Optimum Time Ratio for Maximum Application Efficiency in Furrow Irrigation

F. Konukcu **L. Delibas**

Trakya University, Tekirdag Agricultural Faculty, Farm Structures and Irrigation Department, Tekirdag

Time ratio, which is defined as the ratio of the time required for infiltration of net amount of water needed for the rootzone to the time when the water front reaches the end of the run, plays a key role in determining optimum furrow length to achieve maximum irrigation efficiency. In this study, a model was developed to determine optimum time ratio for maximum application efficiency in furrow irrigation. The model was then tested on potatoes grown furrows, 0.75 m wide and 120 m long, with three different slopes 0.5, 1.0 and 1.5% and each slope had three different inflow rates (0.75, 1.0, 1.25 l/s; 0.4, 0.5, 0.6 l/s; 0.3, 0.4, 0.5 l/s, respectively). Stations with 10 m intervals were marked along the furrows to investigate the advance and recession speed of each rate. The attained application efficiency was 64 % for an average soil. It was concluded that when the intake rate was slow the maximum application efficiency could be attained providing that a relatively longer furrow length was chosen or vice versa.

Keywords: furrow irrigation advance; optimum time ratio; irrigation efficiency; potatoes

Karık Sulamada Maksimum Uygulama Randımanıİçin Optimum Zaman Oranı

Kök bölgesinde ihtiyaç duyulan net su miktarının infiltrasyonu için gerekli zamanın, suyun karığın aşağı ucuna ulaşması için geçen zamana oranı olarak tanımlanan *zaman oranı* maksimum sulama randımanını sağlayacak karık uzunluğunun belirlenmesinde en önemli parametredir. Bu çalışmada, karık sulamada maksimum sulama randımanını sağlamak için gerekli optimum zaman oranını belirleyecek bir model geliştirilmiştir. Model, patates yetiştirilen 0.75 m genişliğindeki, 120 m uzunluğundaki, üç farklı eğimdeki (% 0.5, 1.0 ve 1.5) karıklarda ve her bir eğim için üç farklı debide (sırasıyla 0.75, 1.0 ve 1.25 l/s; 0.4, 0.5 ve 0.6 l/s; 0.3, 0.4 ve 0.5 l/s) test edilmiştir. Her bir debi için karıktaki suyun ilerleme ve çekilme hızlarını belirlemek amacıyla karıklar boyunca 10 m aralıklarla istasyonlar çakılmıştır. Ortalama bir tarım toprağı için % 64 uygulama randımanı elde edilmiştir. Düşük infiltrasyon oranında maksimum uygulama randımanı elde etmek için daha kısa; yüksek infiltrasyon oranlarında ise daha küçük karık boyu seçilmesi gerektiği sonucuna varılmıştır.

Anahtar Kelimeler: Karık ilerlemem hızı, optimum zaman oranı, sulama randımanı, patates

Introduction

On a global basis, 69% of all water withdrawn for human use is currently soaked up by agriculture, most in the form of irrigation (UN/WWAP, 2003; Prinz 2004) with a very low use efficiency (30-40%). Surface irrigation methods having relatively lower water use efficiency when compared to the pressurized systems are responsible for this. Surface irrigation is widely practiced throughout the world, more than 95 % of world's irrigated area (UN/WWAP, 2003). Even in industrialized countries, for instance in the U.S., the area devoted to surface irrigation is still well over 70% (Playan et al. 2004). Also in Turkey, surface irrigation occupies about 90% of the irrigated area with an average water use efficiency of 35% (Anonymous, 1998).

As the world is running into a very serious water crisis in this century (Postel, 1997; Shiklomanov, 2000; UN/WWAP, 2003), increasing water use efficiency in irrigation may be the most appropriate way of preserving our precious water resources since even 10% saving in agriculture is more than enough to meet all domestic use (Postel, 1997). Therefore, the ultimate objective of irrigation systems, especially surface irrigation, design should achieve maximum irrigation efficiency with a minimum cost.

Furrow irrigation is most widely used among the surface irrigation methods. It is designed on the basis of soil, crop, topography, size and shape of the irrigated area. A furrow irrigation system has several design variables that affect its performance. These are the inflow rate, the length of the run in the direction of the flow, the time of irrigation cutoff and soil infiltration characteristics.

