EVALUATION OF INFLOW CUTOFF CRITERION FOR CITRUS AND ALFALFA BASINS IN THE YUMA MESA IRRIGATION DISTRICTS

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Executive summary: Large basins are used to irrigate citrus and alfalfa crops in the Yuma Mesa Irrigation and Drainage Districts (YMIDD) and the Unit B Irrigation and Drainage Districts (UBIDD) of southwest Arizona. Irrigation water is delivered to basins at very high flow rates to force a rapid advance over the highly permeable soils. With large inflows, cutoff times need to be determined accurately to minimize deep percolation losses and maximize performance (efficiency and uniformity) -- within the constraints of the extant inflows. However cutoff time is difficult to determine accurately in the YMIDD/UBIDD area, because the inflow to individual basins is not measured and the discharge supplied to farms is not constant. A management strategy has been proposed that uses the advance time to half the basin length, t_{50}, as the basis for recommending a cutoff time, t_{coReq}, that will match the minimum applied depth, Z_{min}, to the net irrigation requirement, Z_{Req}. The proposed approach does not require flow rate measurement, instead it uses a t_{50} measured in real-time in place of basin unit inflow rate, q_o, to time cutoff. This strategy is premised on the fact that given a basin (defined in terms of length, irrigation requirement, bed slope, surface roughness, and infiltration properties), the corresponding $t_{coReq}(q_o)$ and $t_{50}(q_o)$ functions, defined over a feasible range of q_o, can be used to formulate a direct functional relationship between t_{coReq} and t_{50} $(t_{coReq}(t_{50}))$, resulting in a cutoff criterion without explicit dependence on q_o. If the proposed cutoff criterion proves feasible, the next goal would be to develop practical tools and procedures that could be used by irrigators to apply it in the day-to-day management of basin irrigation systems in the YMIDD/UBIDD area.

A joint research project between the University of Arizona and the USDA-ARS-ALARC explored the feasibility of the proposed inflow cutoff criterion. The problem was examined theoretically, by means of unsteady-flow simulations, and practically, with measured field data. As part of the theoretical analysis, a software tool was developed based on the USDA-ARS surface-irrigation simulation engine, SRFR. This application software was used to develop charts relating t_{50} and t_{coReq}, t_{50} and q_o, and t_{50} and application efficiency, E_a (or distribution uniformity, DU_{min}) for a variety of field conditions and a basin length typical of the YMIDD/UBIDD. Assuming well-defined systems, the t_{50}-t_{coReq} charts were used to examine the performance potential of the t_{50}-

t_{coReq} strategy under the range of conditions encountered in the YMIDD/UBIDD area. These charts were also used to evaluate the sensitivity of the performance potential of the cutoff criterion to inaccurate system parameter estimates and t_{50} measurements. In addition, simulation studies were conducted to evaluate the range of application of the t_{50}-t_{coReq} cutoff criterion.

Simulation studies were conducted to examine potential application efficiency (the application efficiency when the minimum depth in the infiltration distribution just equals the target value, i.e., the maximum application efficiency that can be attained under a given set of field conditions and inflow rate) as a function of q_o for a limited number of combinations of basin dimensions, required depth, slope, roughness, and infiltration characteristics, typical of conditions in the YMIDD/UBIDD area. Some combinations of field conditions lead to high application efficiencies, even over a wide range of inflow rates. Other combinations of conditions lead to lower potential application efficiencies, achievable only within a narrow range of inflow rates; performance degrades rapidly if the inflow rate lies outside the recommended range. The implication is that the proposed cutoff strategy, or any other management strategy, may produce only limited performance improvements if applied to systems with limited potential application efficiency, especially if the inflow rate lies outside a recommended range.

As is the case with any other irrigation management strategy, the t_{50}-t_{coReq} cutoff criterion assumes that field conditions (field slope, roughness, and infiltration characteristics) are defined with sufficient accuracy prior to an irrigation event. In addition, it assumes that mid-field advance, t_{50}, can be measured with sufficient precision leading to an accurate estimate of the corresponding cutoff time, t_{coReq}. However, estimates of field conditions, particularly roughness and infiltration, are inherently uncertain, while measurement of advance times can be imprecise (due to unevenness of the advancing front). Simulation studies were conducted to examine the sensitivity of the t_{50}-t_{coReq} strategy to uncertain inputs.

Under the range of field conditions and unit inflows typically applied in the area, water application times to a basin are relatively short, generally between 30 and 60 min. This means that t_{50} varies over a narrow range for different q_0. As a result, t_{50} measurement errors as small as 1 or 2 min could lead to recommended cutoff times that would result in significant under-irrigation, or even water not reaching the end of the field. Thus, the proposed strategy is sensitive to t_{50} measurement errors. Simulation studies also show that slight changes in slope, roughness, or infiltration characteristics shift the t_{50}-t_{coReq} chart vertically and/or horizontally by several minutes. Consequently, small errors in the determination of any of these inputs can result in inadequate cutoff recommendations or to no recommendation at all in cases where the observed t_{50} value is outside the range of theoretical t_{50} values (the values derived using hydraulic simulation) for the assumed conditions.

Field data were analyzed to evaluate the t_{50}-t_{coReq} cutoff criterion under a range of field conditions in the YMIDD/UBIDD area. Two groups of data sets were used in this study. The first group is based on field data collected by the USBR-Yuma Area office. For this group, post-irrigation mass balance calculations – based on measured advance, recession, and inflow rates – were used to estimate the infiltration parameters and Manning roughness corresponding to each irrigation event. These estimates, together with basin dimensions, slope, and irrigation requirement were then used to develop the theoretical relationships between t_{50} and t_{coReq}, t_{50} and q_o, and t_{50} and E_a. Such infiltration and roughness estimates can be considered more accurate than estimates derived from soil maps and crop type, the sort of information that would be available for everyday use of the method. Hence, the analysis represents a best-case scenario relative to the accuracy of infiltration and roughness estimates. For each data set, an inflow rate to the basin was obtained from the chart and compared with measured flow rates. Relative prediction errors were large, 34% on the average. While these errors were reduced by half through additional calibration efforts, the results suggest limitations in our ability to calibrate these inputs accurately (this could be attributed to limitations in current parameter estimation and/or discrepancies between the algorithms employed in the model and the actual physical processes). Furthermore, significant uncertainty in the measured t_{50} was suspected, resulting from the complex, two-dimensional flow pattern that occurs in most irrigation basins in the YMIDD/UBIDD area.

The t_{50} strategy was tested on a number of basins in private farms and on the University of Arizona Research farm, all located within the YMIDD/UBIDD area. In these analyses, the inputs needed to develop the t_{50}-t_{coReq} charts were not obtained from detailed irrigation field evaluations, but instead were based on readily available soil, crop, and land grading information. Field slope was provided by growers, Manning roughness was determined by crop, and the infiltration family was deduced from soil maps. This approximate data is the type of data that is commonly available to NRCS or university extension personnel when making system improvement recommendations; it characterizes the level of accuracy of inputs that would be used for day-to-day application of the proposed t_{50}-t_{coReq} cutoff strategy. In this analysis too, for each set of assumed field conditions, basin length, and irrigation requirement, charts containing t_{50}-t_{coReq}, t_{50}-q_o, and t_{50}-E_a curves were developed from simulation data. For these tests, differences between the field-measured basin inflow rates and chart-derived inflows were comparable to those computed with the previous group of tests based on evaluation-derived infiltration data. However, for several of these tests, the measured t_{50} was outside the range of the theoretical t_{50} values under the assumed conditions and, therefore, a relative error could not be computed. As mentioned above, several factors may have contributed to the observed large discrepancies between measured and chart derived inflows. From the results it cannot be determined which of the factors contributed the most to the observed errors.

Considering the primary irrigation management constraint in the YMIDD/UBIDD (which is that measurements of inflow rates to individual basins are highly inaccurate, or non-existent), the fact that the t_{50}-t_{coReq} cutoff criterion is not explicitly dependent on flow rate measurement is an advantage. However, because field conditions can only be defined in an approximate sense prior to an irrigation event, safety factors may need to be incorporated into the strategy to overcome the limitations of the t_{50} cutoff criterion. Our results suggest that the t_{50}-t_{coReq} strategy may require significant management effort to be effective. Consequently, other, simpler cutoff criterion (such as advance-distance based cutoff) should be considered in future studies.

1. Introduction

The Yuma Mesa Irrigation and Drainage District (YMIDD) and the Unit B Irrigation and Drainage District (UBIDD) of southwest Arizona supply Colorado River water to more than 8000 ha of irrigated land (Yuma Ag Council, 2006). Large basins, both level and graded, are widely used to irrigate citrus and alfalfa crops grown on the sandy soils of these irrigation districts. Application efficiencies in the YMIDD and UBIDD have been low, averaging less than 40% (USDA-NRCS, 1987). Deep percolation losses from these irrigation districts contribute to drainage problems and elevated nitrate-nitrogen levels in the shallow groundwater of the adjacent lower Colorado and Gila River valleys (United States Bureau of Reclamation, 1991). As a result, stakeholders have a strong interest in improving irrigation practices. Pressurized irrigation systems represent an alternative for improving irrigation efficiency (Roth et al., 1995), however, given the high installation cost associated with pressurized systems and the relatively low cost of water and fertilizer, surface irrigation will remain the primary method of water application to croplands in the YMIDD and UBIDD.

With support from the USBR, the Yuma Agricultural Center of the University of Arizona developed basin irrigation management packages (performance charts, tables, and guidelines) for the YMIDD and UBIDD (Sanchez and Zerihun. 2000a,b). The management packages were further extended to cover three additional basin lengths to the standard 600 ft length used in the area (Sanchez and Zerihun, 2004). These management packages are already being used by operators and are contributing to improvements in irrigation performance. A limitation of these procedures is that, they were developed assuming controlled and accurately measured inflows. Consequently, they cannot be applied to farms where inflow measurements are inaccurate or leakage losses in the field supply channels are high, a prevalent problem in the area. Extensive infrastructure repairs and upgrades are needed to remedy this problem, but because of cost, they are unlikely to be undertaken in the short term. A cutoff criterion that is not explicitly dependent on inflow rate may help overcome this irrigation management constraint.

With support from the Lower Colorado Region of the USBR, the University of California (Bali et al, 2000) developed practical inflow cutoff guidelines based on measured advance over the cracking soils of the Imperial Valley. There, flow rates are measured with satisfactory precision, but infiltration properties, needed for optimal management, are difficult to quantify *a priori* because of the cracks. Following this successful effort, Niblack (United States Bureau of Reclamation, 2005) proposed an alternative cutoff approach for the YMIDD and UBIDD. The proposed approach does not require flow rate measurements, but instead uses a real-time measurement of t_{50}, the advance time to mid-field, as a surrogate for the unknown inflow. The t_{50} is then used to estimate a basin inflow cutoff time, t_{coReq}, that leads to a post-irrigation subsurface distribution with a minimum applied depth equal to the requirement, $Z_{min} = Z_{Req}$.

Irrigation practices in the YMIDD and UBIDD are relatively uniform, in terms of the crops irrigated (alfalfa and citrus), field lengths (between 183 and 215 m), field slopes (either 0.001 or 0.0003), available inflow rates (between 7 and 12 L/s/m), and soil textures (the area is dominated by soils described as Superstition-Rosita's association [Hendricks, 1985]). Hence there is a reasonable expectation that most or all of the basins in these districts could be managed using one or two slide-rule options. Niblack envisioned few charts or slide-rules for basins in the Yuma area such that, given measured t_{50}, they would provide the required inflow cutoff time, t_{coReq}.

This report describes the theoretical and initial field studies conducted to develop and field test the t_{50} –t_{coReq} cutoff criterion. The proposed methodology relies on a number of assumptions which are outlined in Chapter 2. Chapter 3 analyzes the theoretical relationship between t_{50} and t_{coReq} and discusses the potential limitations that this relationship presents as related to the goal of developing a practical management tool.

Chapter 4 discusses the field studies component, including field procedures and results. Chapter 5 summarizes the results obtained and our strategy for future work.

2. Assumptions

Development of the t_{50} –t_{coReq} cutoff criterion for the Yuma-Mesa is predicated on a number of assumptions: (1) given a field condition defined in terms of soil and crop hydraulic parameters, irrigation requirement, and basin length, there is a unique relationship between t_{50} and t_{coReq} over the range of discharges that are typically used for large basin in the Yuma-Mesa; (2) we can discretize the field conditions (combinations of infiltration characteristics, surface roughness, slope, basin length, and irrigation requirement) in the Yuma-Mesa into a few well-defined categories; (3) the infiltration characteristics of a given test farm can be defined with reasonable accuracy based on soil map information using the USDA-NRCS intake families; surface roughness can be defined based exclusively on crop; and slope can be defined based on the design value used during the most recent land-grading operation; and (4) for a particular category of field condition, the corresponding t_{50} –t_{coReq} relationship can be used to determine the cutoff recommendation that will result in reasonable performance.

3. Theoretical basis, performance potential, ranges of applicability, and limitations of the t_{50}-t_{coReq} criterion

This section discusses the theoretical basis of the t_{50}–t_{coReq} inflow cutoff criterion, performance potential of basins operated with the t_{50}–t_{coReq} cutoff criterion, the ranges of applicability of the cutoff criterion, and its limitations in terms of sensitivity to uncertainties in system parameter estimates and measurement errors in t_{50}. The data sets used in these analyses are site and event specific, hence complete validity of the results, and inferences arising thereof, cannot be guaranteed under a different set of condition. However, since general trends in the relationships between dependent and independent irrigation variables can be discerned from particular examples; the use, in subsequent analysis, of limited sets of system variable and parameter combinations, typical of basin irrigation conditions in the YMIDD/UBIDD, is justified.

Because basin unit inflow rate is the basic system variable in surface irrigation hydraulics, the interrelationship between irrigation performance and the underlying hydraulics is better defined when dependent variables are expressed as a function of q_o. Hence some of the discussion presented subsequently (e.g., Figures 1a and 1b) uses q_o, instead of t_{50}, as the independent variable. The results summarized in Figures 1-9 were all obtained with a custom-made software CUSTOM/YUMABSNS specifically developed for this study (Strelkoff, 2005), based on USDA-ARS' surface irrigation simulation engine, SRFR (Strelkoff et al., 1998) or through simulations with WinSRFR (USDA-ARS-ALARC, 2007). Note that only irrigation scenarios that meet the requirement $Z_{min} = Z_{Req}$ are considered here. Pertinent input data (typical of YMIDD/UBIDD conditions) are given in the captions of each figure.

Theoretical basis of the t_{50}-t_{coReq} cutoff criterion

Given a basin (defined in terms of length, L, bottom slope, S_o , the Manning n, and infiltration, represented by the NRCS infiltration families, I_f), different unit inflow rates, q_o, will produce unique advance trajectories. Also for a given basin and a unit inflow rate, there is a unique value of cutoff time that will match the minimum infiltration depth to the irrigation requirement, t_{coReq}. Based on this observation it can be inferred that advance to any given point along a basin, $t_x(q_o)$, can be related to $t_{coReq}(q_o)$ as q_o is varied within a feasible range. Using the range of field conditions typical of the Yuma-Mesa area, a systematic analysis was conducted to establish a relationship between advance to half the basin length, which is a particular case of $t_x(q_o)$, and t_{coReq} as q_o is varied within a feasible range. This analysis was conducted with custom-made software tools, CUSTOM and YUMABSNS, developed by Dr. T. S. Strelkoff at USDA-ARS-ALARC. CUSTOM is a driver program that performs multiple runs of the SRFR simulation engine as a function of a set of field conditions (Table 1) and saves the output in a database. A companion program YUMABSNS reads the output database and displays them graphically. These programs are available upon request from Dr. T. S. Strelkoff.

An example of a typical set of results generated by CUSTOM and YUMABSNS is shown in Figures 1a and 1b. In addition to outputs summarized in Figures 1a and 1b, which consists of $t_{coReq}(t_{50})$, $E_a(t_{50})$, and $q_o(t_{50})$ functions, the CUSTOM/YUMABSNS software displays a plot of the final infiltrated profiles as a function of q_o. Results of the simulation studies, with CUSTOM/YUMABSNS, conducted by Strelkoff (2005) have empirically established that given a field condition the cutoff time needed to match the minimum infiltrated depth, Z_{min}, to Z_{Req} is uniquely related to the advance time to mid-field, as basin inflow rate is varied within a feasible range. Figures 1c and 1d, respectively, show typical $t_{coReq}(q_o)$, $E_a(q_o)$ and $t_{50}(q_o)$ curves for level (0.03%) and graded (0.1%) basins in the YMIDD/UBIDD. Note that in the study area a basin with 0.03% slope is considered as a level basin. For a typical basin in the YMIDD/UBIDD, the hydraulics of a basin with 0.03% slope closely approximates one with a 0.0% slope, provided the Manning roughness and soil intake are sufficiently high.

