SENSITIVITY OF SURFACE IRRIGATION TO INFILTRATION PARAMETERS: IMPLICATIONS FOR MANAGEMENT

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ABSTRACT

Infiltration characteristics are a major source of uncertainty in the design and management of surface irrigation systems. Understanding the sensitivity of the design to errors or variation in the design inputs is needed to develop management recommendations that account for this uncertainty. This paper further analyzes the sensitivity of the level basin design procedure proposed by Clemmens (1998). Results show that the recommended management approach, cutting off inflow when the water advances a fixed distance relative to the field length, works best when actual advance time is more than predicted. If actual advance time is the same or less than predicted, then cutoff based on time may be a better approach, independent from variations due to differences in infiltration, roughness, inflow, or all of these factors combined.

INTRODUCTION

There are three main sources of uncertainty in infiltration predictions for surface irrigation design and management. First is the mathematical formulation of the process. Second is the variability of infiltration and the determination of representative parameters required by the selected infiltration formulation. Last are soil changes, with implications to infiltration characteristics, occurring not only during the course of the irrigation season but even during one irrigation event (consolidation, aggregate dispersal, sealing of cracks, sediment deposition, etc.). Irrigation specialists recognize these uncertainties but tools do not exist yet that can be used to systematically analyze their consequences. Design and management recommendations are made, therefore, under the assumption that the farmer will experiment with the irrigation system and gradually reach reasonable levels of performance (Bautista et al., 2001).

Rather than relying on trial-and-error, irrigation specialists need to provide farmers with measures of how the system will react to differences in the design specifications. Such measures should help develop a framework for identifying likely reasons for the differences between the anticipated and actual performance

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and, consequently, develop a management strategy that effectively compensates for variations in the suspect parameters.

An example of this type of framework was provided by Clemmens (1998), who proposed a design procedure for level basins based on a distance-based cutoff criteria. The sensitivity of the design to changes in design parameters was compared for two management options, with cutoff determined based on distance and cutoff based on time. Clemmens' analysis considered only the effect of individual input parameters, such as infiltration, but not their interaction, and only one infiltration parameter was analyzed. For furrow irrigation, Zerihun et al. (1996) concluded that sensitivity measures for surface irrigation design are difficult to obtain because changes in one parameter aggravates or mitigates the impact of changes in other parameters.

The objective of this study is to further examine Clemmens' (1998) design approach vis-à-vis the uncertainty in the design inputs. The analysis considers infiltration conditions not considered in the original study and the interaction between infiltration and other input parameters. The study falls within the scope of research activities being promoted by ASCE/EWRI Task Committee on Soil and Crop Hydraulic Properties for Surface Irrigation (Strelkoff et al., 2000).

INFILTRATION UNCERTAINTY

Infiltration equations for surface irrigation modeling

A variety of infiltration equations have been used in conjunction with surface irrigation models. Most of those equations are empirical (explicit relationships between cumulative infiltration and opportunity time) but also semi-physical approaches have been tested (Green-Ampt type formulations). When properly calibrated for an individual irrigated unit, i.e., a border, basin, or furrow, these equations can result in reasonable agreement between predicted and field-measured advance, recession, and runoff (Clemmens, 1982; Bautista and Wallender, 1993; Fonteh and Podmore, 1989). The diversity of infiltration formulations reflects the difficulty in modeling the infiltration process. In irrigation modeling research, selection of an infiltration formulation is frequently based on the perceived ability of the equation to fit field-measured infiltration data (Clemmens, 1983; Tarboton and Wallender, 1989; Childs et al., 1993). In irrigation design practice, choice of a formula is more frequently based on familiarity or availability of data, particularly for the SCS equation (Bautista et al., 2001). The use of physical or semi-physical formulations is not common, partly because of their mathematical complexity, but also because of the ability of empirical equations to compensate for measurement errors and to reproduce the initial stage of the infiltration process (which is often dominated by effects not accounted for in the governing equations of porous media flow). A key difficulty in the use of any formulation is that for many field data sets, several equations may fit the data equally well; however predictions for times longer than the duration of the infiltration test can be significantly different (Clemmens, 1982; Tarboton and Wallender, 1989). Thus, infiltration parameters need to be calibrated taking into account the typical duration of irrigation events.

