DESIGN OF LEVEL-BASIN IRRIGATION SYSTEMS FOR ROBUST PERFORMANCE

CONCEPTION DES SYSTEMES D'IRRIGATION AU NIVEAU DU BASSIN POUR UNE PERFORMANCE ROBUSTE

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ABSTRACT

Level-basin irrigation is extensively used in South-Western United States where water is very expensive. A well designed level-basin irrigation system is easy to manage, and has significant potential for achieving higher application efficiency and improved salinity control, particularly when the field is laser-leveled. Over the years, three different criteria have evolved to design level-basin irrigation systems: the volume-balance design criterion proposed by the Soil Conservation Service (SCS) of the United States Department of Agriculture (USDA), the limiting length design criterion, and the completion-of-advance criterion. Each one of these three methods has its own advantages and disadvantages. For achieving higher application efficiency, in addition to proper design, a well-defined irrigation scheduling must be followed so that the soil-moisture deficit at the time of irrigation is close to the design depth of the irrigation system. Otherwise, the actual application efficiency will be different (usually lower) than the design application efficiency, and the actual water requirement efficiency achieved may be significantly different (either under-irrigation or over-irrigation) from the design water requirement efficiency. However, if completion-of-advance design criterion is used, the difference between actual and design efficiencies (application efficiency and water requirement efficiency) kept to a minimum. In addition, the actual performance of a level-basin irrigation system designed using the completion-of-advance criterion would be much closer to the design performance even when the inflow flow rate into level-basins fluctuates. This paper will present the results of a simulation study on the robust performance of level-basin irrigation systems designed using the completion-of-advance criterion.

Key words: *Level basin, Volume balance, Salinity control, Application efficiency, Simulation study.*

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RESUME

L'irrigation au niveau du bassin est largement utilisée au sud-ouest des Etats-Unis où l'eau est très chère. Un système d'irrigation bien conçu au niveau du bassin est facile à gérer, et détient un potentiel important d'atteindre une plus grande efficience d'application et de contrôle de la salinité, en particulier quand le terrain est nivelé par laser. Depuis des années, trois critères différents suivants sont évolués pour le projet des systèmes d'irrigation au niveau du bassin : le critère de projet d'équilibre de volume proposé par « Soil Conservation Service (SCS) » de « United States Department of Agriculture (USDA) »; le critère de projet de longueur limitée; et le critère de réalisation-d'avance. Chacun de ces trois méthodes comporte des avantages et des inconvénients. Pour atteindre la haute efficience d'application, outre la meilleure conception, un régime d'irrigation bien défini doit être suivi afin que le déficit d'humidité du sol lors de l'irrigation soit similaire à la profondeur du projet du système d'irrigation.

Sinon, l'efficience d'application réelle sera différente (normalement plus bas) à l'efficience d'application. L'efficience réelle du besoin en peut être significativement différente (sous-irrigation ou sur-irrigation) à l'efficience du besoin en eau du projet. Cependant, si le critère de réalisation-d'avance est utilisé, la différence entre les rendements réels et les efficiences du projet (efficience d'application et efficience du besoin en eau) sera au minimum. De plus, la performance actuelle du système d'irrigation au niveau du bassin utilisant le critère de réalisation-d'avance sera presque similaire à la performance du projet, même s'il y des fluctuations dans le débit d'entrée au niveau du bassin. Ce document présente les résultats d'une étude de simulation menée sur la performance robuste du projet des systèmes d'irrigation au niveau du bassin utilisant le critère de réalisation-d'avance.

Mots clés : *Niveau du bassin, équilibre du volume, contrôle de la salinité, efficience d'application, étude de simulation.*

1. INTRODUCTION

Basin irrigation systems are characterized by bunds all around the field, and hence no runoff from the field. This method of irrigation has been practiced for centuries in several countries around the world. Water enters a basin from one (most common) or more inlets. For ideal water distribution within basins, the land surface must be level to ensure uniform distribution of water over the basin. Typically, where the land surface is undulating, farmers use small-sized basins that are nearly level, sometimes as small as 5 m x 5 m in size as in Egypt. However, with the advent of land leveling equipment, particularly laser-leveling equipment, the size of level basins has considerably increased to fields of 5 ha or more as in Arizona, United States of America, and in Australia.