These parameters have been extensively studied by many authors in order to design an optimum furrow to achieve maximum application efficiency. The inflow rate design, which is affected by the slope, the length of the furrow and the intake rate of the soil, can be adjusted by the designer to achieve a good uniformity and to irrigate to the required depth in a reasonable time. The effectiveness of an irrigation water supply can be increased by improving the efficiency of water application. Water application efficiency is influenced principally by the amount of water applied, the intake characteristics of the soil and the rate of advance of water in the furrows (Scaloppi et al., 1995; Esfandiari et al., 1997; Alazba, 1999; Jurriens and Lenselink, 2001).

Optimal furrow length and irrigation cutoff can be determined, as related to soil infiltration characteristics, by the time ratio (ratio between the time required for infiltration of total amount of water required for root zone and the time when the water front reaches the end of the run) to achieve maximum application efficiency (Lillevik, 1982; Bautista and Wallender, 1993; Upadhyaya and Raghuwanshi, 1999; Clemmens, 1999; Playan et al., 2004; Garcia-Navarro, 2004; Holzapfel et al., 2004).

It is true that the optimum furrow length where the maximum application efficiency can be achieved, changes with respect to the irrigation depth applied. But the maximum efficiency itself is a constant since it is affected by the infiltration function and advance function only. Irrigation efficiency is a function of furrow length (Mcclymont and Smith, 1996 and 2001; Esfandiari and Maheshwari, 2001; Alvares, 2003; Wohling et al., 2004a and 2004b).

Besides experimental studies, Abbasi et al. (2003a, 2003b, 2003c, 2004) and Garcia-Navarro (2004) developed simulation models for furrow irrigation method.

In this study, a mathematical model was developed using hydraulics of surface irrigation to find out optimal time ratio to prove maximum application efficiency, tested in potatoes grown furrows and extrapolated for different field conditions.

Material and Methods

Theoretical Development

The infiltration pattern along the furrow may be schematized as shown in Figure 1. Advance time increases as the flow rate in a furrow decreases successively downstream due to infiltration of water into the soil. This reduction in the stream size down the furrow results in a decreasing velocity and, thus, a continually decreasing rate of advance with increasing length.

Both the infiltration depth and water advance rate on soil surface in furrow irrigation are a function of irrigation time. This relationships is known as advance function expressed in empirical form as described by Fok and Bishop (1965), Wilke and Smerdon (1965) and Hart et al. (1968):

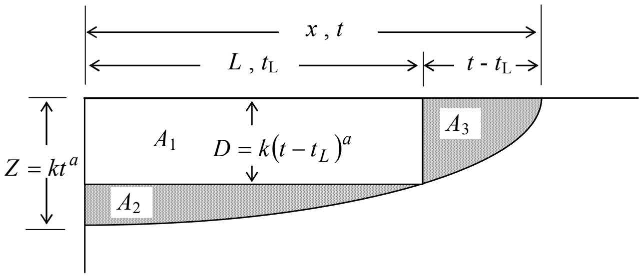

Figure 1. Definition sketch of infiltration pattern through furrow length. *L*: furrow length; D: required depth of irrigation to satisfy the rootzone; *k* and *a*: infiltration parameters; *t*: opportunity time; t_L: time required for the water front to reach the lower end of the furrow. The irrigation water delivered per unit width that is furrow spacing (*W*), is distributed in V_1, V_2, and V_3 where V_1: total volume of water required for the rootzone represented by A_1; V_2: deep percolation loss represented by A_2; V_3: volume of runoff flowing out from the downstream end of furrow having a length *L* represented by A_3

$$x = A\,t^b \qquad 1$$

where *x* is the length covered by water at time *t* (m), *t* is the total water application time (min), *A* and *b* are the empirical constants of advance function. Cumulative infiltration depending on the infiltration opportunity time may be explained by Kostiakov Equation (Bassett, 1972; Hart et al., 1968):

$$Z = k\,t_i^{\,a} \qquad 2$$

where Z is the cumulative infiltration depth (m), t_i is the infiltration opportunity time (min), *k* and *a* are the constants for a given soil at a particular moisture level. The time available for infiltration or opportunity time at any point along the furrow must be known in order to design a furrow precisely.