Comparison of irrigation predictions with alternative infiltration formulations for the same field conditions is lacking. In the case of border irrigation, Clemmens et al. (2001) found that predictions are similar if the infiltrations equations have a similar infiltration characteristic time, i.e., similar intake opportunity time for the required application depth. These findings are based on empirical infiltration equations only and, thus, comparisons with semi-physical approaches are needed. These authors also pointed out the limitations of using this characteristic infiltration time for design, as performance degrades with changes in the irrigation target, which can occur during the course of the irrigation season.

Variability of infiltration

Point-measured cumulative infiltration for fixed opportunity time and infiltration rates can vary by an order of magnitude over an irrigated field and over an irrigation season, with reported coefficients of variation (CV) ranging from 35% up to 90% for both variables (Bautista and Wallender, 1985; Jaynes and Hunsaker, 1989; Childs et al, 1993; Hunsaker et al., 1999). The implication is that many point measurements are needed to characterize infiltration with a high degree of certainty. Infiltration variability estimates are affected by the measurement method and the scale of measurements (Bautista and Wallender, 1985; Jaynes and Hunsaker, 1989). Use of entire irrigated units as infiltrometers (borders, basins, furrows), can reduce the influence of these systematic errors. Still, variability of infiltration measured on larger units can be significant. For example, a CV of 24% for cumulative infiltration (Tarboton and Wallender, 1989) has been measured within furrow sets while a 12% CV has been measured for the time to infiltrate 100 mm of water for a group of borders on a 32 hectare field (Clemmens, 1992).

An alternative approach for assessing infiltration variability is through the distribution of parameters of infiltration functions. Results of studies of this type have been mostly inconclusive because of the correlation between fitted parameters (Jaynes and Hunsaker, 1989; Hunsaker et al., 1999). Studies have shown, however, that the mean and variance of the distribution of advance times, infiltrated depths, distribution uniformity, etc., can be predicted if the mean and variance of infiltration parameter distribution is known and is random (Jaynes and Clemmens, 1986). Since a wide variation in system performance (advance times, infiltrated depths) can result from a given distribution of infiltration characteristics, a conservative approach must be used in formulating design and management recommendations because the performance of individual irrigated units may depart substantially from the average.

SIMULATION PROCEDURES

Clemmens (1998) used the following design specifications to test his design procedure: the target application depth d_{req} is 100 mm, the characteristic infiltration time (for the required application depth) τ_{100} is 210 min. A Kostiakov relationship is assumed for the infiltration function with the exponent $a = 0.5$. The value of K is then determined from τ_{100} and a. The Manning's roughness n is equal to 0.15 and the available discharge is 230 l/s. The proposed design approach requires the designer to specify the distance at which flow will be cut off relative to the field length. Recommended values for this distance-based cutoff ratio, R, are between 0.85 and 1, in accordance with results presented by Clemmens and earlier work by Clemmens and Dedrick (1982). With the given design data and by requiring an R of 0.9 and a potential application efficiency (PAE) of 80%, Clemmens used the BASIN program (Clemmens et al., 1995) to compute the basin dimensions, L= 199 m and W = 85 m (length and width, respectively). The resulting cutoff time t_{co} is 153 minutes.

The sensitivity of the design can be tested through simulation. The SRFR program (Strelkoff et al., 1998) was used in the analysis. Clemmens (1998) studied the impact of infiltration variation by varying the Kostiakov K by ±20 % and ±50%. The corresponding variation in τ_{100} is between -44% and +400%. This study limits the variation in infiltration based on τ_{100} (±25%, ±50%) because it is closer to the CV of cumulative infiltration for a specified time measured in field experiments, as was discussed earlier. The effect of infiltration function form is studied, in a limited way, by varying the exponent a of the Kostiakov relationship. SRFR allows the user to specify the characteristic infiltration time and the value of the Kostiakov a, from which the program internally then determines K. The combined effects of a and τ_{100}, and the impact of these two parameters in combination with Manning n and inflow rate Q, are also considered here. These parameters are likely sources of uncertainty in actual irrigation events. Land leveling precision effects are ignored here as well as changes in d_{req}.