Figures 1c and 1d show that the upper limits of the $t_{50}(q_o)$ and $t_{coReq}(q_o)$ functions correspond to the lower limit of the feasible range of flow rate and conversely the upper limit of q_o corresponds to the lower limit of t_{50} and t_{coReq}. It follows that both t_{50} and t_{coReq} are monotonic decreasing functions of q_o. For both the level and the graded basins, the $t_{50}(q_o)$ and $t_{coReq}(q_o)$ functions exhibit very high sensitivity close to the lower limit of the flow rate range (e.g., q_o < 4.5L/s/m, Figures 1c and 1d). Their sensitivity, however, decreases fast with increasing flow rate (Figures 1c and 1d). The $t_{coReq}(q_o)$ function for the level basin continue to show a relatively higher degree of sensitivity to q_o over a much wider range (q_o <10.0L/s/m, Figure 1c) than is the case with the graded basin. Figure 1c also shows that for sufficiently large flow rates, the $t_{50}(q_o)$ and $t_{coReq}(q_o)$ functions of level basins can intersect. This suggests that the $t_{coReq}(q_o)$ function generally shows relatively higher sensitivity than the corresponding $t_{50}(q_o)$ function and most importantly establishes the theoretical lower bound for the t_{50}-t_{coReq} cutoff criterion.

For the graded basin, the $t_{coReq}(q_o)$ function shows very little sensitivity in the range 5L/s/m < q_o (Figure 1d); however, the $t_{50}(q_o)$ function continue to show relatively higher sensitivity in the same flow rate range. Consequently, the two curves slowly diverge

(Figure 1d). Although this result suggests that, for graded basins, it might not always be possible to establish an upper limit of flow rate (and conversely a theoretical lower bound for t_{coReq}) based on the intersection points of t_{50} and t_{coReq}; the two functions can, however, intersect with a different soil and crop hydraulic parameter combination (see discussion on sensitivity of $t_{50}(q_o)$, $t_{coReq}(q_o)$, and $E_a(q_o)$ to variations in soil intake characteristics).

Figures 1a and 1b depict the $t_{coReq}(t_{50})$, $E_a(t_{50})$, and $q_o(t_{50})$ functions for level and graded basins, respectively. As can be seen from Figure 1a, for the level basin case, t_{coReq} shows high sensitivity to t_{50} throughout the range of variation of t_{50}. Although the $t_{coReq}(t_{50})$ function, for the graded basin, is highly sensitive over a relatively wide range of t_{50}, it shows little sensitivity in the range (of t_{50} or q_o) where Z_{min} occurs at the basin inlet.

The very low sensitivity of the $t_{coReq}(q_o)$ function for the graded basin over a relatively wide range of flow rate (Figure 1d) is related to the shift in the location of the minimum applied depth from the downstream end to the inlet end of the basin as flow rate is increased. For graded basins, irrigated with very small flow rates, the minimum applied depth occurs at the downstream end. However, as flow rate increases, the location of Z_{min} shifts upstream toward the inlet end of the basin and for flow rate exceeding a certain threshold (in this particular example for $q_o \approx 5.0$L/s/m, Figure 1d), the location of the minimum depth is the inlet end. For the case in which the minimum depth is at the inlet end, t_{coReq} can be given as:

$$t_{co\mathrm{Re}q} = \tau_{\mathrm{Re}q} - t_{dep} \tag{1}$$

where τ_{Req} = required intake opportunity time (min), and t_{dep} = duration of depletion phase (min). Nothing that τ_{Req} is constant (given a soil type and Z_{Req}), Eq. 1 shows that the sensitivity of t_{coReq} to q_o is only dependent on the sensitivity of $t_{dep}(q_o)$. As can be seen from Figure 1d, t_{dep} shows little sensitivity to flow rate in the range 5L/s/m < q_o. In this flow rate range, a 100% increase in q_o (that is doubling of q_o) results only in a 16% increase in t_{dep} (Figure 1d). Note that, in this same range, t_{coReq} shows exactly the same level of sensitivity to q_o (Figure 1d, see also Eq. 1); which explains the very low sensitivity of the $t_{coReq}(q_o)$ function for flow rates close to the upper limit of the range (Figure 1d).

The preceding discussion on the behavior of the $t_{coReq}(t_{50})$, $t_{50}(q_o)$, and $t_{coReq}(q_o)$ functions is based on a specific data set (that can be characterized as site and event specific), hence it is general validity cannot be guaranteed. However, experience with simulated results and intuitive reasoning suggest that while variations in soil and crop hydraulic properties can result in functions with slightly different slope and curvature and that some combinations of system parameters and variables may limit the range of variation of q_o and hence $t_{coReq}(t_{50})$, $t_{50}(q_o)$, and $t_{coReq}(q_o)$ functions, the general behavior of these functions remain essentially the same. Hence both t_{coReq} and t_{50} can be described as monotonic decreasing functions of q_o (Figures 1c and 1d) and each can be expressed as a three parameter power function. In addition, Figures 1a and 1b show that t_{coReq} is a monotonic increasing function of t_{50}. Hence either the $t_{coReq}(q_o)$ and $t_{50}(q_o)$ functions can be combined to derive an expression for $t_{coReq}(t_{50})$ or t_{coReq} can be directly related to t_{50}, resulting in a cutoff criterion without explicit dependence on q_o.

$$t_{co\mathrm{Re}q} = \sigma_1 t_{50}^{\sigma_2} + \sigma_3 \tag{2}$$

where σ_1 ($\mathrm{min}^{1-\sigma 2}$), σ_2 (-), and σ_3 (min) = empirical constants to be determined through curve fitting. Eq. 2 is a simple, yet general function that is amenable to compact presentation with potentially useful practical irrigation management applications. Considering the primary irrigation management constraint in the YMIDD and UBIDD (flow rates to individual basins are uncertain); the fact that in Eq. 2, t_{coReq} is not explicitly dependent on q_o is an advantage. With Eq. 2 in place, given a well-defined field condition (estimates of soil and crop hydraulic parameters are accurate), the irrigator can measure t_{50} instead of q_o and determine the t_{coReq} as a function of t_{50}. A corollary to this is that if the assumed field condition closely matches the actual field condition, the actual flow rate can also be derived from the chart as a function of measured t_{50} (chart-derived flow rate closely approximates actual flow rate at the time of irrigation), Figures 1a and

1b. Hence, the validity of the cutoff criteria when applied to field conditions can be evaluated by comparing chart-derived and measured q_o.

A detailed discussion on the performance potential of typical basin irrigation systems in the YMIDD/UBIDD is presented subsequently.

The application efficiency function of basin irrigation

Level basins: Given a soil and crop hydraulic parameter set, basin length, and the requirement $Z_{min} = Z_{Req}$; application efficiency, E_a, is a monotonic increasing concave function of q_o (Figure 1c). Basin irrigation water loss occurs only in the form of deep percolation, which is the result of irrigation nonuniformity (Figure 2). Since recession occurs at the same time over the length of a level basin, irrigation nonuniformity in level basins is due entirely to nonuniform advance. Hence, increasing q_o results in increased advance rate, which in turn results in increased distribution uniformity; and a reduction in deep percolation losses follows, if inflow cutoff is timed appropriately. However, the effect of flow rate on advance rate and hence uniformity decreases progressively with increases in flow rate (Figures 1c and 2). This effect of flow rate on advance rate and irrigation uniformity is reflected on E_a as follows: (1) for very small flow rates, E_a is very low and is highly sensitive to changes in q_o (Figures 1c and 2), (2) as flow rate increases, E_a increases at decreasing rate and approaches a maximum value (dependent on soil and crop hydraulic parameters, irrigation requirement, and basin length) asymptotically (Figures 1c and 2), and (3) increasing flow rate beyond a certain threshold (about 9L/s/m in Figure 1c) or decreasing t_{50} below a certain value will result only in a negligibly small improvement in E_a. The practical implications of these observations in terms bounding the ranges of available management options are discussed subsequently in the section: ranges of applicability of the t_{50}-t_{coReq} cutoff criterion.

Graded basins: In contrast to level basis, the $E_a(q_o)$ function of graded basins attains a clearly defined maximum well within the range of variation of q_o (e.g., Figures 1d and 3a). The $E_a(q_o)$ function increases at a decreasing rate with increasing flow rate, attains a maximum value and then decreases (Figures 1c and 3a). This behavior of the $E_a(q_o)$ function for graded basins is related to the shape of the post-irrigation subsurface profile and the location of Z_{min} along the length of the basin. Schematics of typical post-irrigation subsurface profiles for a graded basin corresponding to different inflow rates are depicted in Figure 3b. For very small flow rates, Z_{min} occurs at the downstream end of the basin (Figure 3b). However, as q_o is increased beyond a certain minimum threshold dependent on soil and crop hydraulic properties and basin dimension, the location of Z_{min} begins to move upstream toward the inlet end of the basin and with further increases in q_o an upper threshold would be reached beyond which the location of Z_{min} is at the basin inlet (Figure 3b).

As can be seen from Figure 3b, the deep percolation fraction, D_f, of the post-irrigation subsurface profile is composed of two sections, a fraction between the inlet end and the location of Z_{min} along the basin, D_{f1}, and a second fraction between the location of Z_{min} and the downstream end of the basin, denoted as D_{f2} (Figure 3b). For small flow rates (range of q_o within which Z_{min} occurs at the downstream end) $D_{f2} = 0$ and $D_f = D_{f1}$ (Figures 3a and 3b). On the other hand, for relatively large flow rates, $D_{f1} = 0$, and hence $D_f = D_{f2}$ (Figures 3a and 3b). As flow rate is increased from a very small value (in the range within which $Z_{min} = Z_{Req}$ is located at the downstream end), the post-irrigation subsurface profile eventually transitions from a scenario in which $D_{f2} = 0$ and $D_f = D_{f1}$ to one in which $D_{f1} = 0$ and $D_f = D_{f2}$. Initial increases in flow rate leads to a decrease in D_{f1} and a gradual increase in D_{f2} (once a minimum threshold flow rate is exceeded). For small flow rates (e.g., $q_o < 4.5$L/s/m, Figure 3a) D_{f1} decreases at a faster rate than the rate at which D_{f2} increases, the combined effect being a decrease in the overall deep percolation fraction, D_f, leading to an increase in E_a. However, with further increases in q_o, the rate of increase of D_{f2} exceeds the rate of decrease in D_{f1}, leading initially to a decrease in the rate with which D_f decreases. Eventually, the D_{f1} and D_{f2} curves intersect and very close to this intersection point D_f attains it is minimum and $E_a(q_o)$ takes its maximum value (e.g., 88%, Figure 3a); this corresponds to the optimum flow rate, q_{oopt} (e.g., 4.5L/s/m in Figure 3a). Further increase in q_o beyond q_{oopt} results in a steady decrease in D_{f1} to zero – a point that marks the completion of the migration of Z_{min} from the downstream end of basin to the inlet end. D_{f2}, on the other hand, continue to increase at a decreasing rate with further increases in q_o; D_f, which is equal to D_{f2} in this range of q_o, increases with increasing q_o; hence E_a decreases with increasing q_o.

Simulated post-irrigation subsurface profiles for a basin with 0.1% slope, shown in Figure 4a, exemplify the movement of the location of Z_{min} from the downstream end to the upstream end as flow rate is increased from 2L/s/m to 12L/s/m. Note that this is not limited to relatively steep slopes. However, keeping all other parameters constant the threshold unit inflow rate at which the movement of Z_{min} from the downstream end toward the inlet end begins is smaller for steeper slopes. For instance, Figures 4b and 4c show that a basin with very small bed slope (e.g., 0.03%) that behaves in a manner analogous to a level basin when Manning *n* is 0.1 (Figures 1a and 2) will have post-irrigation subsurface profiles and an application efficiency function of a graded basin only if Manning *n* is reduced to 0.06. In general, given the length of a basin and irrigation requirement, the minimum flow rate at which Z_{min} starts to move upstream (from the downstream end) is a function of slope, Manning roughness, and soil intake characteristics. Comparison of Figures 1a and 4c show that performance characteristics of basins as a function of flow rate vary significantly with reasonable changes in soil and crop hydraulic properties.

In general, E_a for sloping basins show a higher degree of sensitivity to flow rate over medium to lower ranges (for instance in Figure 3a this range corresponds to $q_o \leq$ 7.0L/s/m, which is in close vicinity of q_{oopt}) and it is sensitivity decreases in the higher ranges of flow rate. Hence, errors in flow rate measurements (if flow rate based cutoff criterion is used) or in t_{50} measurements and/or uncertainties in parameter estimates can have a significant adverse effect on attainable efficiencies if graded basins are operated with flow rate close to q_{oopt}. This underlines the fact that accurate estimates of system parameters are critical for the optimal management of graded basins. Typically, graded basins in the Yuma-Mesa are operated with large flow rates – generally well above the optimal flow rate range, hence application efficiencies are relatively low (Sanchez and Zerihun, 2000a,b).

The preceding characterization of the behavior of the $E_a(q_o)$ function for level and graded basins are for a specific field condition and basin length combinations. Although variations in field conditions can result in differences in slope, curvature, and feasible range of the $E_a(q_o)$ function, the overall behavior of the function for both level and graded basins follow essentially the same pattern described above. In addition, it should be noted that the $E_a(q_o)$ function for both level and graded basins (e.g., Figures 1a-1d) show that, in a zero-deficit irrigation ($Z_{min} \leq Z_{Req}$) scenario, setting $Z_{min} = Z_{Req}$ is only a necessary, and not a sufficient, condition for optimum application efficiency.

In general, *a priori* estimates of soil and crop hydraulic parameters are imprecise and if estimates (assumptions) are significantly different from actual conditions at the time of irrigation, a valid use of the t_{50}-t_{coReq} cutoff criterion cannot be guaranteed. Hence subsequent analysis examines the ranges of applicability of the t_{50}-t_{coReq} cutoff criterion given a well-defined system and its limitations in terms of sensitivity to uncertainties in soil and crop hydraulic parameter estimates and t_{50} measurement errors. The objective is to establish the advantages and limitations of the t_{50}-t_{coReq} cutoff criterion.

The range of applicability of the t_{50}-t_{coReq} cutoff criterion

General discussion on ranges of $t_{50}(q_o)$ and $t_{coReq}(q_o)$: Given a basin (defined in terms of length, irrigation requirement, and soil and crop hydraulic parameters set), the range of its t_{50}-based t_{coReq} varies from a theoretical lower limit of t_{50} to an upper limit that extends to the post-advance phase. The lower limit of t_{coReq} and associated t_{50} is directly related to the upper bound of the feasible flow rate range. Noting that t_{coReq} cannot be lower than the associated t_{50} (see discussion above and Figures 1a and 1b); the flow rate associated with a $t_{coReq} \approx t_{50}$ represents the maximum flow rate that can in theory be used with a t_{50}-t_{coReq} cutoff criterion. Hence the corresponding t_{50} represents the theoretical lower bound for t_{coReq}.

Given a basin with a well defined soil and crop hydraulic parameter set and an irrigation requirement, Z_{Req}; the upper limits of t_{coReq} and the corresponding t_{50} depends on the lower limit of the flow rate range, q_{min}, and Z_{Req}. The lower limit of the flow rate range, q_{min}, can be taken as the minimum flow rate that can advance to the downstream end of the basin considering a soil of finite basic intake rate. Thus, given q_{min} and Z_{Req} and the requirement $Z_{min} = Z_{Req}$, the maximum t_{50} and t_{coReq} automatically follows. Note that the theoretically feasible flow rate range is a function of the soil and crop hydraulic parameters of the basin, Z_{Req}, and basin length; hence its variable as a function of the field condition and needs to be defined for each particular case. Figure 5 exemplify the variation in the ranges of t_{50}-t_{coReq} and associated q_o as a function of soil intake characteristics.

The preceding discussion establishes the theoretical limits of the range of management options covered by the t_{50}-t_{coReq} cutoff criterion. Further bounding of the ranges of applicability of the t_{50}-t_{coReq} criterion is needed based on the sensitivity of basin irrigation hydraulics to very small and large flow rates. Such a discussion is provided subsequently.