The term level basin refers to basin that has zero slopes in all directions within a field. Because of zero slope, larger inflow rates per unit width, compared to sloping fields, are required for efficient irrigation. In addition, because of zero slope, the flow depth in a level basin is deeper than in a sloping field. Therefore, the dykes around level basins should be higher and stronger to contain all the flow that enters the field. In areas with intense rainfall, provision must be made for draining excess water from level basins in order to avoid damage from temporary water stagnation within the field.

Level basins are well suited for medium to heavy textured soils. Because of level surface, it is possible to apply irrigation water from both upstream-end and downstream-end of the field for improving uniformity of application. The basic principle of level basin irrigation system is to apply the required volume of water quickly using a maximum (non-erosive) flow rate, and let the water infiltrate into the soil over a period of a day or so. Because of the potential for achieving uniform application along the length of a level basin, level basins are well suited for salinity control (through leaching and subsurface drainage) in irrigated fields. Level basin irrigation systems are widely used in the South-Western United States where water is expensive. Measured field application efficiencies of level basin irrigation systems were around 78% in Arizona, where a decent irrigation scheduling program was followed by farmers, and the flow rate into a level basin was almost constant. Reddy and Clyma (1985) demonstrated the robustness of performance of a level basin irrigation system in the presence of variable inflow rate into a level basin. The objective of this paper is to demonstrate the robustness of performance of level basin irrigation systems in the absence of a decent irrigation scheduling.

2. APPROACHES USED FOR DESIGN OF LEVEL BASINS

Though farmers practiced basin irrigation systems were for centuries, the design (sizing of technological parameters of basin irrigation system) of these systems was based upon experience. Only towards the middle of 20th century, there have been efforts to develop systematic procedures for design of level basin irrigation systems. In 1974, the Soil Conversation Service of the United States Department of Agriculture developed an empirically-based approach for design of level basin irrigation systems. Later on several other design approaches followed. Some of these approaches will be briefly discussed below.

Soil Conservation Service Approach

The SCS design is an empirically-based, volume-balance approach. Several assumptions are made in developing the design procedure. These are: the volume of water applied to the basin is adequate to cover the area of the basin to an average depth equal to the total irrigation application (total volume of water applied to the basin divided by the basin area); the infiltration opportunity time at the last point covered in the basin equals the time required for the design requirement to enter the soil; the longest infiltration opportunity time at any point on the basin is short enough to prevent detrimental deep percolation; the flow depth in the basin is no greater than that which the basin ridges can contain; and the mean flow depth equals 0.8 of the maximum flow depth. In addition, the infiltration is defined by the SCS intake function instead of the Kostiakov-Lewis function.

An expression for length of advance distance, L, is given as follows:

$$x = \frac{q_u t}{\left[\frac{kt^a}{1+a} + c + K n^{0.375} q_u^{0.5625} t^{0.1875}\right]} \qquad (1)$$

where K = 0.8342; q_u = unit flow rate, $m^3/s/m$; k, a, and c are the SCS intake function parameters; n = Manning roughness coefficient; x = advance distance, m; and t = seconds. If the total advance time t_L is substituted for t in Eq.1, then x becomes the total length of run, L. The above equation provides a volume-balance design equation for level basins.

The design water requirement depth is given by:

$$d_n = (kt_n^a + c) \quad (2)$$

where t_n = design infiltration opportunity time; The design infiltration opportunity time, t_n, required to infiltrate the design depth, d_n, should occur at the last point on the basin. The irrigation application is defined as a gross average depth of applied water, d_a, and is given as:

$$d_a = (kt_{ao}^a + c) \quad (3)$$

where t_{0a} is the average opportunity time over the basin length, L, sec. For the given values of d_n and d_a and if all the applied water infiltrates, the application efficiency is defined as:

$$E_a = \frac{100\, d_n}{d_a} = \frac{100\, d_n L}{q_u t_{co}} \quad (4)$$

where t_{co} = time of application (or time of cutoff) to apply the gross depth to the border, and can be calculated as

$$t_{co} = \frac{100\, d_n L}{q_u E_a} \quad (5)$$

In the design, an appropriate combination of q_u, t_{co}, and L are selected, by trial-and-error procedure, until a preset value of application efficiency is achieved to accomplish a specified design depth, d_n.