The opportunity time for infiltration at section *s*, along the furrow (Figure 2) at a given time *t* is given by

$$t_i = t - t_s \qquad 3$$

where t_s is the advance time. Therefore, the total volume of irrigation water, V_T, infiltrated along the furrow at a given time *t* is expressed by integrating the depth of infiltrated water from the furrow length 0 to *x*;

$$V_T = W\int_0^x k(t - t_s)^a\,\mathrm{d}s \qquad 4$$

Where *W* is the furrow width (m). Equation 4 can be written as:

$$V_T = W\,k\,t^a\int_0^x (1 - \frac{t_s}{t})^a\,\mathrm{d}s \qquad 5$$

Introduction a new variable $r = t_s / t$ and from that $t_s = r\,t$; $\mathrm{d}t_s = t\,\mathrm{d}r$ and $\mathrm{d}s = (\mathrm{d}s / \mathrm{d}t_s)\,\mathrm{d}t_s$ allows Equation 5 to be written in the form:

$$V_T = W\,k\,t^a\int_0^1 (1 - r)^a\,\frac{\mathrm{d}s}{\mathrm{d}t_s}\,t\,\mathrm{d}r \qquad 6$$

When advance function is expressed in terms of *s*, $s = A\,t_s^{\,b}$ can be written and thus,

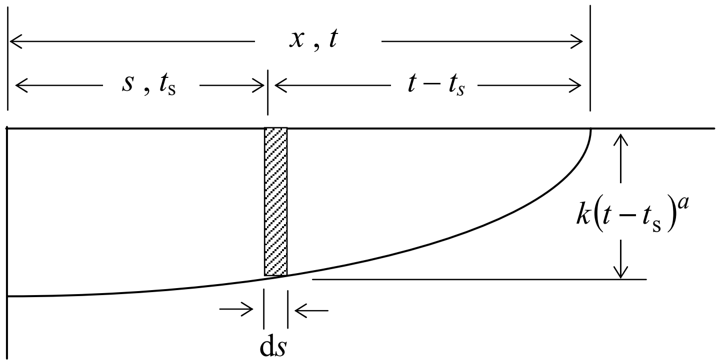

Figure 2. Definition sketch for advance of water down a furrow.

ds / dt_s = $b\ A\ t_s^{b\text{-}1}$ then the following equation can be written;

$$V_T = A\,W\,k\,t^{a+b}\,b\int_0^1 (1-r)^a\,r^{b-1}\,\mathrm{d}r \qquad 7$$

In Equation 7, integral on the right hand is a Beta function (Hart et al., 1968) and expressed as:

$$r_z = b\int_0^1 (1-r)^a\,r^{b-1}\mathrm{d}r \qquad 8$$

where r_z is subsurface shape factor and equal approximately (Delibas, 1991) to:

$$r_z = \frac{2-a+a^2}{2+a-a^2} \qquad 9$$

after this assumption, Equation 7 can be expressed as:

$$V_T = A\,W\,k\,t^{a+b}\,r_z \qquad 10$$

This is the quantitative expression the total volume of water, i.e. $V_1 + V_2 + V_3$, which corresponds the volume of water representing the area A_1, A_2 and A_3, respectively, in Figure 1. The volume of water required for irrigation shown as A_1 can be expressed as:

$$V_1 = W\,k\,L\,(t-t_L)^a \quad \text{or} \qquad 11$$

$$V_1 = W\,A\,t_L{}^b\,k\,t^a\left(1-\frac{t_L}{t}\right)^a \qquad 12$$

The irrigation application efficiency (E_a), thus, can be estimated as:

$$E_a = \frac{V_1}{V_T}100 \qquad 13$$

When Equations 10 and 12 are substituted into Equation 13, the result after simplification and rearrangement is:

$$E_a = \frac{100\,t_L{}^b\,t^a\left(1-\frac{t_L}{t}\right)^a}{t^{a+b}\,r_z} \qquad 14$$

Now, by defining the time ratio (R) as

$$R = \frac{(t-t_L)}{t_L} \qquad 15$$

and substituting it into Equation 14 and simplifying, the resulting equation becomes:

$$E_a = \frac{100\,R^a}{r_z\,(R+1)^{a+b}} \qquad 16)$$

By differentiating Equation 16 in terms of R and making equal to zero for maximal solution:

$$\frac{\mathrm{d}E_a}{\mathrm{d}R} = \frac{100}{r_z}\left[\frac{a\,R^{a-1}(R+1)^{a+b} - (a+b)(R+1)^{a+b-1}R^a}{\left[(R+1)^{a+b}\right]^2}\right] = 0$$