RESULTS

A smaller than assumed τ_{100} slows down the advance because more water infiltrates in a given time relative to the design conditions. In this situation, operating the system based on a specified cutoff time is inappropriate because water would not reach the end of the field, even with just a 25% decrease in τ_{100} (Table 1). In the table, t_L represents the final advance time and L_{max} the maximum advance distance. If cutoff is based on R, then water will reach the end of the field and the minimum depth (d_{min}) will be close to d_{req} (100 mm). If, on the other hand τ_{100} is greater than specified in the design, there is still an advantage in using R as the cutoff criteria because water advances more rapidly than originally anticipated, forcing an earlier cutoff time. This reduces d_{avg} (average application depth) and improves application efficiency (AE). Under these conditions, cutting off at the target t_{co} has no impact on AE but low quarter distribution uniformity (DU_{lq}) improves, so performance will still be close to the design specifications. Thus, if flow rate and roughness are expected to agree with the design specifications but there is uncertainty about τ_{100} (though not about the form of the infiltration function), managing cutoff based on R should provide reasonable performance for likely variations in τ_{100}.

Table 1. Sensitivity of level basin design to □$_{100}$

Variable	τ_{100} (min)									
	Cutoff based on R					Cutoff based on t_{co}				
	-50%	-25%	Design	+25%	+50%	-50%	-25%	Design	+25%	+50%
	105	158	210	263	315	105	158	210	263	315
t_{co} (min)	193	166	153	143	137	153	153	153	153	153
t_L (min)	238	198	179	168	160	∞	∞	179	167	160
R	0.9	0.9	0.9	0.9	0.9	0.77	0.85	0.9	0.94	0.97
AE (%)	63.2	73.7	80.1	85.6	89.5	68.8	77.5	80.1	80.1	80.1
DU_{lq}	0.72	0.82	0.87	0.89	0.90	0.35	0.71	0.87	0.9	0.92
d_{min} (mm)	82.9	98.6	102	98.5	96.8	0	0	102	108	119
DP (mm)	57.4	35.5	24.8	16.7	11.7	38.8	27.6	24.8	24.8	24.8
d_{ave} (mm)	157	136	125	117	112	125	124	125	125	125
L_{max} (m)	199	199	199	199	199	174	199	199	199	199

For a given value of τ_{100}, a reduction in the infiltration exponent a causes more water to infiltrate during the initial wetting; however, infiltration rates decrease more quickly than with the original value. Advance, therefore, should slow down[1]. This is in fact what happens when simulations are carried out with a design based on $a = 0.5$, but with actual $a = 0.3$ (Table 2). These results are in contrast with the findings of Clemmens et al. (2001), who reported little effect of functional form on border design and performance. With cutoff based on R, the slower advance translates into more water being applied to the basin than needed, even when actual τ_{100} is much greater than the design value. The time-based cutoff provides better results than R-based cutoff if actual τ_{100} is greater than in the design. AE remains constant in such case. However, if the actual τ_{100} is less than in the design, advance doesn't reach the field's end. In practice, one would not be able to determine if the problem is in the estimation of τ_{100}, a, or both. Therefore, the best approach would be to cut off based on advance distance.

Table 2. Sensitivity of level basin design to τ_{100} and infiltration function form (a = 0.3)

Variable	τ_{100} (min)									
	Cutoff based on R					Cutoff based on t_{co}				
	-50%	-25%	Design	+25%	+50%	-50%	-25%	Design	+25%	+50%
	105	158	210	263	315	105	158	210	263	315
t_{co} (min)	197	183	174	167	163	153	153	153	153	153
t_L (min)	231	213	202	194	189	∞	∞	229	204	192
R	0.9	0.9	0.9	0.9	0.9	0.74	0.78	0.81	0.83	0.86
AE (%)	62	67	71	73	75	72	78	80	80	80
DU_{lq}	0.93	0.95	0.96	0.96	0.96	0.51	0.78	0.92	0.95	0.96
d_{min} (mm)	146	139	134	130	127	0	0	107	115	118
DP (mm)	61	49.1	41.4	36.4	33.1	35.1	27.6	24.7	24.8	24.8
d_{ave} (mm)	161	149	142	136	133	125	125	125	125	125
L_{max} (m)	199	199	199	199	199	178	193	199	199	199