Level basins: Figures 6a-6d exemplify the sensitivity of level basin irrigation hydraulics and corresponding post-irrigation subsurface profile to variations in q_o close to the lower and upper limits of the feasible range of q_o – obtained through simulations with WinSRFR 2.04 (USDA-ARS-ALARC, 2007). The soil and crop hydraulic parameter set, the net irrigation requirement, and basin length used in these simulations are given in the captions of Figure 6. Figure 6a shows changes in flow depth hydrographs at five computational nodes along a level basin (inlet end, 46m, 92m, 137m, and 183m from the inlet end) as q_o is increased from a minimum values of 1.25L/s/m to 1.75L/s/m and then to 2.25L/s/m. The post-irrigation infiltration profiles corresponding to the three flow rates are depicted in Figure 6b. As can be seen from Figures 6a and 6b, for very small q_o (alternatively for very large t_{50} and t_{coReq}); basin irrigation hydraulics (expressed here in terms of the amplitude and variance of the flow depth hydrographs, associated advance, recession, and intake opportunity time trajectories) and the corresponding post-irrigation subsurface profiles are very sensitive to variations in flow rate. This has two important

implications: (1) at the practical level, it shows that if a level basin is irrigated with very small flow rates (very large t_{50}) small errors in the characterization of field conditions can have a significant adverse effect on the outcome of an irrigation event, leading to a range of possibilities, including - incomplete advance, or severe under-irrigation, or adequate but inefficient irrigation, and (2) in the very low ranges of flow rate (large t_{50}) solutions of the basin hydraulic problem are very sensitive to numerical errors, hence simulated results and management tools based on them can be less reliable.
Figures 6c and 6d show sensitivity of level basin hydraulics and post-irrigation subsurface profile to q_o, when a basin is operated close to the upper limit of the feasible range of q_o. Figure 6c shows changes in flow depth hydrographs at five computational nodes along the basin (inlet end, 46m, 92m, 137m, and 183m) as q_o is increased from 15L/s/m to 18L/s/m and then to 20L/s/m. As q_o is increased from 15L/s/m to 20L/s/m, a 33% increase, the corresponding depth hydrographs (hence advance, recession, and intake opportunity time trajectories) and the post-irrigation subsurface profile remain essentially unchanged (Figures 6c and 6d). The results summarized in Figures 6c and 6d exemplify that for very large q_o, level basin irrigation hydraulics become virtually insensitive to q_o (Figure 6c); hence significantly different flow rates can produce essentially the same irrigation scenarios (Figure 1c), provided appropriate cutoff times are used to match Z_{min} to Z_{Req}.

In general, for very large flow rates the solution of the basin irrigation hydraulic problem tends to be nonunique, hence any difference in surface hydraulics (and in irrigation performance) could be well within the margin of numerical errors. This suggests that, although level basins require the use of large q_o to attain the potential maximum E_a, (Figure 1c), there is no valid reason to operate level basins at flow rates exceeding a certain threshold beyond which $E_a(q_o)$ can be considered insensitive (e.g., about 10L/s/m for Figure 1c). In fact, increasing q_o beyond the sensitivity threshold might only result in adverse consequences, such as scouring at basin inlet, without any concomitant improvement in efficiency and needs to be avoided. In addition, in the very large flow rate ranges cutoff need to occur much early in the advance phase, this makes the surface hydraulics much more sensitive to inaccurate characterization of field conditions, inaccuracies in recommended t_{coReq}, and inflow measurements (if cutoff criterion that requires inflow rate measurements are used).

Graded basins: For very small flow rates, E_a is very low (Figure 1d). E_a, however, increases at a faster rate with q_o and attains a maximum value, it then decreases with further increases in q_o (Figures 1d). As described earlier, unlike level basins, the $E_a(q_o)$ function for graded basins is unimodal (Figure 1d). Graded basins attain high efficiencies when they are irrigated with medium to relatively small flow rates (Figure 1d) – that is well within the feasible range of flow rate. Hence a sound irrigation management requires that graded basins should not be operated close to the lower or upper limits of the flow rate range.

In summary, the preceding discussion shows that: (1) given a basin with a well-defined soil and crop hydraulic parameter set, the t_{50}-t_{coReq} cutoff criterion covers the entire range of management options. The corresponding t_{coReq} ranges from a lower bound limited by its t_{50} to a maximum value determined by the minimum q_o that can advance to the downstream end (considering a soil with a finite steady state intake rate) and the net irrigation requirement. However, practical considerations may require setting t_{coReq} at a higher level than the theoretical lower bound. Uncertainties in field conditions coupled with the relative sensitivity of the surface hydraulic problem to these uncertainties, when flow is cut during the advance phase, means that even with very large flow rates cutoff occurs well after water advanced beyond midfield. Hence the lower limit of t_{coReq} could be well above the absolute minimum (the t_{coReq} approximately equal to its corresponding t_{50}). Clemmens and Dedrick (1982) for example recommended a minimum cutoff ratio (ratio of cutoff distance to basin length) of 0.85 for level basins. In addition, such practical considerations as scouring at the inlet end of the basin and the maximum available flow rate in the field supply channel need to be taken into account when selecting the upper limit of the flow rate range, based on which a lower limit for t_{coReq} and t_{50} can be computed. (2) Given a field condition (which is known only in some approximate sense), a sound irrigation management practice needs to avoid operating close to the limits of the theoretically feasible flow rate ranges (see discussion above).

These considerations need to be taken into account when establishing the ranges of t_{50}-t_{coReq} variation for any given field condition. In any one condition, the most limiting of these values need to be used as the lower bounds for t_{coReq} and t_{50}.

Sensitivity of basin irrigation performance to field conditions when basins are operated under t_{50}-t_{coReq} cutoff criterion

The application of any basin inflow cutoff criterion developed through simulations, including those of t_{50}- t_{coReq}, to real-life irrigation management is predicated on the assumption that the average basin-wide soil and crop hydraulic parameter set at the time of the irrigation event closely matches the conditions assumed in the formulation of the management charts. Field conditions are always imprecisely defined. The main sources of uncertainty in the characterization of soil and crop hydraulic properties are: (1) estimates (or assumptions) of basin-wide average soil and crop hydraulic properties can contain significant error and (2) within a basin there may exist significant localized deviations from the mean that dominates the surface hydraulics and infiltration. Other factors that contribute to uncertainties and limit the usefulness of management recommendations developed based on simulations are: (1) physical configuration of the basin (e.g., furrows running along the border of a basin and consequent flow pattern – interacting channelized and overland flow) is too complex to be represented accurately within the framework of existing surface irrigation modeling capabilities, (2) when flow is introduced at a single point and transverse variations in soil and crop hydraulic parameters are significant, the advancing front for much of the advance phase continue to be irregular and there may be a significant depth gradient in the transverse direction (two-dimensional flow), a condition that may not be accurately simulated with existing surface irrigation hydraulic models, and (3) closely related to the preceding two points above is that measurement of advance trajectory (hence t_{50}) could be inaccurate, hence inflow cutoff decisions made on the basis of inaccurate measurement of advance trajectories can have adverse effects on irrigation performance and over all validity of the management chart.

In subsequent sections, the limitations of the t_{50}-t_{coReq} cutoff criterion is evaluated by examining the sensitivity of E_a, Z_{min}, and the feasible range of variations of t_{50} to uncertainties in field conditions (specifically soil intake characteristics and Manning *n*) and t_{50} measurement errors, for both level and graded basins.

A formal sensitivity analysis of the t_{50}-t_{coReq} cutoff criterion to soil and crop hydraulic parameter sets asks what will be the shift in the t_{50}-t_{coReq} chart if the soil and crop hydraulic parameters (say Manning *n* or soil intake family or both) change by a certain amount in a certain direction relative to an assumed value. Such an analysis can be useful in establishing the feasible ranges of the t_{50}-t_{coReq} function and maximum attainable levels of performance under different field conditions (e.g. Figure 5). However, it cannot be used to answer such questions as what will be the effect, in quantitative terms, on E_a and Z_{min} if a chart prepared for a certain set of field conditions is used in a basin with a different soil and crop hydraulic parameter set? Will the resulting irrigations be feasible? Answers to such questions will establish the limitations of the cutoff criterion when used under imprecisely defined field conditions. However, such an analysis also requires a different approach than the procedure commonly used with a formal sensitive analysis. The following is a description of the procedure used here to simulate the effect - on E_a, Z_{min} and range of t_{50} - of using a t_{50}-t_{coReq} chart in a basin with a soil and crop hydraulic properties that are different from the assumed condition. This procedure will also be used to evaluate the effects of t_{50} measurement errors:

(1) Generate a t_{50}-t_{coReq} chart for the assumed field condition. A Z_{min} curve, which is essentially Z_{Req}, is also included in the t_{50}-t_{coReq} chart to allow for evaluation of the effect of changes in field conditions or errors in t_{50} measurement on the resulting Z_{min} relative to the requirement. Note that this chart represents the assumed field condition and a case in which there is no error in t_{50} measurement.

(2) Generate a t_{50}-t_{coReq} chart for the actual field condition. Note that the t_{50} from this chart corresponds to the measured t_{50} during an irrigation event. If the purpose is to examine the effect of error in t_{50} measurement only, the measured t_{50} is generated simply by adding or subtracting the expected error from the t_{50} obtained in step 1 above.

(3) Use the t_{50} values from step 2 and t_{50}-t_{coReq} chart from step 1 to estimate t_{coReq}. This step represents the process of selecting a t_{coReq}, from a t_{50}-t_{coReq} chart prepared for an assumed field condition, based on a measured t_{50} which is a function of the actual field condition and/or measurement error.

(4) Use the t_{coReq} from step 3 and the parameter set for the actual field condition to estimate consequent E_a and Z_{min}, any effect on the range of t_{50} , hence t_{coReq}, will follow automatically.

Figures 7a and 7b (level basin, 0.03% slope) and Figures 7d and 7e (graded basin, 0.1% slope) exemplify the effect on E_a and Z_{min} as well as on the feasible range of variation of t_{50} (alternatively q_o), if only the Manning n or the soil intake characteristics, at the time of irrigation, is different from what has been assumed in the formulation of the t_{50}-t_{coReq} chart. Figures 7c and 7f show the effect of realistic levels of t_{50} measurement errors (±1min) on consequent E_a and Z_{min} and ranges of t_{50} (or q_o). In Figures 7a-7f, the solid lines represent assumed conditions (with no t_{50} measurement error), dotted and dashed lines represent actual conditions at the time of irrigation, including errors in t_{50} measurement.

__Level basin (0.03% slope)__: Figure 7a depicts the effect, on E_a, Z_{min}, and range of t_{50}, of using a t_{50}-t_{coReq} chart prepared for a basin with Manning $n = 0.1$ in a basin where $n = 0.125$ (a 25% increase). In general, a condition in which the actual Manning n exceeds the assumed n results in larger t_{50} and hence larger t_{coReq} relative to the assumed condition. However, a larger t_{coReq} (obtained from the chart) may not necessarily mean that at the time inflow is cut there will be sufficient volume of water under surface storage to match Z_{min} to Z_{Req} under the actual condition. If cutoff is to occur during the advance phase, which is generally the case with basins in the YMIDD and UBIDD, the interactive effects of volume accumulated on the surface at cutoff and increased Manning n (and other system parameters) in the dry segment of the basin determines whether: (1) the resulting irrigation event is feasible (a feasible irrigation scenario is defined here as one in which water reaches the downstream end of the basin and a finite minimum depth is applied) and (2) if feasible, will it lead to a significant under- or over-irrigation. In the rare scenario that flow rate is too small and hence inflow must be cut in the post-advance phase, the resulting irrigation would automatically be feasible.

In the particular example considered here (Figure 7a), a 25% increase in n ($n = 0.125$) results in feasible irrigations with the following attributes over much of the range of variation of t_{50}: (1) the E_a curve for $n = 0.125$ is below the E_a curve for $n = 0.1$, the average decrease in E_a is 10.8%; (2) the Z_{min} curve for the actual condition is on average 25.0mm above Z_{Req}; and (3) the upper limit of the t_{50} range for the actual condition (n = 0.125) is smaller than the upper limit of the t_{50} range for the assumed field condition. The narrowing of the range of t_{50} under actual field conditions is related to the higher than assumed n value that slowed the rate of advance and hence led to a larger t_{50}. Consequently when $n = 0.125$, the t_{50} for q_o = 2L/s/m (the lower limit of the q_o range), which is 71.9min, fell outside the t_{50} range of the t_{50}-t_{coReq} chart prepared for the assumed condition (Figure 7a). This result suggests that the t_{50}-t_{coReq} chart prepared for the assumed condition cannot be used under the actual field condition, if the measured t_{50} is close to the upper limit of the t_{50} range (Figure 7a).

For the same basin another set of simulations were conducted to evaluate the effect, on E_a, Z_{min}, and range of t_{50}, of applying a t_{50}-t_{coReq} chart in a field where the Manning n is 25% less than the assumed, $n = 0.0725$ (Figure 7a). Keeping all other factors unchanged, a smaller Manning n (0.075) compared to the assumed n (0.1) means a faster advance prior to cutoff and a smaller t_{50} than would have been the case with $n = 0.1$. Hence, the volume of water under surface storage at cutoff would be smaller relative to the volume that would have been under surface storage if $n = 0.1$. As discussed above for $n = 0.125$, here also if inflow cutoff is to occur during the advance phase, the interaction of the relatively smaller surface storage and the reduced flow resistance (along with the other system parameters) over the dry section of the basin determines the resulting irrigation scenario. Simulations conducted with WinSRFR showed that the resulting irrigations over the entire range of variation of t_{50} are infeasible; hence, they are not shown in Figure 7a. The simulations show that there was not sufficient volume of water under surface storage at the time of inflow cutoff for the flow to complete advance in all the irrigation scenarios considered. This result suggests that a physically realistic change in Manning n (-25% change from an assumed value) can render a t_{50}-t_{coReq} chart completely unusable, which is a significant level of sensitivity.

Figure 7b depicts the effect, on E_a, Z_{min}, and range of t_{50}, of using a t_{50}-t_{coReq} chart in a basin with slightly different intake characteristics than the one assumed in formulating the chart. $I_f = 1.0$ corresponds to the assumed field condition (Figure 7b), actual soil intake characteristics considered here are $I_f = 0.8$ and 1.5. Considering the case in which $I_f = 0.8$, the low infiltration rate relative to the assumed ($I_f = 1.0$) condition means faster advance at least prior to inflow cutoff, if cutoff is to occur during the advance phase; which also means a smaller t_{50} and t_{coReq}. While the total volume applied is smaller compared to the assumed condition, a relatively larger fraction of the applied volume will be under surface storage at any given time, t, for $t < t_{coReq}$, However, assuming a cutoff that occurs during the advance phase, whether the resulting irrigation scenario is: (1) feasible or infeasible and (2) if feasible will it meet the requirement over the entire length of the basin or will there be significant under-irrigation over a section of the basin depends on the interactive effects of surface storage volume at t_{coReq} and the reduced intake as well as roughness and bed slope.

In this particular case (Figure 7b) the net interactive effect of the system variables and parameters is such that surface storage volume at the time of cutoff was sufficient for irrigation to reach the downstream end and replenish the root zone in full ($Z_{Req} < Z_{min}$ over the entire range of variation of t_{50}). The following is a summary of the results for $I_f = 0.8$: (1) The upper limit of t_{50} for the condition $I_f = 0.8$ is slightly smaller than the upper limit of t_{50} for the assumed condition - the range of t_{50} narrows slightly, (2) Resulting E_a curve for $I_f = 0.8$ is slightly above the same curve for the assumed condition, the average increase in E_a is 2.7%, and (3) Z_{min} values for $I_f = 0.8$ exceeds Z_{Req} over the entire range of variation of the corresponding t_{50} by an average value of 15.7mm. Note that with different set of field conditions a different irrigation scenario may emerge – with the possibility of infeasible irrigations or severely under irrigated conditions, hence this observation is cannot be generalized to other cases. Note that for $I_f = 0.8$ the increase in E_a is the result of increased uniformity - for the purpose of comparison DU_{min} is included in Figure 7b.

Simulations for $I_f = 1.5$ show that the resulting irrigations over the entire range of variation of t_{50} (or q_o) are infeasible, thus not shown in Figure 7b. When $I_f = 1.5$, the error in t_{coReq} estimates, obtained from the chart prepared for $I_f = 1.0$, results in significant underestimation of the actual t_{coReq} over the entire range of variation of t_{50}. Hence the volume of water that is under surface storage at cutoff is insufficient to reach the downstream end. This results show that a change in soil intake characteristics from an intake family of 1.0 to 1.5 will render a t_{50}-t_{coReq} chart prepared for an $I_f = 1.0$ useless. This may represent a significant change in soil intake characteristics; nonetheless, it is not an entirely impossible scenario, considering seasonal changes in field conditions.