After simplification,

$$a(R+1)=(a+b)R \qquad 18$$

is obtained. From this, a simple relationship between time ratio and exponents of infiltration and advance function is found as follows:

$$R=\frac{a}{b} \qquad 19$$

where $b = 1 - a$ as pointed out by Hart et al. (1968) and Delibas (1991). Hence rearranging Equation 19, the optimum time ratio may be expressed as a function of *a* only:

$$R=\frac{a}{1-a} \qquad 20$$

Experimental

Experiments were conducted to test the model in field plots prepared specifically for this research. Soil texture was clay loam with bulk density ranging from 1.36 to 1.38 g/cm^3 and 19 % (volume basis) available water holding capacity.

The research field was first leveled and three plots were formed with the slopes of 0.5 (plot A), 1.0 (plot B) and 1.5 (plot C) %. Then three furrows with 0.75 m width and 120 m length were constructed on each plot. Potatoes seedlings were planted on the furrows in the first week of May and three irrigations were applied during August. The inflow rates were 0.75, 1.0 and 1.25 l/s to plot A, 0.4, 0.5 and 0.6 l/s to plot B and 0.3, 0.4 and 0.5 l/s to plot C. The rates were measured using Parshall and 60° triangular weirs and maintained stable during the irrigations. Measurements were done only on the middle furrows of each plot to eliminate the side effects.

Stations with 10 m intervals were marked along the side of the furrows to investigate the water advance and recession speed of each rate. The time elapsed, both, for the advancing water front to reach to each station after the application from the top end of the furrow and the recession from the station were recorded. Then, parameters *a* and *b* in advance equation (Equation 1) were computed for each slope and application rate applying regression analysis on these recorded data. Similarly, parameters *k* and *a* in infiltration equation (Equation 2) were determined from the volume-balance method. Note that parameter *a* in Equation 1 and 2 is the same.

Irrigation time was decided through examining the moisture deficit in the soil profile up to 0.90 m depth every two days. Irrigation was applied when half of the available water was consumed in this profile and 8.55 cm water was applied in each irrigation to bring the soil moisture level to the field capacity.

Although the length of the furrows were design 120 m, irrigation efficiencies were also calculated when the furrow lengths were 60, 70, 90, 100 and 110 m for each of the three slope and inflow rate. Noting t_L (the time elapsed for the advancing water front to reach to a particular length or station), t-t_L (the time required for the net amount of 8.55 cm deep water to infiltrate fully), and *R* (time ratio computed using Equation 15), the irrigation efficiencies were calculated from Equation 16. As for the maximum attainable irrigation efficiencies, first *R* was obtained from Equation 19 noting parameters *a* and *b*, and then this was substituted into Equation 16. Optimum furrow lengths were calculated from $L = A\, t_L^{\,b}$, where t_L was obtained using the relation $t_L = t\,/\,(R+1)$.

Results and Discussion

Water advance and infiltration parameters obtained from the experiments are presented in Table 1. Table 1 shows that parameter *a* (power of the infiltration equation) is indirectly proportional to the furrow length and the inflow rate whereas parameter *b* (power of the advance equation) is directly proportional. The water application efficiency strongly depends on these two parameters reflecting the hydraulic behavior of the soil as can also be seen in Equation 16. The maximum efficiency also depends on the magnitude of these parameters (Equation 16 and 19).

At a specific slope and inflow rate, *R* will decrease with increasing furrow length since t_L increases and *t* remains constant in Equation 15. For any given furrow length, either increasing inflow rate with a constant slope or increasing slope with constant inflow ate will increase t_L and therefore R value. This means that changes in the furrow lengths and inflow rates will ultimately influence the water application efficiency (Table 2). Therefore, a well-balanced design of these three variables (inflow rate, slope and furrow length) may lead the designer to a maximum efficiency. Mathematical analysis showed that the time ratio (*R*) was the factor for this well-balanced design. Generally, efficiency increases with decreasing *R* value. However, for a particular inflow rate, this increase is not continuous but starts decreasing after a certain *R* value (Table 2).