Table 3. Sensitivity of level basin design to τ_{100} and infiltration function form (a = 0.7)

Variable	τ_{100} (min)									
	Cutoff based on R					Cutoff based on t_{co}				
	-50%	-25%	Design	+25%	+50%	-50%	-25%	Design	+25%	+50%
	105	158	210	263	315	105	158	210	263	315
T_{co} (min)	196	151	133	123	117	153	153	153	153	153
T_L (min)	∞	185	159	146	138	∞	183	158	145	137
R	0.9	0.9	0.9	0.9	0.9	0.79	0.9	0.98	>1	>1
AE (%)	58	78	89	95	98	66	77	80	80	80
DU_{lq}	0.49	0.66	0.79	0.83	0.85	0.23	0.68	0.83	0.88	0.90
d_{min} (mm)	0	59.3	74.7	75.8	76	0	65.3	93.6	103	108
DP (mm)	66	27.3	12	5.5	2.1	42.2	28.4	25.1	24.8	24.8
d_{ave} (mm)	159	123	109	101	95.8	125	125	125	125	125
L_{max} (m)	192	199	199	199	199	171	199	199	199	199

Increasing the exponent a from 0.5 to 0.7 has quite different implications (Table 3). In this case, initial infiltration is less than in the original design so advance is faster (except in a very long basin). In this case, severe underestimation of τ_{100} (-50%) will cause water not to reach the end of the basin with either cutoff criterion. If τ_{100} is underestimated by only 25%, the R-based cutoff time is close to the design value, so results are similar. For all other conditions (conditions under which the advance time to the end of the field is less than specified in the design) the time-based criterion provides clearly better results.

Clemmens (1998) showed that if the only source of uncertainty in the operation of the irrigation system is in the determination of Manning n (with n varying by ± 50%), then determining cutoff based on time provides better performance than based on R. Changes in roughness and infiltration characteristics can have equal or opposing effects on the advance rate of the surface flow. Their interaction is examined next.

A Manning n of 0.15 is the NRCS recommended value for alfalfa or broadcast small grains. A value of 0.10 is recommended for drilled grains, while a value of 0.2 is recommended for a dense alfalfa. Thus differences of this magnitude would not be unlikely between the design and the field values. If the actual n = 0.20, advance will be slower, but both the time- and distance-based cutoff criteria will result in reasonable performance (Table 4). If cutoff is time-based, there will be some underirrigation near the end of the field, but with distance-based cutoff there will be greater deep percolation and lower AE. The choice of criteria for cutoff would depend on the sensitivity of the crop to a water deficit, cost of water, and possibly other factors.

Table 4. Combined effect of change in n, τ_{100}, a and Q with n = 0.2.

Variable	n = 0.2		□$_{100}$ = 158 min		a = 0.3		Q = 207 l/s	
	Cutoff criteria							
	t_{co}	R	t_{co}	R	t_{co}	R	t_{co}	R
t_{co} (min)	153	167	153	182	153	198	153	217
t_L (min)	206	197	∞	216	∞	229	∞	253
R	0.8	0.9	0.80	0.9	0.73	0.9	0.68	0.9
AE (%)	80	73	75	67	75	62	77	63
DU_{lq}	0.83	0.88	0.6	0.84	0.68	0.96	0.48	0.95
d_{min} (mm)	92.1	113.6	0	113	0	152.2	0	149.2
DP (mm)	25	36.4	31.1	48.2	30.9	61.2	26.1	59.5
d_{ave} (mm)	125	136	125	148	125	161	112	160
L_{max} (m)	199	199	190	199	187	199	171	199

If in addition to n being in error, τ_{100} is also in error by -25%, then the time based criteria no longer works because the water does not reach the end of the field (Table 4). While the alternative criterion (R) allows irrigation of the entire field, the drop-off in AE is noticeable.

Two other scenarios are presented in Table 4, one in which in addition to the previously noted changes, the exponent a is also in error ($a = 0.3$). The last scenario considers a flow rate reduction of 10%. All of these factors cause the advance to be slower. As a result, the time-based criteria is inadequate in all of these cases. If using distance to determine cutoff, water will reach the end of the field in all cases, but AE will be low.