A third scenario examined here assumes a field in which the actual soil and crop hydraulic properties at the time of irrigation are close to the assumed, but the t_{50} measurements are inaccurate by ±1min, a realistic level of measurement error. For a given q_o, increasing t_{50} leads to a higher t_{co} than t_{coReq}, hence a lower E_a and a $Z_{min} > Z_{Req}$ than would be the case if there was no error in t_{50} measurement. Consistent to this general observation, results summarized in Figure 7c show that increasing the t_{50} by 1min leads to: (1) a reduction in the range of t_{50} relative to the assumed condition - close to the upper limit of t_{50} measured t_{50} falls outside the range of the chart, making the chart unusable in that section of the t_{50} range; (2) E_a under actual conditions are lower than the assumed, on average by about 5%, over the entire range of variation of t_{50}; and (3) Z_{min} is larger than Z_{Req} over the entire range of variation of t_{50}. On the other hand, for a given q_o, decreasing t_{50} results in a lower t_{co} than t_{coReq}, and hence a $Z_{min} < Z_{Req}$ and a larger E_a than would be the case if there was no error in t_{50} measurement. However it could also lead to an infeasible irrigation. In line with this observation, decreasing t_{50} by 1min results in: (1) in the lower half of the t_{50} range, the t_{coReq} obtained from chart will lead to infeasible irrigations, shown in Figure 7c as a narrowing of the t_{50} range; (2) E_a, over the entire range of t_{50}, is close to the E_a for the assumed condition (an average increase of 1.5%); and (3) Z_{Req} exceeds Z_{min} by an average amount of 17.7mm over the range of variation of

t_{50}. In summary, errors in t_{50} measurement may lead to a significant narrowing of the range of applicability of the chart and some under irrigation or a decrease in performance.

Graded basins (0.1% slope): Figure 7d depicts the effect, on E_a, Z_{min}, and feasible ranges of variation of t_{50}, of using a t_{50}-t_{coReq} chart prepared for a graded basin with an assumed Manning $n = 0.08$ in a basin where $n = 0.096$ or $n = 0.064$, which represents a ±20% change relative to the assumed value. The effect of changes in Manning n on surface hydraulics and hence on E_a, Z_{min} and range of t_{50} can be explained the same way as for level basins (0.03% slope). The only difference here is the effect of a larger bed slope. Keeping all other factors constant, a steeper bed slope leads to a higher energy gradient, hence a faster advance and smaller t_{50}. Alternatively, a steeper slope results in a reduced surface storage capacity (smaller normal depth) during advance, which contributes to faster advance. Noting that for a given q_o, bed slope has the opposite effect on advance and surface storage volume relative to Manning n. The preceding discussion suggests that basin bed slopes can have a moderating or enhancing effect on the sensitivity of system hydraulics to Manning n. The same can be said about the interactive effects of basin bed slope and soil intake characteristics on surface irrigation hydraulics.

Consistent to the preceding discussion, when n is increased from 0.08 to 0.096, the following effects were noted on E_a, Z_{min} and ranges of t_{50} (Figure 7d): (1) over the entire range of variation of t_{50}, E_a for the assumed condition exceeds E_a for $n = 0.096$ - the average decrease in E_a being 6.1%; and (2) over the same range, Z_{min} for the actual condition is, on average, 8.9mm higher than Z_{Req}; and (3) the range of variation of t_{50} is essentially the same. On the other hand, decreasing n by 20% from the assumed value to 0.064 resulted in: (1) the range of t_{50} is narrowed significantly (Figure 7d), because the corresponding irrigation scenarios in the upper rages of t_{50} are infeasible; (2) E_a exceeds the E_a for the assumed field condition (the average increase being 3.4%); and (3) Z_{min} is slightly lower than Z_{Req} over the entire range of variation of t_{50} (on average 3.5mm). The explanation for the narrowing of the t_{50} range, with $n = 0.064$, is the same as for level basin (Figure 7a). However, it can be noted from Figure 5d that because of the relatively steeper slope the effect of reduced Manning *n* is less severe than would have been the case for a level basin (Figure 7a).

Figure 7e depicts the effect, on E_a and Z_{min}, of using a chart prepared for an I_f = 0.8 in a basin with I_f = 0.7 or 0.9. With I_f = 0.7, E_a shows very little sensitivity and closely matches E_a for the assumed condition (Figure 7e). The corresponding Z_{min} curve relative to Z_{Req} shows that, over the entire range of variation of t_{50} the irrigation requirement is nearly met and often exceeded (Figure 7e). The explanation for this observation is similar to the one given in relation to Figure 7b. Note that, compared to the assumed condition, the feasible range of variation remains nearly unaffected. For I_f = 0.9, E_a and Z_{min} are slightly lower than would have been the case with the assumed intake characteristics (I_f = 0.8). The upper limit of t_{50} with I_f = 0.9 is smaller than the upper limit of t_{50} for I_f = 0.8. The higher infiltration under actual field condition, compared to the assumed condition, resulted in incomplete advance close to the lower end of the flow rate range, lowering the upper limit of the t_{50} for I_f = 0.9. As described above, this is the flow rate range where advance and surface hydraulics is most sensitivity to changes in field conditions.

Figure 7f shows the effect, on E_a and Z_{min}, of using a t_{50}-t_{coReq} chart with a ±1min error in the measured t_{50}. E_a shows very little sensitivity to realistic measurement errors in t_{50} (±1min error). Z_{min} is generally close to the requirement, for both +1min and -1min error. However, for the case in which measured t_{50} contains +1min error, the Z_{min} is slightly larger than Z_{Req} close to the upper limit of the t_{50} range. The opposite holds for -1min error in t_{50} measurement. The upper bound of the t_{50} range is smaller than the upper bound of the t_{50} for the assumed condition. This is due to the fact that the t_{coReq} obtained from the chart with -1min error is too small leading to incomplete advance, hence infeasible irrigations, close to the upper limit of the t_{50} range.

Sensitivity to simultaneous variation of Manning n and soil intake family: The preceding analysis assumes that all soil and crop hydraulic parameters of a basin remain unchanged (at the assumed level), when a single parameter is varied within a physically realistic range (a one-dimensional sensitivity analysis). While this makes the problem amenable to a simplified analysis like the one presented above, in practice it is likely that most of the soil and crop hydraulic parameters may differ from their respective assumed values and it is their net interactive effect that determines consequent surface hydraulics and irrigation performance. The changes in the different parameters can at times complement one another the resulting effect being a cumulative one (for instance, higher roughness, higher infiltration, and lower bed slope all have the effect of slowing advance and the opposite combination of parameters leads to a faster advance – however, it ought to be noted that the effect of these parameters on surface storage may not follow this pattern). At times the variation in parameters can be such that their effect negates one another, the net effect on the system hydraulics being minimal. Hence, a practically useful evaluation of the sensitivity of a t_{50}-t_{coReq} criterion, given an assumed field condition, requires establishing realistic ranges of variation of the soil and crop hydraulic parameters around the assumed parameter set (field condition) taking all, or at least most, of the parameters together. Subsequent analysis exemplifies the effect on surface irrigation hydraulics, and consequent E_a, Z_{min}, and ranges of t_{50}, if a t_{50}-t_{coReq} chart prepared for an assumed field condition is used in a basin with a different soil intake characteristics and Manning n.

Considering the results summarized in Figures 7a and 7b, it can be noted that a combination of n = 0.075 and I_f = 1.5 represent a field condition in which all irrigations within the range of variation of t_{50} can be infeasible. On the other hand, the combination n = 0.125 and I_f = 0.8 can be used to define the opposite end of a realistic range of variation in field conditions around the assumed field condition (n = 0.1 and I_f = 1.0). Figure 8a depicts the result for Manning n = 0.125 and $I_f =0.8$. Relative to the range of variation of t_{50} for the assumed condition (sold line in Figure 8a), the range of t_{50} for the actual condition is narrower. The resulting E_a is less than the E_a for the assumed field condition over the entire range of t_{50} (an average decrease of 8.8%) and Z_{min} for the actual field condition is larger than Z_{Req} throughout the range of variation of t_{50}. Comparing Figures 7a and 7b with Figure 8a, it can be noted that n may have a significant effect on E_a and the range of t_{50} than the change in soil intake characteristics. Consistent with expectation, on the opposite end of the range of variation of field conditions (n = 0.075 and I_f = 1.5), the simulation results show that advance is incomplete for all the irrigations over the entire range of variation of t_{50}, hence E_a and Z_{min} cannot be evaluated for those irrigations and are not shown in Figure 8a.

The discussion so far shows how a t_{50}-t_{coReq} chart derived through simulations for an assumed set of field conditions would perform if used under a set of field conditions that are realistically different from the assumed conditions. For reasons outlined above (parameter estimation errors, gaps between modeling capabilities and the complexities of real-life surface irrigation hydraulics, and measurement errors), the irrigation system characteristics is always imprecisely defined. In order to allow for uncertainties in system parameter estimates and prevent failure, it is a standard engineering practice to incorporate into system design prescriptions a safety margin. In the context of irrigation management, failure can be defined as incomplete advance or the failure to apply a certain minimum depth (infeasible irrigation scenario). Hence, the preceding discussion suggest that if an inflow cutoff criteria exhibits a degree of sensitivity to uncertainties in field conditions, it does not necessarily mean that it cannot be used in practice. Instead it shows the need for a procedure for deriving an appropriate safety factor that can be incorporated into the t_{50}-t_{coReq} cutoff criterion, given the level of uncertainty (probable range of variation) in soil and crop hydraulic parameter estimates for a basin or an irrigation management block.

A detailed discussion on this is beyond the scope of the current study, however, it is so vital an ingredient for the development of a practically useful irrigation design and management recommendation for any given set of conditions that subsequent studies need to address it. Important questions are: (1) given a basin or an irrigation management unit, how to establish limits to the probable range of variations of system parameters with a certain level of confidence defined in probabilistic terms? (2) how to derive a safety factor based on probable ranges of system parameters and related uncertainty (or confidence level)? and from these follows answers to such question as (3) given a basin or an irrigation management block, what are the ranges of attainable levels of performance and minimum depth? The following is a simple example aimed at illustrating the potential uses of a safety factor in overcoming the limitations of the t_{50}-t_{coReq} criterion.

A note on the potential uses of safety factor in overcoming the limitations of the t_{50}-t_{coReq} cutoff criterion: Considering the parameter ranges in Figure 8a, on one end of the range we have Manning $n = 0.125$ and $I_f = 0.08$ and on the other end of the range is Manning $n = 0.075$ and $I_f = 1.5$. Although the irrigation scenarios for $n = 0.075$ and $I_f = 1.5$ are all infeasible, increasing the field measured t_{50} by 20% results in feasible irrigation scenarios over a relatively wider range of t_{50} (Figure 8b). Corresponding E_a values are lower than E_a for the assumed conditions and all the irrigation scenarios meet the requirement. Because field conditions are generally imprecisely defined at the time of irrigation, once an appropriate safety factor is derived it will be applied uniformly irrespective of the actual field conditions. Hence a uniform application of the safety factor means, depending on actual field conditions the resulting irrigation scenarios can vary and in some cases they can be less efficient than when $n = 0.075$ and $I_f = 1.5$. To show the range of options in this particular example, the same safety factor (20% increase in t_{50}) is applied to the case where $n = 0.125$ and $I_f = 0.8$ (the other end of the spectrum of variation of field conditions consider here). The resulting irrigation scenarios are shown with dotted lines in Figure 8b. E_a would be much lower than the E_a for the assumed condition (solid line in Figure 8b) and the corresponding Z_{min} is much higher than Z_{Req}. Assuming these two pair of Manning n and intake family values as the probable ranges of field variability for this particular example, the corresponding E_a and Z_{min} curves represent the upper and lower bounds on the possible ranges of variability of E_a and Z_{min}.

In this example, the safety factor was selected such that feasible irrigation scenarios are guaranteed under the most extreme set of field conditions ($n = 0.075$ and $I_f = 1.5$). However, other options include deriving a smaller safety factor based on a narrower range of parameter variability with a higher probability of occurrence than the most severe case. This may mean higher level of uncertainty and higher likelihood for infeasible irrigations, but also it means a limited decrease in irrigation performance for the feasible irrigations.

The preceding brief discussion suggests that given the expected value (statistically speaking the average) of a soil and crop hydraulic parameter set and a bound on the ranges of variability of these parameters upon which a confidence can be placed in probabilistic terms, an appropriate safety factor can be determined and based on it probable ranges of variability of expected irrigation performance can be drawn.

A comparison of the t_{50}-t_{coReq} cutoff criterion with other inflow cutoff criteria

An evaluation of the advantages and limitations of an inflow cutoff criterion can be made based on: (1) A consideration of the limiting operational constraint (irrigation crew do not have watches to time cutoff, imprecise/inaccurate flow rate measurement, etc.); (2) The range of feasible set (flow rate and cutoff time combinations or management options) covered by the cutoff criterion; (3) Limitations as related to the sensitivity of the cutoff criterion to soil and crop hydraulic parameters; and (4) Convenience. A brief comparison of the t_{50}-t_{coReq} cutoff criterion with other commonly used criterion (distance based cutoff criterion and completion-of-advance based cutoff criterion) is presented subsequently.

Limiting operational constraint: The limiting operational constraint in the YMIDD and UBIDD irrigation districts is: flow rate into individual basins is uncertain and infrastructural upgrades to improve measurement accuracy are impractical, at least in the short term. Given this constraint an irrigation management strategy based on a cutoff criterion that is not explicitly dependent on flow rate (such as the t_{50}-t_{coReq} cutoff criterion) or that is relatively insensitive to flow rate (e.g., completion-of-advance based cutoff criterion, Wattenburger and Clyma, 1989a,b; Clemmens, 1998) is a useful option. A generic distance-based or time-based cutoff criterion that require accurate measurement of flow rates into basins are not suitable for parts of the YMIDD and UBIDD irrigation districts where flow rate measurements are inaccurate.

Ranges of management options: Note that different cutoff criterion merely represent different ways of describing inflow cutoff event and in the range they overlap, they are equivalent in terms of resulting performance, provided a clear constraint is set on the minimum depth (e.g., $Z_{min} = Z_{Req}$). For instance, given a feasible range of variation of q_o, the behavior of the $E_a(q_o)$ function remains the same irrespective of the cutoff criterion used, provided the requirement $Z_{min} = Z_{Req}$ is met. However, different cutoff criterion has different ranges of applicability. Zerihun et al. (2005) discussed advantages and limitations of different cutoff criterion in terms of ranges of applicability. Basin inflow can be cut during the advance phase or in the post-advance phase. Advance phase (possibly distance-based) cutoff has the advantage of being convenient and in some cases effective (e.g., Figure 4c), however, it has limitations: (1) it is limited to the advance phase, hence it covers a relatively limited range of the feasible set and attainable maximum E_a can be suboptimal and (2) there are ranges of flow rate for which it cannot be applied if the requirement $Z_{min} = Z_{Req}$ is to be met. When inflow cutoff occurs during the advance phase, distance-based cutoff criterion can be used instead of the corresponding time, however, time-based cutoff criterion (including t_{50}-t_{coReq}) can still be used alternatively. If field conditions, basin length, required depth, and range of available flow rate is such that, the requirement $Z_{min} = Z_{Req}$ can be met only with inflow cutoff in the post-advance phase, then only time-based cutoff criterion is useful. If field conditions are well-defined, the fact that the t_{50}-t_{coReq} criterion is feasible both during the advance phase and in the post-advance phase means that the range of management options it covers is wide enough that both distance-based cutoff criterion and a time-based cutoff criterion, that is limited to the post-advance phase, can be shown to be particular cases of it.

It should be noted that the completion-of-advance cutoff criterion is based on the notion that inflow is cut when water reaches the downstream end of the basin. Given a basin there is only one q_o and advance time that matches Z_{min} to Z_{Req}, hence the behavior of the E_a function is different under this cutoff criterion compared to both a more generic distance-based cutoff criterion and a time-based cutoff criterion (including the t_{50}-t_{coReq} cutoff criterion). For instance the maximum E_a under this cutoff criterion may not occur when Z_{min} to Z_{Req}. However, the completion-of-advance cutoff criterion covers the entire feasible range of variation of q_o, hence it has a comparable scope of applicability as the t_{50}-t_{coReq} cutoff criterion.

Limitations as related to sensitivity to soil and crop hydraulic parameters: To the extent that *a priori* estimates of soil and crop hydraulic parameters are always imprecise and that errors in t_{50} measurements are unavoidable; the sensitivity of the cutoff criterion to realistic levels of parameter estimation and t_{50} measurement errors is an important limitation of the t_{50}-t_{coReq} cutoff criterion. Another important limitation of the cutoff criterion is that the t_{coReq} is determined based on advance time to midfield, which is a function of the soil and crop hydraulic parameter set in addition to q_o. Although it is generally assumed that field condition is homogeneous over the entire basin; variations do exist and if the field condition in the lower-half of the basin is significantly different from the upper-half of the basin, the t_{coReq} determined as a function of t_{50} could lead to infeasible irrigations or feasible but inadequate irrigations or very inefficient irrigations. Distance based cutoff criterion is also sensitive to errors in flow rate measurements and estimates of system parameters. The completion-of-advance based criterion is relatively insensitive to uncertainties in flow rate measurement and field conditions (Wattenburger and Clyma, 1989a,b, Clemmens, 1998), which is an advantage. But it can lead to very low performance if the system is not designed in such a way that it can be optimally managed with the completion-of-advance criterion – i.e., length and irrigation requirement need to be matched with flow rate for optimal efficiency at the design stage.