Limiting Length Design Procedure

Clemmens and Dedrick (1982) developed the concept of limiting length for designing level basins. This limiting length is defined as the point where for lesser lengths, design depth, opportunity time and flow rate interact to accomplish a design. The limiting length design procedure was developed based upon simulations of irrigations using the zero-inertia model (Strelkoff and Katopodes, 1977). This design procedure was developed to improve upon the SCS design procedure that is explained above. The procedure is as follows:

First, the following three variables are defined:

$$Y_1 = n^{0.375} q_u^{0.5625} t_{co}^{0.1875} \quad (6)$$

$$K^* = \frac{k t_{co}^{a-3/16}}{q_u^{9/16} n^{3/8}} \quad (7)$$

$$y_{max} = y_{01}^* Y_1 \quad (8)$$

where Y_1 = characteristic depth, m; K^* = characteristic infiltration coefficient; y_{max} = maximum flow depth, m; and y_{01}^* = dimensionless maximum flow depth at the head of the level basin.

From empirical data and simulation runs, a graphical relationship was developed between y_{01}*, K* and a.

Then, reference variables for distance (X), discharge (Q), depth (Y), and time (T) are defined as follows:

$$X = t_n^{2/3} d_n^{7/9} n^{-2/3} \quad (9)$$

$$Q = X\, d_n\, t_n^{-1} \quad (10)$$

$$Y = L^{3/13} n^{-6/13} \quad (11)$$

$$T = Y\, L\, q_u^{-1} \quad (12)$$

where t_n is the time required to infiltrate the net depth of application, and is calculated as follows:

$$t_n = \left(\frac{D_n}{k}\right)^{1/a} \quad (13)$$

Finally, the reference variables are used to relate dimensionless variables to the dimensional variables used in the design. They are as follows:

$$q_u^* = \frac{q_u}{Q} \quad (14)$$

$$L^* = \frac{L}{X} \quad (15)$$

$$D_n^* = \frac{D_n}{Y} \quad (16)$$

$$T_n^* = \frac{t_n}{T} \quad (17)$$

In the design of level basin irrigation systems, the distribution uniformity, DU, is assumed to be equal to application efficiency which is defined by Eq. 4. Using simulation runs from zero-inertia model, graphical relationships were developed between L* and q_u* for different values of Kostiakov exponent ***a = 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9*** and DU, along with limiting (maximum) length line. The developed graphs together with Eqs.14 and 15 are used to solve for q_u and L first. Then, Eq.5 is used to calculate the time of cutoff. The computer program SIRMOD, developed by Walker (2004), was used to accomplish the design by simulation. In order to achieve a system performance that is close to the design performance, the operational values for the design variables must be as close as possible to the values specified by design.

Completion-of-Advance Approach

Flow measurement is very important for efficient irrigation. Yet, in most of the developing countries, flow into fields is not usually measured. Also, the flow rate into fields fluctuates considerably during any given irrigation event. According to Clyma and Ali (1977), farmers in many countries including the United States use the criterion of completing an irrigation event when water reaches the other end of the field. This criterion is used for level fields as well as graded fields. Watterburger and Clyma (1989 a and b), through mathematical simulations using the zero-inertia model (Strelkoff and Katopodes, 1977), found that level basins can be properly sized such that a target depth of irrigation water can be applied using the criterion of cutting off inflow when the water advances to the downstream end of the basin. Based upon this hypothesis, a procedure for design of level basins called completion-of-advance approach was developed by Wattenburger and Clyma (1989 a and b). An added value of the design is that the amount applied does not change appreciably even when the average flow rate changes considerably from the assumed design flow.