An alternative set of scenarios is presented in Table 5. Actual Manning n is 0.10 (faster advance) but then τ_{100}, a, and Q are varied as in the previous example so the changes in these variables have opposing effects on advance. Results show that if n, τ_{100}, and a are uncertain, but less hydraulic resistance is anticipated than specified in the design, then cutting off based on time will be a better alternative than if based on distance. This assumes that the design Q is accurately delivered. If Q cannot be accurately measured or not measured at all, but the operator has reasons to believe that it is less than the design value, then a better approach is to manage the system based on distance. It should be noted, however, that if the operator has knowledge of the difference in discharge with respect to the design value and adjusts the cutoff time accordingly, then the time based approach will still result in the expected AE and near the expected uniformity.

Table 5. Combined effect of change in n, τ_{100}, a and Q with $n = 0.1$.

Variable	n = 0.1		τ_{100} = 158 min		a = 0.3		Q = 207 l/s	
	Cutoff criteria							
	t_{co}	R	t_{co}	R	t_{co}	R	t_{co}	R
t_{co} (min)	153	133	153	147	153	165	153	182
t_L (min)	157	158	174	177	210	193	∞	214
R	0.98	0.9	0.92	0.9	0.85	0.9	0.78	0.9
AE (%)	80	90	80	82	80	74	83	75
DU_{lq}	0.89	0.83	0.81	0.78	0.89	0.93	0.64	0.92
d_{min} (mm)	104.9	82.3	89.4	79.2	102.5	122	0	119.2
DP (mm)	24.9	11	25.2	21.6	24.7	34.3	19.4	33.8
d_{ave} (mm)	125	109	125	120	125	134	112	134
L_{max} (m)	199	199	199	199	199	199	186	199

DISCUSSION

In general, results indicate that, for the indicated scenario, if water advances nearly as fast or faster than anticipated in the design to the cutoff point, then the system should be managed based on time. In such cases, final infiltrated depth distribution depends mostly on the total volume of water applied, independent from various sources of error. If advance is significantly lower than expected, then a safe approach is to irrigate based on cutoff distance, although performance could be poor, especially if the design underestimated roughness and infiltration characteristics, and flow rate is less than expected. An important consideration in the management of the system under conditions where advance is much slower and performance potentially much poorer, is determining which inputs are most different from the design specifications.

Given that level basin systems represent a significant investment, especially for large basins typical in the U.S., one could argue that reasonable flow rate measurement should be required with those systems and that irrigators need to be familiar with the effect of inflow rates different that the design value on advance (a readily available performance measure). If actual advance behaves in accordance with predictions for the actual inflow rate, then other design inputs are likely in agreement with field values. In such cases, use of either cutoff criterion should yield levels of performance close to the target, even for significant differences in flow rate relative to the design value (Clemmens, 1998). The hydraulic roughness characteristics of bare and cropped field have been analyzed (Gilley and Finkner, 1991; Gilley and Kottwitz, 1994) and these analyses suggest that the recommended NRCS Manning *n* values are reasonable. Designing the system for mid-season roughness conditions, when resistance to flow is highest, provides a way to partially compensate for higher than anticipated infiltration conditions (Table 5) and assures that slower than predicted advance will be the result of differences in infiltration characteristics.

The results of Tables 2 and 3 show that the infiltration function form impacts performance, even when τ_{100} is accurately known. Again, the consequences seem minor if actual advance time is less than expected but the interaction between τ_{100} and a seems significant if advance is slower than expected. It is important to note that this part of the analysis assumes that τ_{100} and a are estimated independently. In situations where τ_{100} is calculated based on an assumed a, underestimating a would likely result in an overestimation of τ_{100} while the opposite would be true if a is overestimated. This has implications for the results presented in Tables 2 and 3. In the former case (Table 2), an actual τ_{100} □ 210 min would be less likely to occur and, therefore, the recommendation would always be to cutoff based on distance. In the latter case (Table 3), an actual τ_{100} □ 210 min would be less likely to occur and time-base cutoff would always be the preferred management choice.

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[1] For a very long field, if near steady-state infiltration rates are reached in the upstream portions of the field during the course of the irrigation, actual advance may be initially slower than predicted but later in the irrigation actual advance may be faster than predicted.