Convenience: Convenience is a less important criterion compared to the above three. In general the completion-of-advance and a generic distance-based criterion can be most convenient compared to time-based (including a t_{50}-t_{coReq}) cutoff criterion.

Summary

The inferences that stem from the preceding analysis are:

(1) The outcome of an irrigation event (whether it is a feasible or infeasible irrigation and the corresponding performance – efficiency and adequacy) resulting from the selection of

a cutoff time, based on a t_{50}-t_{coReq} chart can be highly sensitive to realistic changes in field conditions relative to the conditions assumed in the formulation of the chart. The results show that the t_{50}-t_{coReq} cutoff criterion is most sensitive when basins are operated close to the lower and upper limits of the feasible range of flow rate. The results also suggest that changes in field conditions relative to the assumed conditions have a more pronounced effect on E_a, Z_{min}, and ranges of t_{50}, when the slope of the basin is nearly flat (S_o = 0.0003) than is the case with graded basins (S_o = 0.001). An important observation that may need further study is that bed slope may have a moderating effect on the sensitivity of a t_{50}-t_{coReq} chart to changes in field conditions, particularly Manning *n* and soil intake characteristics (Figures 7a, 7b, 7c, and 7d).

(2) The results also show that realistic levels of decrease in Manning *n* and/or increase in soil intake rate (increased intake family), relative to the assumed field condition, are likely to cause infeasible irrigations. While a realistic increase in Manning *n* generally result in feasible irrigations with reduced performance, a slight decrease in soil intake is likely to lead to a feasible irrigation with increased performance.

(3) The most notable effect of t_{50} measurement error is the significant narrowing of the t_{50} range with level basins (Figure 7c). In level basins significant under irrigation may also occur toward the lower limit of the t_{50} range.

(4) Significant spatial variations that are systematic along the basin length (e.g., significant differences in field conditions between the upper and lower reaches of the basin) can have adverse effects on the usefulness of the t_{50}-t_{coReq} criterion.

(5) The results in general show that accurate characterization of soil and crop hydraulic properties of irrigation basins is essential for a useful application of the t_{50}-t_{coReq} inflow cutoff criterion. This is particularly important in flow rate ranges where the basin irrigation hydraulic problem is highly sensitive to system variables and parameters – close to the limits of the feasible range of flow rate. However, it should also be noted that soil and crop hydraulic parameter sets are always imprecisely defined ahead of an irrigation event and can only be known in some approximate sense – only its range of variation can be defined with a confidence level expressed in probabilistic terms.

(6) Potentially, the use of appropriate safety factor can extend the range of application of the t_{50}-t_{coReq} cutoff criterion.

(7) Completion-of-advance cutoff criterion is relatively insensitive to uncertainties in flow rate measurement and field conditions. With this cutoff criterion feasible irrigations are generally guaranteed, unless very small flow rates are used. However, performance can be very low, if the system is not properly designed.

4. Field studies

The objective of the field study is to evaluate the feasibility of the t_{50}-t_{coReq} criterion under a range of field conditions in the YMIDD/UBIDD area. A description of the general field evaluation methodology, including the procedure developed for evaluating the t_{50}-t_{coReq} cutoff criterion, and results are presented subsequently.

Plan of field study

The YMIDD and UBIDD will be divided into management blocks that can realistically be considered homogeneous with respect to infiltration properties characterized by NRCS intake families, Manning roughness, basin longitudinal slope, and required depth of application. The soil intake family for a basin will be determined based on soil map of the YMIDD and UBIDD, the Manning n will be assumed crop dependent, and basin longitudinal slope will be taken as the standard slope used in the latest land grading design. This parameter set is referred to as the assumed field condition, as the actual field condition at the time of irrigation is unknown. Accordingly, the YMIDD and UBIDD is divided into four different soil groups in terms of their infiltration properties as 0.8, 1.0, 1.5, and 2.0 NRCS intake families. Within each soil subdivision, crop type and basin longitudinal slopes will be considered as main experiment variables, Table 2. Considering two crops (namely, citrus and alfalfa), commonly grown in the YMIDD and UBIDD, and two longitudinal slopes (level and 0.1%), standard grades used in the area; all possible combinations of crops and slopes within each soil subdivision results in 4 test basins. Four irrigations are planned on each of the test basins leading to a total of 16 irrigation evaluations in a soil intake family, Table 2.

On each citrus basin, 50% of the irrigations are to be conducted on a freshly tilled surface and 50% will be on sealed and crusted surfaces, Table 2. On the alfalfa basins, on the other hand, due to agronomic considerations only one in four of the test irrigations are to be conducted on freshly tilled surface (Table 2). Furthermore, half of the irrigations are to be conducted while the alfalfa crop is emerging or newly-cut and the remaining half are to be conducted at full vegetative growth. The goal is to take into account the effects of crop type and growth stage on Manning n. Two different basin surface conditions, freshly tilled as well as crusted and sealed, were included in the study to take into account these effects on both soil infiltration characteristics and Manning n. Note that in the Yuma Mesa, the term level basin refers to a basin with longitudinal slope of 0.03%, however, the assumed grade for level basins in simulations presented in this study are 0.0%.

Field procedure

Selected basins in each of the four blocks of the project area (defined by the associated USDA-NRCS intake family) will be instrumented for field experiments. Staff gauges are to be installed at multiple points spaced at regular intervals along the central transect of each test basin. A level survey will be conducted along the central transect of each test basin prior to an irrigation event to determine basin bed longitudinal profile at the time of an irrigation event, this data can be used in diagnostic evaluations. In addition, advance and recession trajectories, t_{50}, cutoff time, t_{co}, obtained from a simulation-based chart and the corresponding advance distance, L_{co}, will be recorded during each irrigation evaluation. Basin inflow will be measured with long throated flumes located at the off-take from the main canal (in which case supply canal leakage losses could be significant) or with the velocity-area method, based on measured average cross-sectional velocity, near the basin inlet. These data are to be used both in descriptive and diagnostic evaluations of the t_{50}-t_{coReq} inflow cutoff criterion.

Evaluation of the t_{50}-t_{coReq} cutoff criterion based on field data

Basins selected for irrigation evaluations will be divided into discrete groupings of slope, roughness, and infiltration as well as basin length and irrigation requirement. For each unique combination, t_{50}-t_{coReq} charts will be prepared, prior to a test irrigation event, using data generated through simulation runs conducted with SRFR by varying basin inflow rates over a feasible range (Figures 9a-9d). The inflow rates in each chart will vary from a minimum that can reach field end (considering a soil of finite steady state intake rate) to a maximum for which $t_{50} \approx t_{coReq}$. In each simulation the cutoff time will be set such that the minimum applied depth just equals the requirement.

Figures 9a-9d show typical t_{50}-t_{coReq} charts prepared for graded and level basins in 0.8, 1.5, and 2.0 intake family soils of the YMIDD/UBIDD. These charts contain $t_{coReq}(t_{50})$, $q_o(t_{50})$, and $E_a(t_{50})$ curves. As will be shown subsequently, the $q_o(t_{50})$ curve will be used in the evaluation of the t_{50}-t_{coReq} cutoff criterion and the $E_a(t_{50})$ curve shows the performance potential of irrigation basins managed using the t_{50}-t_{coReq} cutoff criterion. In general, given a soil and crop hydraulic parameter set, and Z_{Req} and L (and the condition that $Z_{min} = Z_{Req}$); the $E_a(t_{50})$ function of graded basins has a maximum (e.g., Figure 9a). On the other hand, the application efficiency of level basin irrigation is a decreasing function of t_{50} (e.g., Figures 9b and 9d).

In a typical test irrigation event, a t_{50}-t_{coReq} chart appropriate to a particular basin irrigation parameter set is selected, an irrigation is initiated, and the inflow is cut in accord with field measured t_{50}. As discussed above in the field procedure section, advance and recession trajectory and other pertinent variables will be measured during each test irrigation event.

Evaluation of the cutoff criterion will be conducted in two steps. Based on criteria relating to feasibility and irrigation adequacy, the first evaluation step determines the percentage of the total number of test irrigations to which the t_{50}-t_{coReq} inflow cutoff criterion is applicable. Considering the test irrigations as representative samples of field conditions in the YMIDD and UBIDD, the results from this step can be viewed as indicators of whether the t_{50}-t_{coReq} criterion is practical in these irrigation districts. The second step would explain poor results from the first step with a diagnostic analysis based on comparisons of assumed and actual field conditions.

Step I (Descriptive evaluation): In the first step a descriptive evaluation of the t_{50}-t_{coReq} chart is conducted based on the following set of criteria:

(i) Does t_{50m} fall within the range [t_{50min}, t_{50max}]? where t_{50m} = measured t_{50}, and t_{50min} and t_{50max} = the lower and upper limits, respectively, of the ranges of the t_{50} in the charts,

(ii) Does water reaches field end?

(iii) Is irrigation adequate ($Z_{Req} \leq Z_{min}$)?

(iv) Is measured q_o close to the corresponding chart-derived q_o?

Step II (Diagnostic evaluation): The second step constitutes a diagnostic evaluation and is based on a comparison of actual field conditions (estimates of soil and crop hydraulic parameters based on measured data at the time of irrigation) with assumed field conditions. Determination of actual field conditions includes estimation of infiltration parameters using the Merriam-Keller approach, as implemented in the Evaluation World of WinSRFR (Bautista et al, 2008). In addition to infiltration parameters, both the Manning roughness and longitudinal slope can be adjusted to obtain a better fit between measured and model predicted advance and recession trajectories. A comparison of measured basin inflows with chart-derived inflows can be used to evaluate the potential causes of failure for the t_{50}-t_{coReq} criterion in the descriptive evaluation step.

Results and discussion, field study

Data description: During the fall and winter seasons of 2006/2007 and the spring of 2007, field experiments were conducted in selected basins in the University of Arizona Yuma Mesa Research Farm and in growers’ farms within the YMIDD/UBIDD. Twenty six irrigation evaluations were performed in citrus and alfalfa basins characterized by three of the four USDA-NRCS intake families: 0.8, 1.5, and 2.0 (Table 2). The dimensions of the test basins, measured flow rates, intake families, Manning roughness, average basin longitudinal slope, and required depth of application are summarized in Tables 2 and 3.

All thirteen data sets in the 0.8 USDA-NRCS soil intake family (Table 2) were collected at the University farm. The crop was citrus and all basins were 177.7m long and 33.5m wide (Table 3). Four out of the thirteen test basins in the 0.8 intake family were freshly tilled. The nominal grade for five of the thirteen basins was 0.1% (Table 2). In addition, five test irrigations were conducted in growers' farms with the 1.5 USDA-NRCS soil intake family (Table 2). Three of these test irrigations were performed on alfalfa basins with 0.1% longitudinal slope and the remaining two test irrigation events were conducted on citrus basins with a zero slope. The dimensions of these basins range from 177-205m in length and 35-63m in width. Other relevant details of the basins are summarized in Tables 3 and 4. Eight more field evaluations were conducted in growers' farms on a 2.0 USDA-NRCS intake family soil. The dimensions of these basins range from 161 to 195 m in length and from 51 to 112m in width (Table 3). Two of these basins were used to irrigate a citrus crop and six of them were alfalfa basins (Table 2). All the citrus basins were level, while the alfalfa basins had a 0.1% slope.

Measured unit inflow rates and assumed field conditions (expressed in terms of soil and crop hydraulic parameters) are summarized in Table 3. Advance trajectories were measured at regularly spaced stations along the central transect of the basin. In addition, during each test irrigation event, measured t_{50}, associated chart-derived t_{co}, and L_{co} were also recorded. The bed profile along the central transect of each test basin was measured a day before each test irrigation event (e.g., Figures 10a-10d). Figures 10a-10d depict actual bed profiles at the time of irrigation, assumed nominal longitudinal slopes, and estimated average longitudinal slopes. These average slopes were selected such that the cut and fill over the entire length of the basin is zero. Actual basin bed profiles along the central transect exhibit variations in bed elevations resulting in an average effective longitudinal slope that is significantly different from the assumed average (Figures 10a-

10d). This indicates that basin longitudinal slopes are sources of error in t_{50}-t_{coReq} chart predictions.

In addition to the 26 data sets presented above, referred to as the University of Arizona (UA) data (Tables 3 and 4), 10 more data sets (labeled BR) obtained from the US Bureau of Reclamation Yuma Area Office will be used in subsequent analysis. One of the BR data sets is obtained from a basin in a 0.8 intake family, five of them are from basins in a 1.5 intake family and the remaining four were obtained from basins with a 2.0 intake family (Table 3). An important difference between the UA and BR data sets are that soil intake families for the BR data sets were estimated based on post-irrigation mass balance calculations based on measured advance and recession trajectories and basin inflows. Seven of the basins have an assumed slope of 0.1% and the remaining three basins have a level slope. Nine of the ten BR basins were used to grow citrus, and one of them is an alfalfa basin. Basin dimensions in the BR data sets range from 164m to 198m in length and 24m to 75m in width (Table 3). Each of the 10 BR data sets contains advance and recession trajectories, in addition to data on basin inflow rates and cutoff times (Table 3). Since the BR data sets contain both advance and recession trajectories, they can be used to estimate intake parameters relatively accurately. Hence, they are amenable to the more complete (two-step) evaluation of the t_{50}-t_{coReq} cutoff criterion. The UA data sets, on the other hand, do not contain recession trajectories, hence they will be used for descriptive evaluation only.

Descriptive evaluation

As described above, evaluation of the t_{50}-t_{coReq} cutoff criteria will be conducted in two-steps, with a descriptive evaluation based on feasibility and irrigation adequacy tests in the first step (Step I) followed by a diagnostic evaluation in the second step (Step II). Due to limitations in the level of detail of available data, the preliminary analysis presented here relies on a truncated descriptive evaluation procedure using only three of the four criteria described above (excluding the criterion - is $Z_{Req} \leq Z_{min}$?).

A t_{50}-t_{coReq} chart is prepared for each unique combination of field condition and basin length. The 36 irrigation evaluations presented in this report require a total of 17 different t_{50}-t_{coReq} charts (e.g., Figures 9a-9d), three charts for basins in the 0.8 intake family, seven charts for basins in the 1.5 intake family, and seven charts for those in the 2.0 intake family. Assumed field conditions for preparing the charts are given in Tables 2 and 3. As discussed earlier, basin slopes (0.0% and 0.1%) are nominal estimates based on standard grades used in the last land grading design of the basin. The values of Manning roughness used in developing the charts are 0.08 for citrus basins and 0.2 for alfalfa basins (Tables 2 and 3). These values were obtained from an earlier study by Sanchez and Zerihun (2000a,b) in the University of Arizona Yuma Mesa research farm.

Following the approach described above, feasibility tests were conducted on the 26 test irrigations of the UA data sets and the 10 BR data sets, the results are summarized in Table 4. These tests show that the t_{50}-t_{coReq} charts can be used in all of the BR data sets; however, in 27% of the UA data sets, that is in 7 out of a total of 26 data sets, the field observed t_{50} is less than the corresponding chart minimum ($t_{50m} < t_{50min}$) – note earlier discussion about the range of q_o used in developing the charts. Thus, 19 data sets from the UA data pool (73 percent of the total) and all 10 BR data sets will be used in the next step of the descriptive evaluation process. Due to lack of recession data, a diagnostic analysis cannot be done to establish the reasons for the failure of 7 of the 26 UA data sets to meet the feasibility requirements.

Additional descriptive evaluation, involving a comparison of measured and chart derived q_o, was conducted on the data sets that were deemed feasible in the preceding analysis. The results are summarized in Figures 11a-11c for the UA data sets and in Figures 12a-12f for the BR data sets. Figures 11a, 12a, and 12d present a comparison of chart-derived and measured q_o, a qualitative criterion for evaluating the goodness of fit between measurements and model predictions (in this particular case) based on the degree of observed data scatter about a 1:1 line. Figures 11b, 12b, and 12e are residual plots and are useful in determining presence or absence of a trend in the data – whether residuals are random or systematic; which is helpful in making a better determination of the source of the residuals. Figures 11c, 12c, and 12f depict the distribution of residuals, based on which a more quantitative evaluation of the effectiveness of the cut off criteria can be made. If, for instance, the residuals for a large percentage of the data sets (say 85%) are less than some acceptable threshold (say < 20%), then the cutoff criterion can be considered useful based on the field tests conducted. Based on Figures 11c, 12c, and 12f; a similar criterion can be set to characterize failure. In subsequent discussions, results for the UA data sets are presented first, followed by the BR data.