Table 1. Changes in the infiltration and advance parameters with slope and inflow rate

Furrow	Slope (%)	Inflow rate (l/s)	Infiltration parameters*		Advance parameters**	
			k	*a*	*A*	*b*
A	0.5	0.75	0.00592	0.493	6.974	0.582
		1.00	0.00712	0.455	7.284	0.623
		1.25	0.00860	0.422	7.277	0.648
B	1.0	0.40	0.00428	0.565	6.912	0.505
		0.50	0.00503	0.492	7.047	0.584
		0.60	0.00608	0.418	7.148	0.647
C	1.5	0.30	0.00404	0.484	6.476	0.554
		0.40	0.00436	0.449	6.650	0.607
		0,50	0.00493	0.428	7.470	0.636

* $Z = k \cdot t_i^a$ Z: cumulative infiltration depth (m); *t*: infiltration opportunity time (min).

** $x = A \cdot t^b$ x: the length covered by water at time *t* (m).

Table 2. Influence of furrow length, slope and inflow rate on water application efficiency

Slope (%)	Infl. rate (l/s)	Furrow lengths (m)													
		60		70		80		90		100		110		120	
		R	E_a	*R*	E_a	*R*	E_a	*R*	E_a	*R*	E_a	*R*	E_a	*R*	E_a
0.5	0.75	5.6	39	4.2	44	3.4	48	2.8	51	2.3	54	2.0	56	1.7	57
	1.00	7.9	31	6.2	35	5.0	39	4.1	42	3.5	45	3.0	47	2.6	50
	1.25	8.9	28	7.0	31	5.8	35	4.8	38	4.1	41	3.5	43	3.0	46
1.0	0.40	2.8	55	2.0	58	1.6	60	1.2	61	1.0	61	0.8	60	0.7	59
	0.50	8.1	33	6.2	38	5.0	41	4.1	45	3.4	48	2.9	50	2.5	53
	0.60	20.7	17	16.4	20	13.3	22	11.2	24	9.5	27	8.2	29	7.2	31
1.5	0.30	9.8	33	7.5	37	5.9	41	4.7	45	3.9	48	3.3	50	2.8	53
	0.40	20.4	20	15.8	23	12.6	25	10.4	28	8.7	31	7.4	33	6.5	35
	0.50	30.2	14	23.1	17	18.7	19	15.7	21	13.3	23	11.4	25	9.9	27

R: time ratio; E_a: irrigation application efficiency (%).

Using the parameters obtained in the field experiments, calculated *R* values to realize maximum efficiencies, furrow lengths to achieve theses efficiencies and some other elements of calculations are summarized in Table 3. At a particular slope, decreasing a value with increasing inflow rate (Table 1) leads R to decrease (Equation 20). Therefore, maximum efficiency and furrow length to provide this efficiency will increase while inflow rate increases at the same slope. For instance, maximum efficiency was 61 % and the optimum furrow length to realize this efficiency was 180 m for 0.75 l/s inflow rate whereas maximum efficiencies were 62 % and 62 % and optimum furrow lengths were 267 m and 327 m for 1.0 and 1.25 l/s inflow rates, respectively, when the slope was constant at 0.5 %. This implies that, at a certain slope, maximum efficiency for a particular furrow length is achieved applying the smallest inflow tare. If the inflow rate is to increase, furrow lengths should be increased in order not to decrease the efficiency (Table 2) but this is limited with the range given in Table 3. As seen in Table 3, either increases in the slope or increases in the flow rate at the same slope cause to increase the maximum attainable water application efficiency but furrow lengths should also be increased depending on the inflow rate and the slope to achieve this efficiency.

Infiltration characteristics of the soil reflected by the parameters in power function of infiltration in the form $Z = k\ t_i^a$ Also, water advance and infiltration are not independent of each other. The fact that the value of parameter a in infiltration function is close to zero, in such fine textured soils, means the soil is non-permeable and non-irrigable. At the contrary, the higher the value of a is the more permeable the soil is.

The interrelation among a, R and E_a are presented in Table 4. As seen in table 4, maximum efficiency takes the smallest value when a was 0.5 where R is 1 at this point. The value of 0.5 for a points that the infiltration rate of the soil is moderate. Irrigation efficiency was low for this kind of soil since deep percolation and surface runoff losses are relatively greater. While a approaches 1 from 0.5, both optimum R value and maximum E_a will increase. But, as explained earlier, this is true as long as the furrow length is also shortened. While a approaches 0 from 0.5, maximum efficiency increases against decreases in optimum R value. In this case, furrow length should be increased to maintain higher efficiency.

