todas las combinaciones de localidad, cultivo, caudal de riego (Q) y desviación estándar de la elevación del terreno (SD)

Alfalfa in Zaragoza					Wheat in Zaragoza				
SD (mm)	Q (m^3 s^{-1})				SD (mm)	Q (m^3 s^{-1})			
	0.05	0.10	0.15	0.20		0.05	0.10	0.15	0.20
0	1,689	798	453	240	0	704	319	201	90
10	1,914	1,306	1,083	963	10	798	653	481	481
20	3,657	2,638	2,213	2,063	20	1,688	1,199	886	917
30	—	4,568	3,836	3,398	30	—	2,109	1,743	1,359

Alfalfa in Daroca					Wheat in Daroca				
SD (mm)	Q (m^3 s^{-1})				SD (mm)	Q (m^3 s^{-1})			
	0.05	0.10	0.15	0.20		0.05	0.10	0.15	0.20
0	1,126	479	252	150	0	422	239	101	60
10	1,117	784	722	602	10	479	392	241	241
20	2,251	1,679	1,328	1,375	20	844	719	664	458
30	—	2,811	2,441	2,039	30	—	1,054	1,046	680

CONCLUSIONS

Irrigation discharge should be optimized for basin irrigation systems in order to determine a value that produces a high application efficiency while resulting in an irrigation depth not exceeding the water holding capacity of the soil. While in this study the time of irrigation was set to the time of complete advance, other alternatives implicating earlier cutoff should be considered. Undulations of the soil surface can have a very important effect on the performance of a basin irrigation system. This variable was almost as relevant as inflow discharge (in the considered ranges of both variables). The seasonal number of irrigations (for the four combinations of crops and locations) was severely affected by Q and SD. While Q is usually fixed by the irrigation delivery system, SD can be easily altered by the individual farmer using Laser guided scrapers, which can reduce SD down to about 10 mm. The effect of this practice on water and labor conservation can explain its swift adoption by farmers all over the world. Deep percolation losses can be drastically reduced by proper measures at the farm level.

RESUMEN

Simulación de la programación del riego por inundación en función del caudal de riego y de la calidad de la explanación.

Se realizó una simulación de una programación de riegos para varios casos con riego por inundación mediante un modelo hidrodinámico bidimensional. La programación se realizó para dos cultivos y dos localidades. Los cultivos fueron trigo y alfalfa, y las localidades fueron Zaragoza y Daroca, con evapotranspiración de referencia de 1.194 y 926 mm año^{-1}, respectivamente. Se consideraron dos variables de riego, relacionadas con el diseño y el manejo. La primera de las variables fue el caudal de riego, para el que se consideraron valores de 0,05 a 0,20 m^3 s^{-1}. La calidad de la explanación, cuantificada con la desviación estándar de la elevación del terreno (SD), fue la segunda variable utilizada. Se utilizaron valores de SD de 0 a 30 mm. Los resultados indicaron que el aumento del caudal de 0,05 a 0,20 m^3 s^{-1} reduce el número de riegos estacionales en un 32% en promedio. En cuanto a la explanación, si se mejorara la SD de 30 a 0 mm, el número de riegos estacionales se reduciría en un 22%. Un bajo caudal de riego y una mala calidad de la explanación se traducen en una baja eficiencia del riego por inundación que produce un volumen importante de pérdidas por percolación profunda.

PALABRAS CLAVE: Inundación
Láser
Caudal
Eficiencia
Percolación profunda
Programación

REFERENCES

ALLEN R.G., PRUITT W.O., 1986. Rational use of the FAO Blaney-Criddle formula. J. Irrig. Drain. Engrg. 112 (2): 139-155.

BUCKS D.A., HUNSAKER D.J., 1987. Water use variability in irrigated level-basins. Trans. ASAE. 30 (4): 1090-1098.

CLEMMENS A.J., 1994. Level basin design based on cutoff criteria. 1994 ASAE International Summer Meeting. Paper 94-2135, vol. 16. ASAE, St. Joseph, Michigan, USA.

CUENCA R.H., 1989. Irrigation system design: an engineering approach. Prentice Hall, Englewood Cliff, New Jersey, USA, 552 pp.

DOORENBOS J., PRUITT W.O., 1977. Crop water requirements. FAO Irrigation and Drainage Paper No. 24. FAO, Rome, Italy, 144 pp.

FACI J.M., MARTINEZ-COB A., 1991. Cálculo de la evapotranspiración de referencia en Aragón. Diputación General de Aragón, Zaragoza, España, 115 pp.

FAO, 1977 Carte mondiale de la désertification à l’échelle de 1:25.000.000. Conférence des Nations Unies sur la désertification. August 29 - September 9. Note Explicative FAO. 11 pp.

PLAYAN E., WALKER W.R., MERKLEY G.P., 1994. Two-dimensional simulation of basin irrigation. I. Theory. J. Irrig. Drain. Engrg. 120 (5): 837-856.

PLAYAN E., 1996. Mejora del riego por inundación: efectos combinados del caudal y de la explanación del cantero. In: XII Jornadas técnicas sobre riegos, Puerto de la Cruz, Tenerife, España. pp. 342-349.

PLAYAN E., FACI J. M., SERRETA A., 1996a. Characterizing microtopographical effects on level-basin irrigation performance. Agric. Wat. Manag., 29: 129-145.

PLAYAN E., FACI J.M., SERRETA A. 1996b. Modeling microtopography in basin irrigation. J. Irrig. Drain. Engrg., 122(6): 339-347.

WALKER W.R., SKOGERBOE G.V., 1987. Surface irrigation. Theory and practice. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, USA. 386 pp.