Figure 11a shows a comparison of measured and chart-derived unit inflow rates. As can be seen from Figure 11a, the (q_{om},q_{oc}) data points, where q_{om} = unit inflow rate and q_{oc} = chart-derived unit inflow rate, are almost entirely above the 1:1 line. Weighted Mean Relative Residual (WMRR), Eq. 2, is used to evaluate residuals between measured and chart-derived flow rates. The mean relative residual assigns disproportionately high weights to errors in the very low ranges of flow rate (close to zero), hence weighing the relative error by the ratio, q_{omi}/q_{av}, moderates this limitation of the mean relative residual in the lower range of q_o. Weighted Mean Relative Residuals (WMRR) is calculated using Eq. 3. The relatively high *WMRR*, 27.0% (Figure 11a), indicates a significant difference between q_{om} and q_{oc} values. This suggests that either inflow rate measurements are inaccurate and/or actual field conditions at the time of irrigation are significantly different from values assumed when developing the charts.:

$$WMRR = \frac{1}{N}\sum_{i=1}^{N}\frac{\left|q_{oci} - q_{omi}\right|}{q_{oav}} \qquad (3)$$

where *i* = data set index, *N* = number of data sets used in the analysis, and q_{oav} = the average inflow rate for the *N* data sets.

Examination of Figure 11b, a plot of relative residuals, RR, defined as

$$RR = \frac{q_{oci} - q_{omi}}{q_{omi}}100 \qquad (4)$$

shows that, in general, there is a systematic over-prediction of basin inflow rates by the charts compared to field measurements. The systematic nature of the residuals about the zero residual line (Figure 11b) suggests that any, or a combination, of the following factors are possible sources of the observed residuals: (1) inflow rate measurement errors, which are generally biased low (underestimated) in this case, (2) assumed infiltration rates could be higher than infiltration rates at the time of irrigation, (3) average hydraulic resistance coefficient at the time of irrigation could be lower than assumed, (4) average basin longitudinal slope at the time of irrigation could be higher than assumed standard basin longitudinal slopes, and (5) noting that tracking advance trajectory in basins is always an approximation, real-time determination of t_{50} can also be a possible source of error.

As can be seen from Figures 11b and 11c, the RR between q_{om} and q_{oc} is largely accounted for by six data points that can be grouped into three clusters (Figure 11b and 11c). Each of these data clusters are obtained from the same farm. The systematic nature of the residuals, and that the residuals from the same farm show the same bias with respect to the zero-residual line, suggests flow measurement errors could have played a more important role than differences between assumed and actual field conditions. Nonetheless, in most test irrigations some combination of all of the factors enumerated above may have contributed to the observed discrepancy between chart predictions and field observations. However, a more definitive analysis will have to await the collection of additional data with enough detail to allow a diagnostic evaluation.

Figure 11c shows the frequency distribution of residuals between measured and chart-derived q_o. For about 47% of the test cases chart-derived flow rates are within 20% of measured flow rates. About 37% of the test irrigations show residuals exceeding 30% and the residuals for the remaining 16% of the test irrigations range between 20% and 30%. Hence these preliminary results suggest that in about 50% of the cases chart-derived flow rates can be in error by more than 20%. The effect of these errors on t_{50} and the corresponding t_{coReq} and E_a depends on the range of flow rate used and the type of basins – graded or level (Discussion on Chapter 3). In the Yuma-Mesa typical flow rates exceed 6.0L/s/m. Hence for both level and graded basins, basins are typically operated in the management range where performance is less sensitive to variations in flow rate (Figure 1c and 1d). In this flow rate range performance could be high for level basins, however, it could be very low for graded basin (Figures 1c and 1d).

Results of comparisons between measured and chart-derived q_o for the BR data sets is summarized in Figures 12a-12f. There is little correlation between measured and chart-obtained flow rates (Figure 12a). This observation is confirmed by the relatively high WMRR of 33.2%, Figure 12b. In general, the relatively high WMRR between q_{om} and q_{oc} indicates that either flow rate measurements are inaccurate and/or actual field conditions at the time of irrigation are significantly different from the values assumed in developing the charts. Approximating advance time to the mid-field can also be a source error. However, an examination of Figure 12b, a plot of relative residuals versus measured q_o, shows that the residuals are randomly distributed about the zero-residual line and exhibit no trend, indicating the absence of systematic error. It follows then that, although flow measurement errors should not be considered negligible, at least in some of the test irrigations, the results summarized in Figure 12b generally suggest that the residuals can be largely explained by discrepancies between assumed and actual field conditions. Thus, a revision of soil and crop hydraulic parameter estimates, based on data collected during test irrigation events, may significantly narrow the discrepancy between measured and chart derived q_o.

Figure 12c shows that in 30% of the test irrigations, the WMRR is less than 20% of the measured q_o and that in about 40% of the cases, residuals are larger than 30% of the measured q_o. The remaining 30% of the test irrigations show residuals between 20-30%. In about 70% of the tests irrigations residuals between chart-derived and measured flow rates exceed 20%, which is a significant. The same observation about the effect of these residuals on system performance can be made as has been made in relation to the UA data. Out of the seven test irrigations with relatively large residuals (Figure 12b and 12c), four test irrigations were selected for a diagnostic evaluation involving readjustment of soil and crop hydraulic parameters. The four data sets used in a revision of the parameters consists of a data set each from the 0.8 and 1.5 intake families and two data sets from the 2.0 intake family.

Preliminary diagnostic results

As explained in the preceding discussion, flow rate measurements in the BR data sets were generally considered accurate. Hence the diagnostic evaluation presented here is based on a revised estimate, using field measured data, of soil and crop hydraulic parameters only. Infiltration parameters for the four selected data sets were estimated via the event-analysis functionality of WinSRFR 2.04 (Bautista et al., 2008). WinSRFR utilizes the Merriam-Keller approach, a post-irrigation mass balance, to select an appropriate intake family from the USDA-NRCS intake families or to determine the coefficient in alternative infiltration functions (Bautista et al., 2008). In addition to the infiltration parameters, the average basin longitudinal slope and Manning roughness were adjusted to provide satisfactory fit between model predicted and measured advance and recession trajectories and consequent infiltration opportunity times and infiltrated depths. The resulting parameter estimates and associated measures of goodness of fit are summarized in Table 5. Average relative error of intake opportunity time and infiltrated depth is generally < 2.0%. For three out of the four data sets investigated here, a Philip type equation gave a better fit to the field data than the USDA-NRCS infiltration function, suggesting that not only the infiltration parameters, but also the functional form is important in characterizing infiltration.

Using the revised parameter estimates, new t_{50}-t_{co} charts were generated for each of the four test irrigations considered for diagnostic evaluations. A comparison of measured basin unit inflow rates and those obtained from the revised charts is summarized in Figures 12d-12f. As can be seen from Figures 12d and 12e, a revision of the parameter estimates for only four of the data sets resulted in a significant decrease in the scatter of the data around the 1:1 line and the WMRR is reduced from 33.2% to 17.4%, indicating a significant improvement in the accuracy of t_{50}-t_{coReq} chart predictions. With the revised charts, chart predictions and field measurements agree within 20% for about 70% of the data sets; 20% of the data sets show residuals ranging between 20-30%, and the remaining 10% of the data sets show residuals exceeding 30% (Figure 12f), a dramatic improvement in the accuracy of the chart-predicted q_o (see Figure 12c and 12f). For the typical range of flow rate commonly used in the Yuma-Mesa (in general 6.0L/s/m < q_o), this result along with those summarized in Figures 7a-7f indicate that inaccurate characterization of infiltration, Manning roughness, and slope could be a significant source of error for the t_{50}-t_{coReq} method. Given the very approximate nature of the methods used to characterize field conditions: (1) soil intake properties are determined by subdividing the entire project area into just four soil intake families using soil maps, (2) Manning n was considered crop dependent, and (3) assumed slopes are based on the last land grading design (note that significant differences were observed between actual average slopes and assumed slope, Figures 10a and 10c); this finding suggest that the observed limitation of the t_{50}-t_{coReq} criterion is related to the accuracy with which soil and crop hydraulic parameters were estimated.

5. Summary and Conclusions

The theoretical and field studies presented in this report show that the t_{50}-t_{coReq} inflow cutoff criterion has a sound theoretical basis and that it can be expressed in terms of a simple, yet general mathematical relationship that is amenable to compact presentations with useful practical applications in surface irrigation management.

Given a well-defined field condition, the ranges of applicability and limitations of the t_{50}-t_{coReq} inflow cutoff criterion were examined and the analysis showed that the t_{50}-t_{coReq} inflow cutoff criterion covers a broader range of management options compared to a distance based cutoff criterion or a time based cutoff criterion limited to the post-advance phase only. The study also highlighted the fact that the completion-of-advance criterion can have as wide a range of application as the t_{50}-t_{coReq} criterion.

The analysis also shows that the t_{50}-t_{coReq} cutoff criterion can be highly sensitive to soil and crop hydraulic parameters, especially when basins are operated close to the upper or lower limit of the flow rate range. This suggests that accurate characterization of soil and crop hydraulic properties of irrigation basins may be essential for a useful application of the t_{50}-t_{coReq} cutoff criterion in irrigation management. However, the analysis has also indicated that *a priori* estimates of soil and crop hydraulic parameters are always approximate and that the best that can be done is to define the limits of their probable ranges of variations with a certain level of confidence expressed in probabilistic terms. Hence, the report highlights the need for the development of a procedure for deriving realistic limits on the ranges of variation of system parameters, given a basin or an irrigation management block. It also discussed the potential uses of safety factors, as related to bounds on the ranges of parameters, in accounting for uncertainties in system characteristics and indicated the need for further study in this regard.

The analysis highlighted that the completion-of-advance cutoff criterion exhibits a relatively low sensitivity to uncertainties in flow rate measurement and field conditions compared to the t_{50}-t_{coReq} criterion. However, under existing designs, typical basin length and Z_{Req} combinations in the YMIDD and UBIDD are such that maximum attainable E_a with the completion-of-advance cutoff criterion can be relatively low. However, further studies are needed to definitively establish the advantages and limitations of the completion-of-advance cutoff criterion in the YMIDD and UBIDD compared to the t_{50}-t_{coReq} criterion.

Preliminary field results show significant differences between chart-predicted and measured flow rates, however, these errors can be attributed to the approximate methods used to characterize soil intake and Manning roughness. To a certain extent, flow rate measurement errors may have contributed as well. However, in future field evaluations flow rate measurement errors will be minimized through proper calibration of water measuring devices.

The preliminary results also show that significant variations exist in basin longitudinal profiles in the YMIDD and UBIDD. Because uniform and efficient irrigation requires a uniformly graded basin surface, micro-topographic variations, especially in mature orchards, could be an important constraint in the practical application of any inflow cutoff criterion, including a t_{50}-t_{coReq} criterion.

Given the relatively high variability of soil and crop hydraulic parameters and the sensitivity of the t_{50}-t_{coReq} cutoff criterion to these variations, the preliminary results presented in this report suggest that a useful application of the t_{50}-t_{coReq} cutoff criterion may not be made using the approximate approach used to characterize field conditions in this study. On the other hand, the dramatic reduction in the residuals between chart-derived and measured flow rates with revised parameter estimates for the BR data sets confirms the theoretical observation that accurate characterization of field conditions is the key to a useful practical application of the t_{50}-t_{coReq} cutoff criterion.

The preceding exemplifies the conflict between the requirements of practical irrigation management (using rough approximations of soil and crop hydraulic parameters) and the need for a more accurate definition of field conditions (engendered by the high variability of soil and crop hydraulic properties and their effect on surface irrigation hydraulics and consequent irrigation performance). As highlighted in the theoretical development, establishing limits on probable ranges of variation of parameters and using that to develop safety factors and management recommendations may enable to transfer model based irrigation management criteria to the realm of practical field application. However, such a study can only be part of follow up project to this one.

In order to test some of the theoretical observations outlined in this report a limited but more detailed field study under controlled conditions (better defined soil and crop hydraulic parameter set and accurately measured inflow rate) will be conducted within the framework of this study. Field protocol is being developed for these experiments. Once the development of the field protocol is completed field experiments will follow.

The final report may also outline further recommendations for a more comprehensive study, including possible field evaluation of other inflow cutoff criteria, and also exploring possible application in the Yuma Mesa of inherently more efficient irrigation technologies such as drip – mainly in some of the irrigated farms where possibilities for efficiency improvements with surface methods are limited (such as mature orchards with land grading limited to a small fraction of the basin surface).

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List of Tables

Table 1. Ranges of data used in CUSTOM/YUMABSNS

Field length	200 m (656 ft)
Bottom slope	0, 0.03%, 0.05%, and 0.1%
Manning *n*	0.02, 0.3 and 0.1
Infiltration Families	0.8-4.0
Irrigation requirement	50mm (2in)
Unit inflow rate	varied between 4L/s/m (≈ 0.04cfs/ft) and 12L/s/m (≈0.12cfs/ft) in increments of 1L/s/m (0.01cfs/ft)

Table 2 Plan of field study and inventory of t_{50}-t_{coReq} cutoff criterion field evaluations

$I_f = 0.8$

Crop	**Crop growth stage**	**Basin bed slope (%)**	**Number of irrigations**		**Total number of irrigations**
			Surface condition		
			Freshly-tilled	**Sealed and crusted**	
Alfalfa	Emerging/Newly cut	0.0	0/1[a]	0/1	**0/2**
		0.1	0/1	0/1	**0/2**
	Full vegetative growth	0.0	0/0	0/2	**0/2**
		0.1	0/0	0/2	**0/2**
Citrus	Not applicable	0.0	**3/2**	**5/2**	**8/4**
		0.1	0/2	**5/2**	**5/4**
Total number of irrigations			**3/6**	**10/10**	**13/16**

$I_f = 1.0$

Crop	**Crop growth stage**	**Basin bed slope (%)**	**Number of irrigations**		**Total number of irrigations**
			Surface condition		
			Freshly-tilled	**Sealed and crusted**	
Alfalfa	Emerging/Newly cut	0.0	0/1	0/1	**0/2**
		0.1	0/1	0/1	**0/2**
	Full vegetative growth	0.0	0/0	0/2	**0/2**
		0.1	0/0	0/2	**0/2**
Citrus	Not applicable	0.0	0/2	0/2	**0/4**
		0.1	0/2	0/2	**0/4**
Total number of irrigations			**0/6**	**0/10**	**0/16**

$I_f = 1.5$

Crop	**Crop growth stage**	**Basin bed slope (%)**	**Number of irrigations**		**Total number of irrigations**
			Surface condition		
			Freshly-tilled	**Sealed and crusted**	
Alfalfa	Emerging/Newly cut	0.0	0/1	0/1	**0/2**
		0.1	0/1	**1/1**	**1/2**
	Full vegetative growth	0.0	0/0	0/2	**0/2**
		0.1	0/0	**2/2**	**2/2**
Citrus	Not applicable	0.0	0/2	**2/2**	**2/4**
		0.1	0/2	0/2	**0/4**
Total number of irrigations			**0/6**	**5/10**	**5/16**

$I_f = 2.0$

Crop	**Crop growth stage**	**Basin bed slope (%)**	**Number of irrigations**		**Total number of irrigations**
			Surface condition		
			Freshly-tilled	**Sealed and crusted**	
Alfalfa	Emerging/Newly cut	0.0	0/1	0/1	**0/2**
		0.1	0/1	**1/1**	**1/2**
	Full vegetative growth	0.0	0/0	0/2	**0/2**
		0.1	0/0	**5/2**	**5/2**
Citrus	Not applicable	0.0	0/2	**2/2**	**2/2**
		0.1	0/2	0/2	**0/2**
Total number of irrigations			**0/6**	**8/10**	**8/16**

[a] = number of irrigations already conducted/total number of irrigations planned. A total of 26 irrigations have already been conducted.