Table 3. Maximum attainable water application efficiencies and furrow length to achieve these efficiencies as a function of inflow rates and slopes

Slope (%)	Inflow rate (l/s)	k	a	A	b	R	t-t_L	t_L	L	E_a
0.5	0,75	0,00592	0.493	6.974	0.582	0.847	225	266	180	61
	1.00	0.00712	0.455	7.284	0.623	0.730	236	323	267	62
	1.25	0.00860	0.422	7.277	0.648	0.651	231	355	327	62
1.0	0.40	0.00428	0.565	6.912	0.505	1.119	200	179	95	61
	0.50	0.00503	0.492	7.047	0.584	0.842	317	376	225	61
	0.60	0.00608	0.418	7.148	0.647	0.646	558	864	568	63
1.5	0.30	0,.00404	0.484	6.476	0.554	0.809	548	677	240	65
	0.40	0.00436	0.449	6.650	0.607	0.740	756	1022	446	62
	0.50	0.00493	0.428	7.470	0.636	0.673	784	1165	666	62

t_L: time required for the water front to reach the lower end of the furrow (min), t: opportunity time (min), L: furrow length (m); E_a: water application efficiency; R: time ratio; k and a: infiltration parameters; A and b: advance parameters.

Table 4. Optimal values of time ratio(R) and maximum attainable application efficiency (E_a).

a	R	r_z	E_a (%)
0.1	0.11	0.91	79
0.2	0.25	0.85	71
0.3	0.43	0.81	67
0.4	0.67	0.79	65
0.5	1.00	0.78	64
0.6	1.50	0.79	65
0.7	2.33	0.81	67
0.8	4.00	0.85	71
0.9	9.00	0.91	79

a: infiltration parameters; R: time ratio; r_z: subsurface shape factor; E_a: water application efficiency

Conclusions

A mathematical model was developed to investigate optimal time ratio to prove maximum application efficiency in furrow irrigation using the principles of surface irrigation hydraulics and the model was tested under potatoes grown field.

Mathematical analysis and field applications proved that an optimum furrow length was possible to design to realize maximum irrigation efficiency for any given soil and the infiltration rate of this soil is the key factor for this.

Some deep percolation loss is unavoidable near the upper end of the run in order to allow the soils at the lower end of the run to become fully irrigated. However, when water is applied after the whole root zone has been satisfied, all additional water will be lost by deep percolation or surface runoff and water application efficiency will decrease rapidly.

The application efficiency is 64 % for an average soil with $a = 0.5$ and $R = 1$. An R value of 1 represents the length of the run in which the contact time required to fully irrigate the root zone is equal to the advance time. For $R = 1$, the root zone at the upper end of the run is fully irrigated by the time the water reaches the end of the run.

When the intake rate is slow (i.e. a is smaller than 0.5) the maximum application efficiency can be attained providing that a relatively longer furrow length is chosen. For the soils with high intake characteristics (i.e. a is greater than 0.5), the length of the furrow must be select shorter, which means greater value of R, in order to attain the maximum water application efficiency.

References

Abbasi, F., J. Feyen, R. L. Roth, M. Sheedy and M. T. van Genuchten, 2003a. Water flow and solute transport in furrow-irrigated fields. Irrigation Science 22: 57-65.

Abbasi F., F. J. Adamsen, D. J. Hunsaker, J. Feyen, P. Shouse and M. T. van Genuchten, 2003b. Effects of flow depth on water flow and solute transport in furrow irrigation: Field data analysis. Journal of Irrigation and Drainage Engineering-ASCE 129: 237-246.

Abbasi, F., M. M. Shooshtari and J. Feyen, 2003c. Evaluation of various surface irrigation numerical simulation models. Journal of Irrigation and Drainage Engineering-ASCE 129: 208-213.

Abbasi, F., J. Feyen and M. T. van Genuchten, 2004. Two-dimensional simulation of water flow and solute transport below furrows: model calibration and validation. Journal of Hydrology 290: 63-79.

Alazba, A. A. 1999. Simulating furrow irrigation with different inflow patterns. Journal of Irrigation and Drainage Engineering-ASCE 125: 12-18.

Alvarez, J. A. R. 2003. Estimation of advance and infiltration equations in furrow irrigation for untested discharges. Agricultural Water Management 60: 227-239.

Anonymous, 1998. Ergene Havzası Yeraltı Suyu Etütleri. Devlet Su İşleri. Ankara.