In the design procedure, first the following relationship was derived by setting the time of cutoff equal to the time of advance, and infiltration was characterized by the Kostiakov infiltration function:

$$K^* = \frac{k\, t_{co}^{a-3/16}}{q_u^{9/16}\; n^{3/8}} \qquad (18)$$

where K* is a dimensionless infiltration variable. Wattenburger and Clyma (1989 a and b) presented graphical relationships between K* and DU, and K* and L*, respectively, as a function of a. The other dimensionless parameters defined were:

$$L^* = \frac{L\, n^{3/8}}{q_u^{7/16}\, t_{co}^{13/16}} \qquad (19)$$

$$D_a^* = \frac{d_a}{k t_{co}^{a}} \qquad (20)$$

$$D_a^* = \frac{1}{K^*\; L^*} \qquad (21)$$

The average amount of water applied, d_a, is also the average amount of infiltrated water since there is no runoff from the basin. The average amount of water applied is calculated using $d_a = q_u\, t_{co}/L$ for a unit width of basin. The assumptions of Clemmens and Dedrick (1982) that $DU = d_n/d_a = E_a$ is also valid for the design.

The relationships above are the basis for a design process for designing a level basin based upon the completion-of-advance criterion. The design can be developed specifying a design depth and determining the design length of basin. Alternatively, the design can be developed by specifying the design length of basin and determining the design depth. Both parameters cannot be specified simultaneously. Here also, the SIRMOD computer simulation model was used to design a level basin irrigation system.

3. EFFECT OF INITIAL SOIL-MOISTURE CONTENT ON SOIL INFILTRATION RATE, Z_{req} AND IRRIGATION ADVANCE RATE

As discussed in the previous section, the rate of advance in a level basin depends upon the infiltration characteristics of the soil. In addition to soil texture and structure, the infiltration characteristics of a soil depend upon the moisture content at the time of irrigation (Tables 1 and 2). Therefore, the rate of advance depends upon the soil-moisture content at the time of irrigation. Consequently, the performance of a level basin irrigation system, on a given field, will be different for each irrigation event during the season even if the same design values for the flow rate and time of cutoff are used for each irrigation event during the irrigation season.

Philip (1957) derived an infiltration equation of the following form:

$$z = St^{1/2} + At \qquad (22)$$

in which z = cumulative infiltration depth; S= soil sorptivity; A= soil absorptivity; and t=time. Then, for Yolo light clay soil, Philip (1957) presented numerical values for soil sorptivity and absorptivity as a function of initial soil-moisture content (Table 1). Based upon these values, the cumulative infiltration depth values were calculated using Eq. 22 (Table 2), and are plotted in Figure 1. As expected, when the soil is drier at the time of irrigation, the cumulative infiltration is higher compared to a wetter soil for the same duration of time. However, because of lack of information on the total available water per unit depth of soil, the information on the dependence of soil infiltration rate on the initial soil-moisture content presented by Philip (1957) was not used in this paper. Instead, the infiltration function defined by the SCS is used in this paper.

Table 1. Sorptivity and absorptivity coefficients of Philip's (1957) infiltration equation as a function of initial moisture content

Θ (Fraction)	Sorptivity, S (Θ) ($cm/min^{1/2}$)	Absorptivity, A (Θ) (cm/min)
0.000	0.1394	0.000252
0.100	0.1239	0.000258
0.200	0.1053	0.000270
0.300	0.08056	0.00030
0.400	0.04957	0.000384
0.450	0.02943	0.00048
0.495	0.0000	0.00072

Table 2. Cumulative Infiltration, z(cm), as a function of initial moisture content (Yolo light clay soil)

T, seconds	Θ, moisture content					
	0	0.1241	0.2376	0.3663	0.440	0.4950
50000	4.3	3.7	3.0	2.0	1.3	0.7
1,00000	6.2	5.35	4.5	3.0	2.0	1.2
2,00000	9.0	8.0	6.7	4.7	3.6	2.5
3,00000	11.3	10.0	8.6	6.4	5.0	3.7
4,00000	13.6	12.0	10.2	7.9	6.4	5.0
5,00000	15.3	13.8	11.8	9.0	7.6	6.2
K (cm/seca)	.0109	.00767	0.005	.00151	.00027	.00002028
K (cm/hra)	.985	.823	.6269	.344	.1618	.05415
a	.55	0.571	0.59	.663	0.781	0.964