Table 3 Data used to generate t_{50}-t_{coReq} charts

	Variables and parameters	*Units*	*USDA-NRCS intake family*		
			0.8	1.5	2.0
			UA data set		
Ranges of variables and assumed parameter sets	L	m	177.7	177-205	161-195
	W	m	33.5	35-63	51-112
	q_o	L/s/m	11.8-16	7.8-10.6	4.1-11.1
	S_o	-	level/0.001	level/0.001	level/0.001
	Z_{Req}	mm	37.5	34	30
	n	-	0.08/0.2	0.08/0.2	0.08/0.2
			BR data sets		
	L	m	164	183-198	183-198
	W	m	75	34-75	24-61
	q_o	L/s/m	5.6	5.6-10.1	5.9-11
	S_o	-	level/0.001	level/0.001	level/0.001
	Z_{Req}	mm	37.5	34	30
	n	-	0.08/0.2	0.08/0.2	0.08/0.2

UA = university of Arizona, BR = Bureau of Reclamation, L = basin length, W = basin width, q_o = unit inflow rate used in the field experiment, S_o = basin bed slope, Z_{Req} = required depth of application, and n = Manning roughness coefficient (n = 0.2 and 0.08 are used for alfalfa and citrus basins, respectively, Sanchez and Zerihun, 2000a,b)

Table 4 Total number of irrigation evaluations and results of feasibility tests

Data sets	**USDA-NRCS Intake family**	**0.8**	**1.5**	**2.0**
UA data sets	Total number of test irrigations	13	5	8
	Is $t_{50min} \le t_{50m} \le t_{50max}$?	7	4	8
BR data sets	Total number of test irrigations	1	5	4
	Is $t_{50min} \le t_{50m} \le t_{50max}$?	1	5	4

t_{50min} = minimum t_{50} in chart, t_{50m} = measured t_{50}, and t_{50max} = maximum t_{50} in chart. Data has not yet been collected in a 1.0 intake family soil

Table 5 A comparison of assumed and revised system parameters for BR data sets

BR data, assumed system parameters				BR data, revised system parameters				Measure of goodness of fit for revised parameter sets	
Basin longitudinal slope (S_o)	Manning n	Infiltration parameters		Basin longitudinal slope (S_o)	Manning n	Infiltration parameters		Average relative error for intake opportunity time (%)	Average relative error for infiltrated depth[3] (%)
		Function type	value			Function type	value		
0.001	0.08	I_f	0.8	0.0004	0.05	I_f	0.8	1.4	0.9
0.0	0.2	I_f	1.5	0.00052	0.09	k[1] (mm/h^a)	71.7	0	0.1
						a (-)	0.5		
						b (mm/h)	15		
0.001	0.08	I_f	2.0	0.0003	0.01	k[1] (mm/h^a)	69.3	-0.5	-0.2
						a (-)	0.5		
						b (mm/h)	10.0		
0.001	0.08	I_f	2.0	0.00075	0.11	k[1] (mm/h^a)	117.5	-0.1	-0.2
						a (-)	0.5		
						b (mm/hr)	2.0		

I_f = USDA-NRCS intake family and [1] Modified Kostiakov infiltration function parameters

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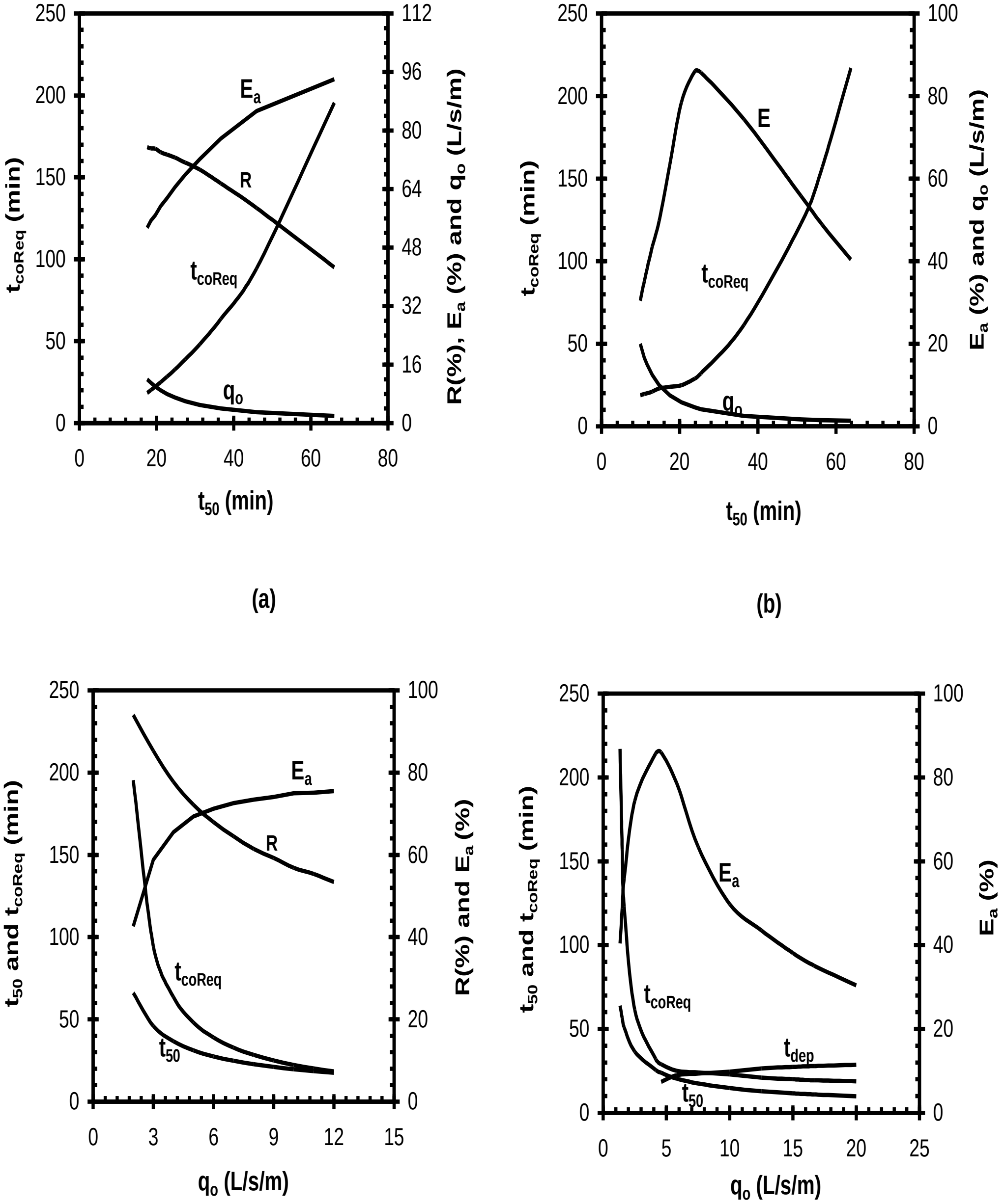
Figure 10 Longitudinal profile along the central transect of four test basins at the UA Mesa farm: (a) Basin C, (b) basin G, (c) Basin F, and (d) basin D

Figure 11 (a) A comparison of measured and chart derived unit inflow rate, q_o, UA data, (b) Relative residuals between measured and chart derived q_o, UA data, (Ovals encompass outlier data points obtained from the same farms) and (c) Relative and cumulative frequency of relative residuals between measured and chart derived q_o, UA data

Figure 12 (a) A comparison of measured and chart derived unit inflow rate, q_o, BR data, (b) Relative residuals between measured and chart derived q_o, BR data, (c) Relative frequency histogram and cumulative frequency of residuals between measured and chart derived q_o, BR data, (d) A comparison of measured and chart derived q_o, revised parameter estimates BR data, (e) Relative residuals between measured and chart derived q_o, revised parameter estimates, BR data, (f) Relative frequency histogram and cumulative frequency of residuals between measured and chart derived q_o, revised parameter estimates, BR data



(a)

(b)

(c)

(d)

Figure 1 Example charts for $E_a(t_{50})$, $R(t_{50})$, $t_{coReq}(t_{50})$ and $q_o(t_{50})$functions: (a) $I_f = 1.0$, $L = 200$m, $n = 0.1$, $Z_{Req} = 50$mm and $S_o = 0.0003$, and (b) $I_f = 0.8$, $L = 183$m, $n = 0.08$, $Z_{Req} = 37.5$mm, and $S_o = 0.001$; Example charts for $E_a(q_o)$, $R(q_o)$, $t_{coReq}(q_o)$, $t_{50}(q_o)$, and $t_{dep}(q_o)$ functions: (c) $I_f = 1.0$, $L = 200$m, $n = 0.1$, $Z_{Req} = 50$mm and $S_o = 0.0003$, and (d) $I_f = 0.8$, $L = 183$m, $n = 0.08$, $Z_{Req} = 37.5$mm, and $S_o = 0.001$

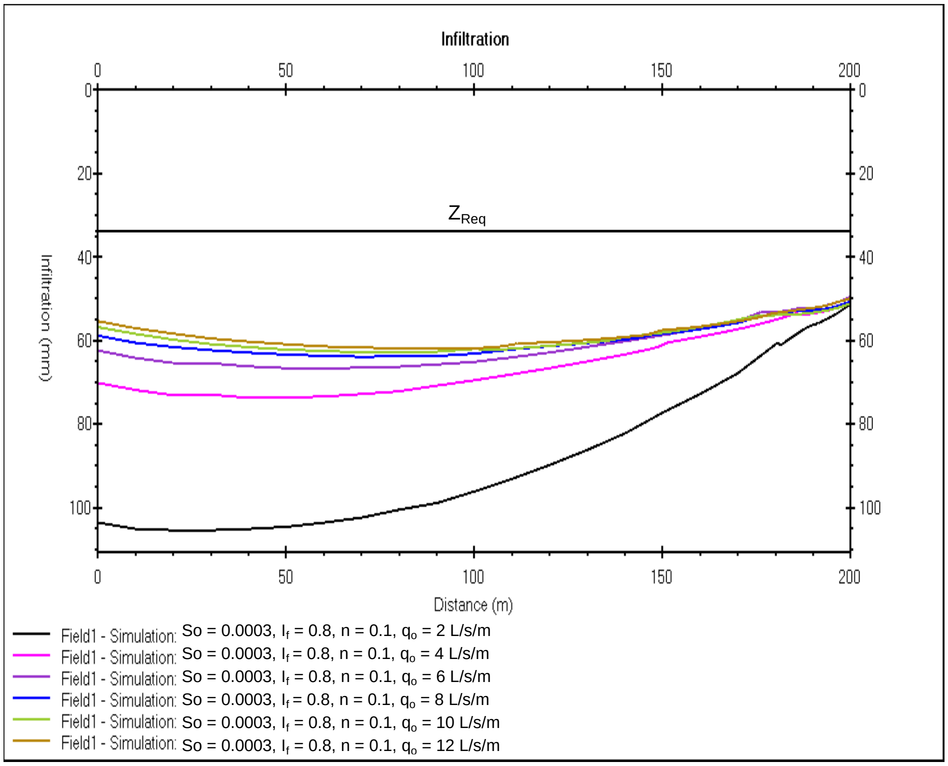
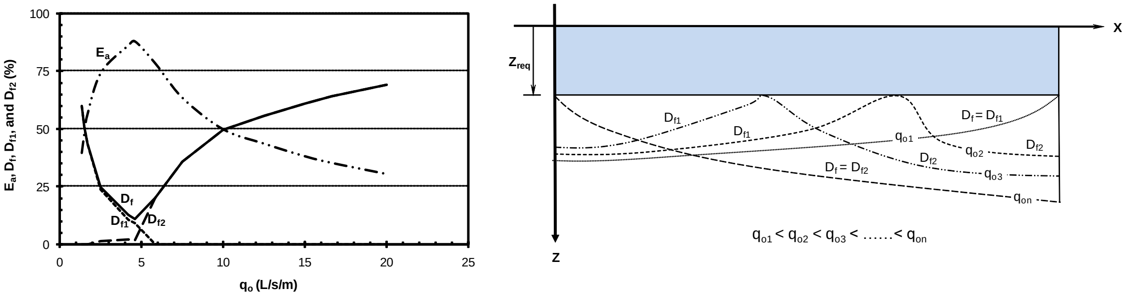
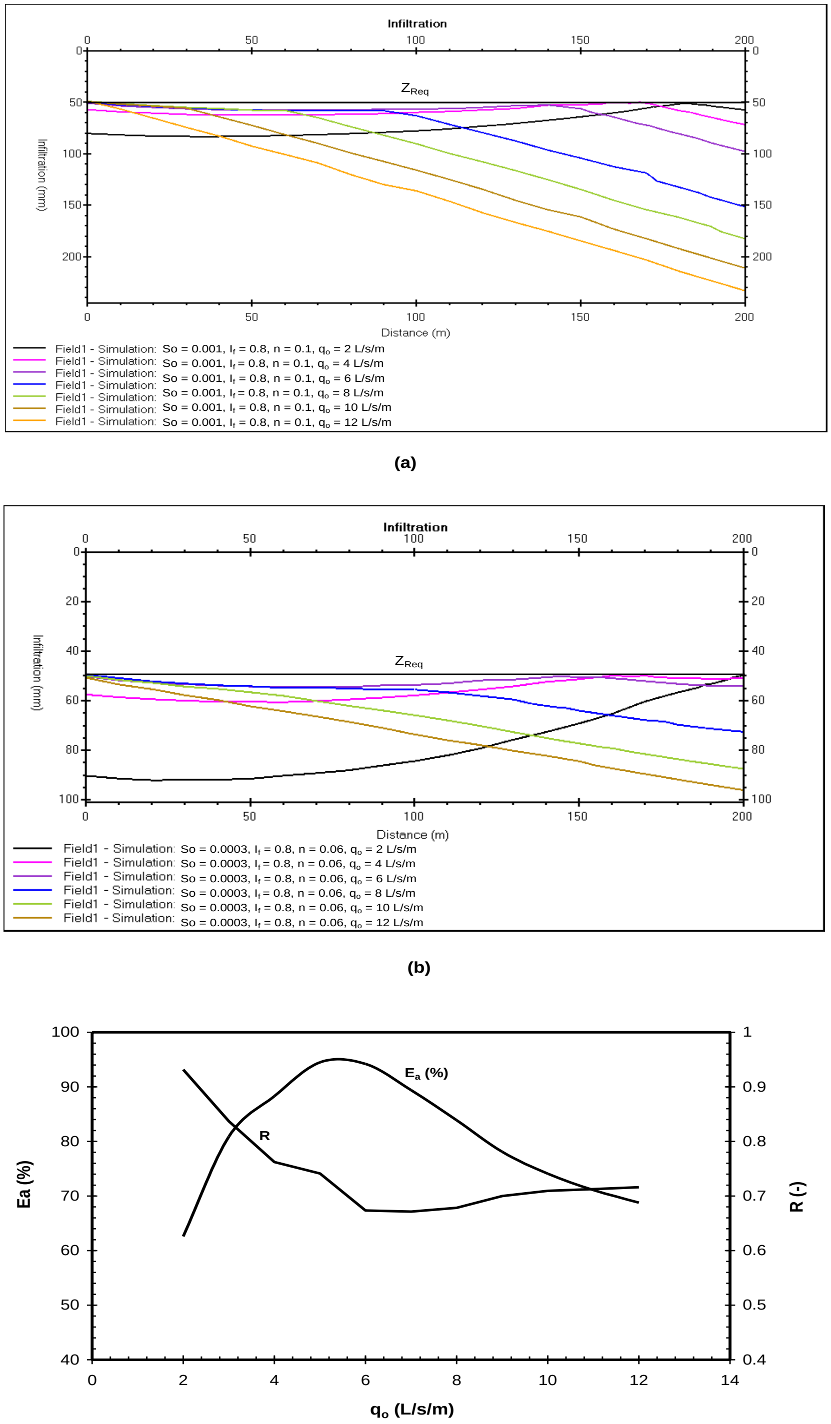


Figure 2 Variation in subsurface profiles as a function of basin unit inflow rate (Level basin, same data as in Figure 1a is used)



(a) **(b)**

Figure 3 (a) The relationship between application efficiency, E_a, deep percolation fraction, D_f, deep percolation fraction in the upper section of the post-irrigation subsurface profile, D_{f1}, and deep percolation fraction in the lower section of the post-irrigation subsurface profile, D_{f2}, with varying flow rate [same data as in Figure 1b] and (b) Schematics of a post-irrigation subsurface profile for a graded basin with varying flow rates



(c)

Figure 4 Post-irrigation subsurface profiles as a function of flow rate: (a) I_f = 0.8, S_o = 0.001, n = 0.1, L = 200m, Z_{req} = 50mm, (b) I_f = 0.8, S_o = 0.0003, n = 0.06, L = 200m, Z_{req} = 50mm, and (c) E_a and R as a function of unit flow rate for I_f = 0.8, S_o = 0.0003, n = 0.06, L = 200m, Z_{req} = 50mm