Bassett, D. L. 1972. Mathematical model of water advance in border irrigation. Transactions of the ASAE 15: 992-995.

Bautista, E. and W. W. Wallender, 1993.Optimal management strategies for cutback furrow irrigation Journal of Irrigation and Drainage Engineering-ASCE 119: 1099-1114.

Clemmens, A. J. 1999. Kostiakov infiltration parameters from kinematics wave model – Discussion Journal of Irrigation and Drainage Engineering-ASCE 125: 386-387.

Delibas, L. 1991. A new technique to measurement infiltration. Technical Bulletin of Turkish State Hydraulic Works 74, pp: 51-56.

Esfandiari, M., B. L. Maheshwari and P. S. Cornish, 1997. Estimating recession times in furrows with small longitudinal slope on a clay soil. Agricultural Water Management 34: 187-193.

Esfandiari, M. and B. L. Maheshwari, 2001. Field evaluation of furrow irrigation models. Journal of Agricultural Engineering Research 79: 459-479.

Fok, Y. S. and A. A. Bishop, 1965. Analysis of water advance in surface irrigation. Journal of Irrigation and Drainage Engineering-ASCE 91: 99-116.

Garcia-Navarro, P., A. Sanchez, N. Clavero and E. Playan, 2004. Simulation model for level furrows. II: Description, validation, and application. Journal of Irrigation and Drainage Engineering-ASCE 130: 113-121.

Hart, W. E., D. L. Bassett and T. Strelkoff, 1968. Surface irrigation hydraulics-kinematics. Journal of Irrigation and Drainage Engineering-ASCE 94: 419-440.

Holzapfel, E. A., J. Jara, C. Zuniga, M. A Marino, J. Paredes and M. Billib, 2004. Infiltration parameters for furrow irrigation. Agricultural Water Management 68: 19-32.

Jurriens, M., K. J. Lenselink, 2001. Straightforward furrow irrigation can be 70% efficient. Irrigation and Drainage 50: 195-204.

Lillevik, S. L. 1982. Discrete-time, cutback furrow irrigation. Transactions of the ASAE 25: 1646-1650.

McClymont, D. J. and R. J. Smith, 1996. Infiltration parameters from optimization on furrow irrigation advance data. Irrigation Science 17: 15-22.

Playan, E., J.A. Rodriguez and Garcia-Navarro, 2004. Simulation model for level furrows. I: Analysis of field experiments. Journal of Irrigation and Drainage Engineering-ASCE 130: 106-112.

Postel, S. 1997. Last Oasis: Facing Water Scarcity. W. W. Norton and Co inc (2nd ed.). Washington. 218p.

Prinz, D. 2004. Water and development (the challenge ahead). Water Resources Management: Risks and Challenges for the 21st Century. EWRA Symposium, September 2-4, 2004 Izmir, Turkey.

Scaloppi, E. J., G. P. Merkley and L. S. Willardson, 1995. Intake parameters from advance and wetting phases of surface irrigation. Journal of Irrigation and Drainage Engineering-ASCE 121: 57-70.

Shiklomanow, I. A. 2000. Appraisal and assessment of world water resources. Water International, 25: 11-32.

UN/WWAP, 2003. UN World Water Development Report. Water for People, Water for Life. UNESCO, Berghahn Books.

Upadhyaya, S. K. and N. S. Raghuwanshi, 1999. Semi-empirical infiltration equation for furrow irrigation systems. Journal of Irrigation and Drainage Engineering-ASCE 125: 173-178.

Valiantzas, J.D. 2001. Optimal furrow design. II: Explicit calculation of design variables. Journal of Irrigation and Drainage Engineering-ASCE 127: 209-215.

Wilke, O. C. and E. T. Smerdon, 1965. A Solution of the Irrigation Advance Problem. Journal of Irrigation and Drainage-ASCE 91: 23-34.

Wohling, T., R. Singh and G. H. Schmitz, 2004a. Physically based modeling of interacting surface-subsurface flow during furrow irrigation advance. Journal of Irrigation and Drainage Engineering-ASCE 130: 349-356.

Wohling, T., G. H. Schmitz and J.C. Mailhol, 2004b. Modeling two-dimensional infiltration from irrigation furrows. Journal of Irrigation and Drainage Engineering-ASCE 130: 296-303.