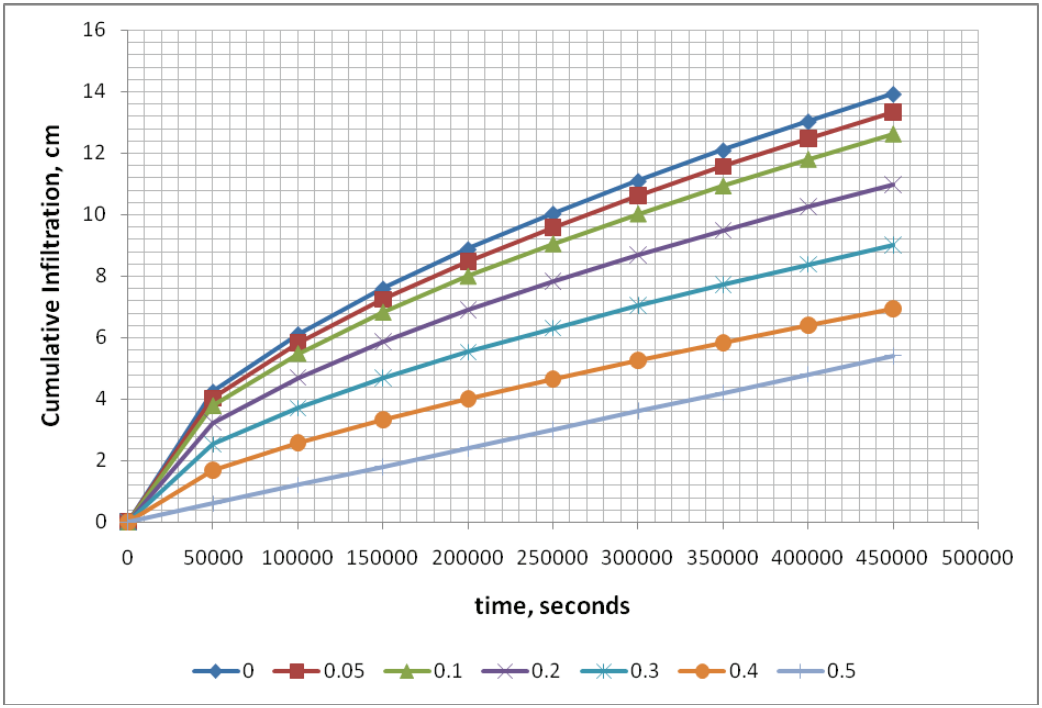

Fig. 1. Cumulative infiltration as a function of time and initial soil-moisture content of Yolo Light Clay soil (as adapted from Philip, 1957)

The infiltration equation of the SCS-USDA is given as follows:

$$z = kt^a + c \tag{23}$$

in which *k*, *c*, and a are empirical coefficients defined for each intake family; and z = cumulative infiltration. The SCS grouped the entire range of irrigated soils into 17 different Intake Families (IF), and the values for *k*, *a* and *c* were defined for each IF. These values were later fitted to a Kostiakov-Lewis type infiltration function which is given below:

$$z = kt^a + ct \quad (24)$$

The values for k, a, and c of Eq. 24 can be found in Walker (1989). Here, a medium textured soil whose infiltration characteristics can be described by **IF** = 0.60 was selected for design of a level basin irrigation system. The coefficients for the Kostiakov-Lewis equation are given in Table 3.

A design depth, i.e. the soil-moisture deficit at the time of irrigation, of 10 cm was considered. Using Eq. 24, the time required to infiltrate the design depth was calculated to be 278 minutes. Then, it was assumed that the soil is drier, and the soil-moisture deficit was about 12.5 cm. Based upon Figure 2, a medium textured soil with intake family IF=0.80 would have a cumulative infiltration depth of 12.7 cm in 278 minutes.

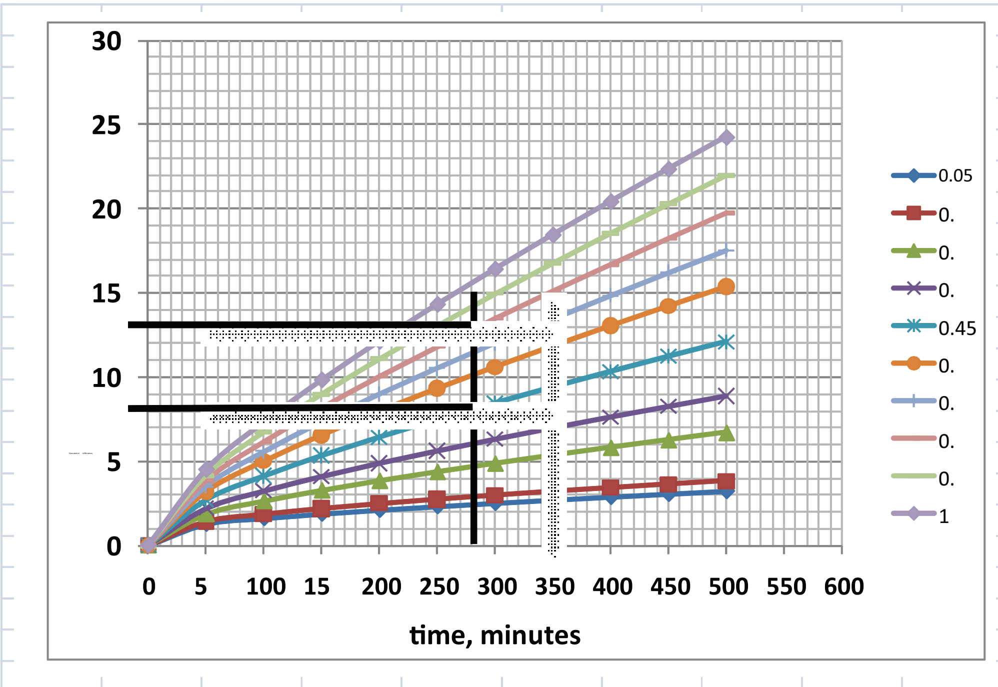

Fig. 2. Cumulative infiltration as a function of time for different Intake Families

Therefore, it was assumed that at this higher soil-moisture deficit the infiltration characteristics of the medium textured soil would be very similar to the infiltration characteristics of soil of **IF = 0.80**. Similarly, when the soil-moisture deficit is only 8 cm, this medium textured soil would behave like a soil of **IF = 0.45**. The Kostiakov-Lewis infiltration constants for these three intake families are given in Table 3.

Table 3. Infiltration coefficients for the selected SCS intake families

IF	k	a	c	Dn, m	T, min	Dactual, m
0.45	0.00321	0.49	0.000107	0.1	385	0.0803
0.6	0.0032	0.529	0.000136	0.1	278	0.1000
0.8	0.00324	0.568	0.000174	0.1	200	0.1276

4. RESULTS AND DISCUSSION

In order to evaluate the robustness (of performance) of the two different approaches - the limiting length approach and the completion-of-advance approach - used to design level basin irrigation systems, two example field situations were analyzed.

Example 1

Length of the field, L = 200 m

Width of the field, W = 200 m

Field roughness, n = 0.04

SCS Intake Family # of the soil = 0.60

(See Table 3 for values of infiltration constants)

Design depth, D_n = 10 cm

Using the completion-of-advance design approach, the following design values were obtained for the level basin irrigation system:

q = 1.5 lps t_{co} = 190 min L = 200 m

The following performance values were obtained for this design:

E_a = 73.83% DU = 90.17% E_r = 99.67% D_{pf} = 25.89 %

The same design values were assumed for a limiting length design approach. Traditionally, once a level basin is designed, the same design and operational parameters are used for each irrigation event during the season. As long as the soil-moisture content and Manning's roughness parameter values at the time of each irrigation event are the same as the values used at the time of design, the performance of level basin irrigation systems is expected to be close to the design performance values. In order to achieve the same performance values for each irrigation event during the irrigation season, the soil-moisture content at the time of each irrigation event must be the same, i.e. the soil-moisture deficit in the crop root zone at the time of each irrigation event should be equal to D_n. This means, the farmers must follow an accurate irrigation schedule. In the absence of such an irrigation schedule, the soil-moisture content at the time of each irrigation event may be different, and hence the performance of a level basin irrigation system will be different. However, depending upon the design approach used, the performance of a level basin irrigation system may or may not change significantly.

Here, the performance of the above level basin irrigation system when the soil-moisture deficit at the time of irrigation is only 8 cm (as opposed to the design depth of 10 cm) is evaluated using a simulation model. As shown in Table 4, the application efficiency and water requirement efficiency were, respectively, 91% and 97 % for the limiting length design approach, whereas for the completion-of-advance approach the application efficiency and water requirement efficiency values were, respectively, 99.6% and 86.%, resulting in about 14% deficit irrigation. However, the application efficiency was very high, 100%, in the case of completion-of-advance approach. Conversely, when the soil-moisture deficit at the time of irrigation is 12.6 cm (as opposed to the design depth of 10 cm), the simulated application efficiency and water requirement efficiency were, respectively, 100% and 67% for the limiting length design approach, whereas for the completion-of-advance approach the application efficiency and water requirement efficiency values were, respectively, 95% and 87.6%, resulting in under-irrigation of 33%.

Table 4. Performance of a level basin for n = 0.04

IF →	0.6	0.45		0.8	
	Trad/CA	Trad	CA	Trad	CA
L, m	200	200	200	200	200
q, lps/m	1.5	1.5	1.5	1.5	1.5
Tco, min	190	190	155	190	260
Ea, %	73.83	91.14	99.6	99.86	95.01
Er, %	99.67	97.4	86.24	67.23	87.53
Dpf, %	25.89	8.55	0.16	0	4.8
DU, %	90.17	88.77	84.44	73.27	77.35

Table 5. Performance of Level Basins for n = 0.10

IF →	0.6	0.45		0.8	
	Trad/CA	Trad	CA	Trad	CA
L, m	200	200	200	200	200
Q, lps/m	2.5	2.5	2.5	2.5	2.5
Tco, min	140	140	127	140	158
Ea, %	92.5	75	84.4	99.7	98.5
Er, %	97	99.7	99.67	73.6	90
Dpf, %	7.21	23.7	15	0	1.22
DU, %	89	93	92.3	76.2	86

Example 2

Length of the field, L = 200 m

Width of the field, W = 200 m

Field roughness, n = 0.10

SCS Intake Family # of the soil = 0.60

(See Table 3 for values of infiltration constants)

Design depth, D_n = 10 cm

Using the completion-of-advance design approach, the following design values were obtained for the level basin irrigation system:

q = 2.5 lps t_{co} = 140 min L = 200 m

The following performance values were obtained for this design:

E_a = 92.5 % DU = 89 % E_r = 97 % D_{pf} = 7.21 %

The same design values were assumed for the limiting length design approach. Here also, the performance of the above level basin irrigation system when the soil-moisture deficit at the time of irrigation is only 8 cm (as opposed to the design depth of 10 cm) was evaluated using a simulation model. As shown in Table 5, the application efficiency and water requirement efficiency were, respectively, 75% and 99.7 % for the limiting length design approach, whereas for the completion-of-advance approach the application efficiency and water requirement efficiency values were, respectively, 84.4% and 99.7%. Conversely, when the soil-moisture deficit at the time of irrigation is 12.6 cm (as opposed to the design depth of 10 cm), the simulated application efficiency and water requirement efficiency were, respectively, 100% and

Based upon the above two examples, the completion-of-advance design criterion minimizes under-irrigation in most cases without sacrificing the value of application efficiency. And, similar trend is expected to continue for n=0.25.

5. CONCLUSIONS

Based upon the above simulations, it can be concluded that the performance of a level basin designed based upon the completion-of-advance criterion is more robust than the performance of a level basin irrigation system that is designed based upon the limiting length concept. And, this is true both in the case of variable inflow rate into a basin as well as when the soil-moisture deficit at the time of irrigation is different from the design depth. This attribute of completion-of-advance design criterion is advantageous in situations where flow rate at field level is fluctuating, farmers do not measure water, and farmers do not have any control on the amount of water they receive as happens in many developing countries. In addition, the performance of a level basin irrigation system can be expected to be very robust in situations where farmers do not follow any irrigation scheduling.

However, since the time of advance to the end of a level basin is not known *a priori*, it is very difficult to prepare a time-based water distribution system among a group of farmers that take water from a common outlet. The start of the turn time of farmers that are in sequence to receive water, for example in a rotational water distribution system within the command of a single outlet, is difficult to calculate. Conversely, if the farmer using the completion-of-advance operation criterion is irrigating independently, then the delivery system must be flexible so that when the farmer is done irrigating his field, the flow rate in the canal automatically reduces proportionately to minimize operational water losses.

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