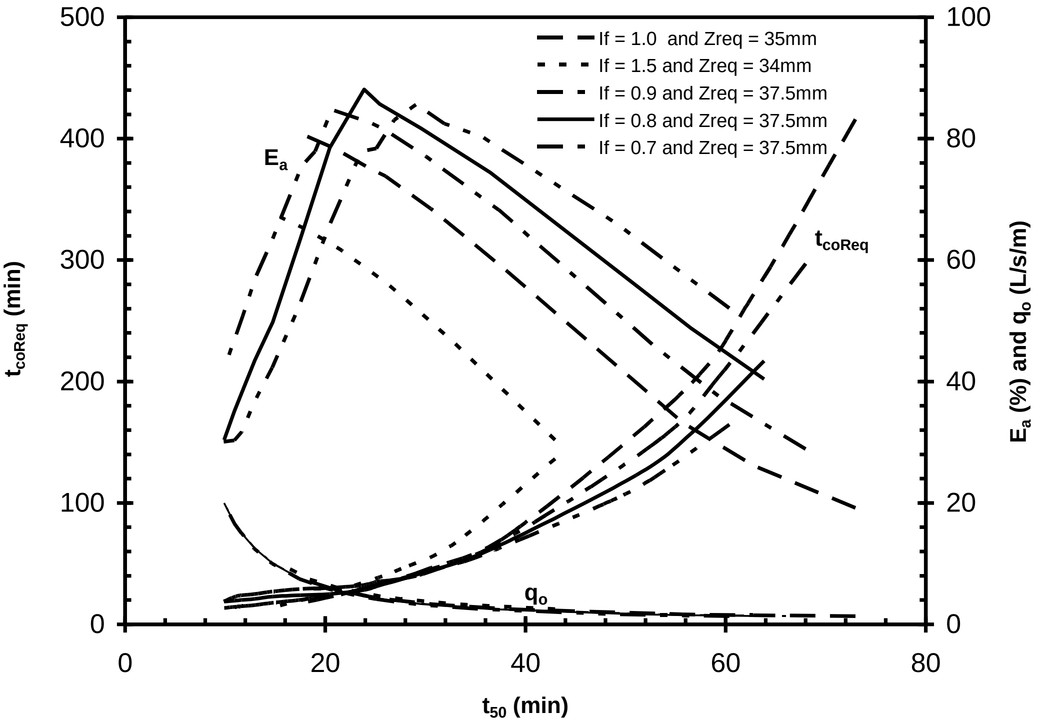
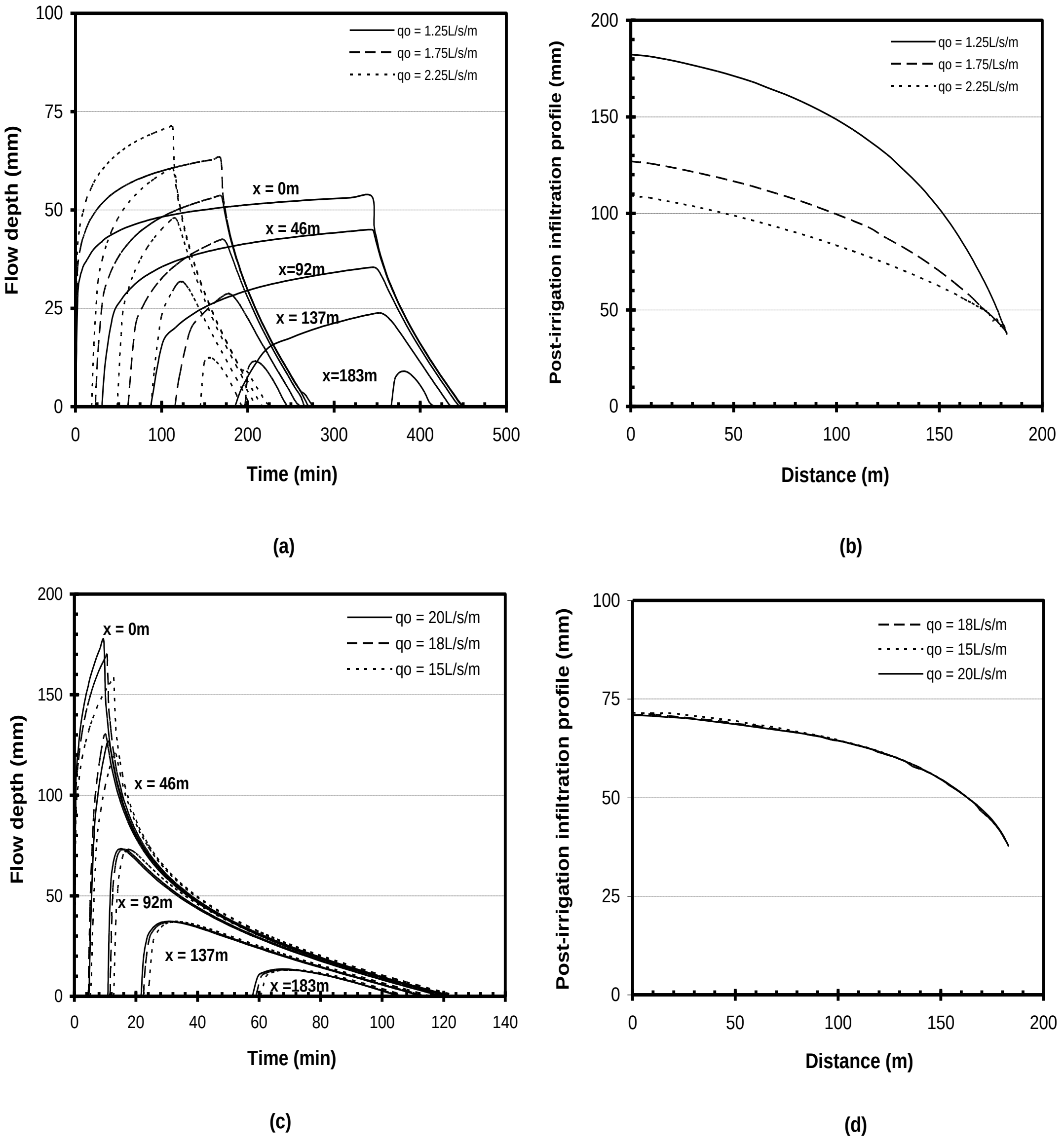


Figure 5 Ranges of t_{coReq}, E_a, and q_o as affected by soil intake characteristics: L = 183m, n = 0.08, and S_o = 0.001



(a)

(b)

(c)

(d)

Figure 6 Sensitivity of the hydraulics of a level basin (L = 183m, S_o = 0.0, n = 0.08, I_f = 0.8, and Z_{Req} = 37.5mm) to variations in inflow rate close to the lower limit of the feasible flow rate range: (a) flow depth hydrographs at five points along the basin and (b) post-irrigation subsurface profiles; Sensitivity of the hydraulics of a level basin (same data as in Figures 6a and 6b) to changes in flow rate close to the upper limit of the feasible flow rate range: (c) flow depth hydrographs at five points along the basin and (d) post-irrigation subsurface profiles

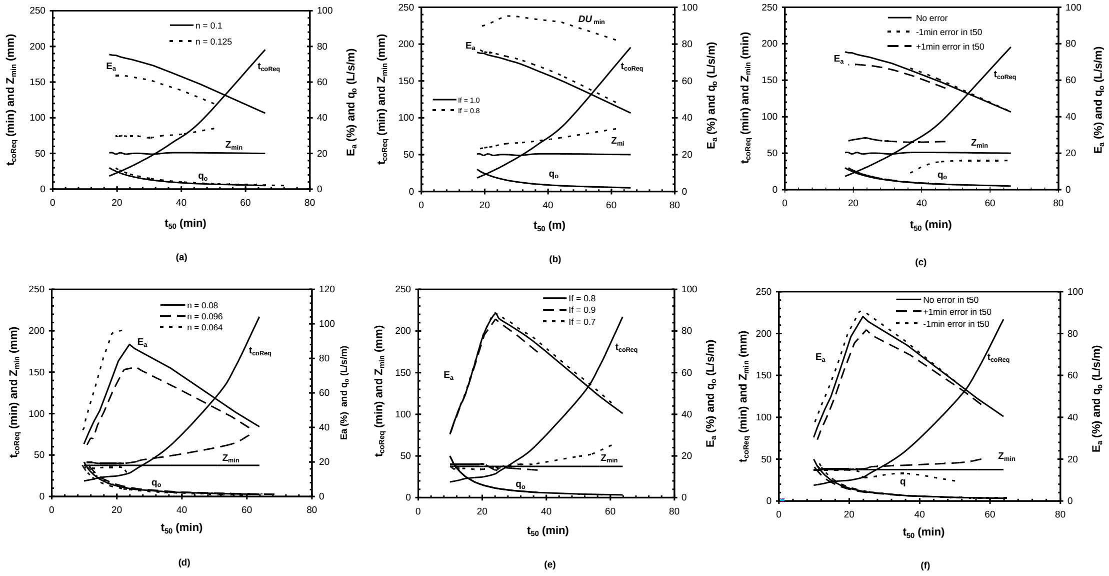
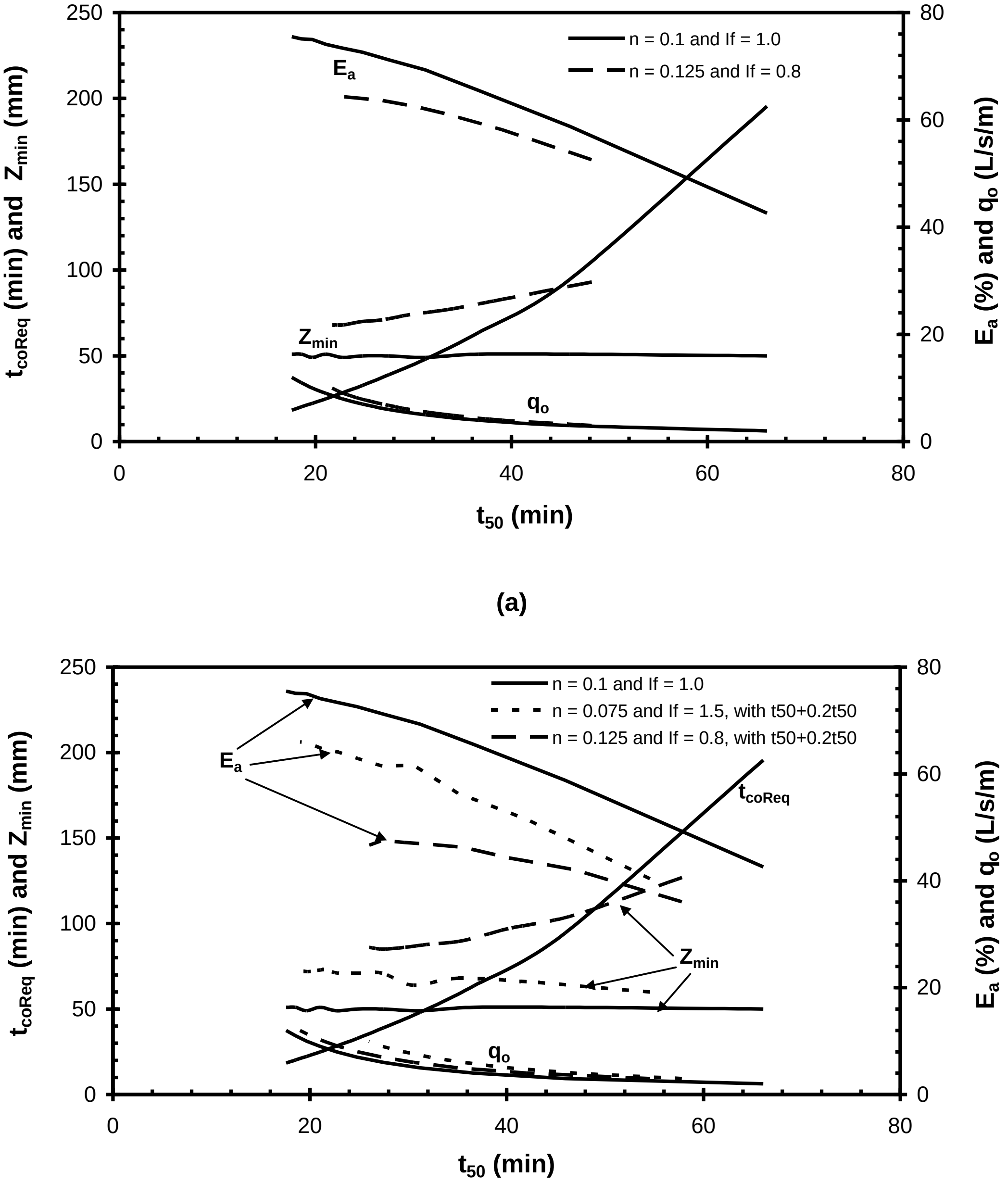


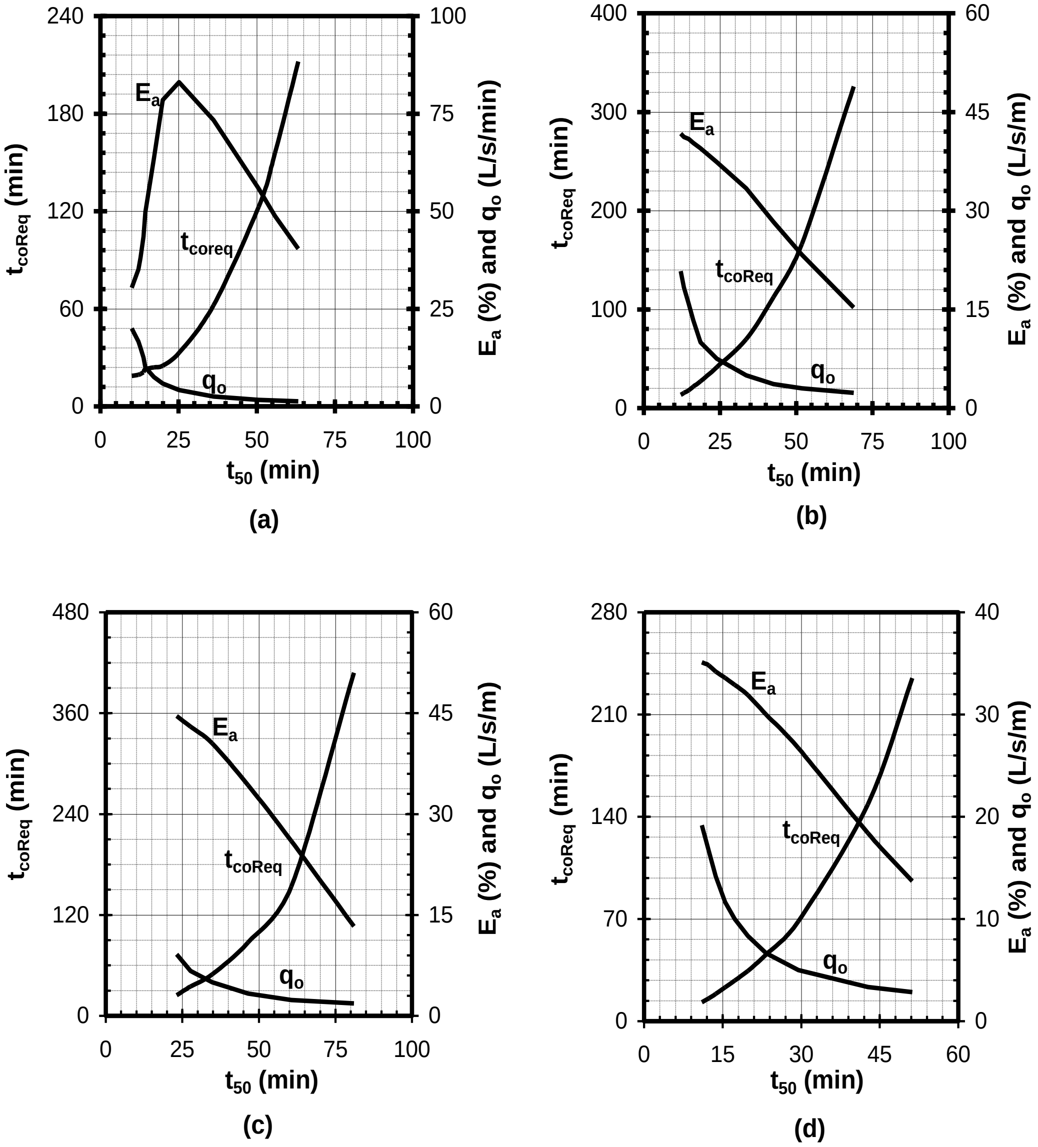
Figure 7 The sensitivity of E_a, Z_{min}, and range of t_{50} (for a basin with L = 200m, S_o = 0.0003, and Z_{Req} = 50mm) due to: (a) errors in Manning n estimates (I_f = 1.0), (b) errors in infiltration characterization (n = 0.1), and (c) errors in t_{50} measurement (n = 0.1 and I_f = 1.0); The sensitivity of E_a, Z_{min}, and range of t_{50} (for a basin with L = 183m, S_o = 0.001, and Z_{Req} = 37.5mm) due to: (c) errors in Manning n estimate (I_f = 0.8), (e) errors in infiltration characteristics (n = 0.08), and (f) errors in t_{50} measurement (n = 0.08 and I_f = 0.8)



(a)

(b)

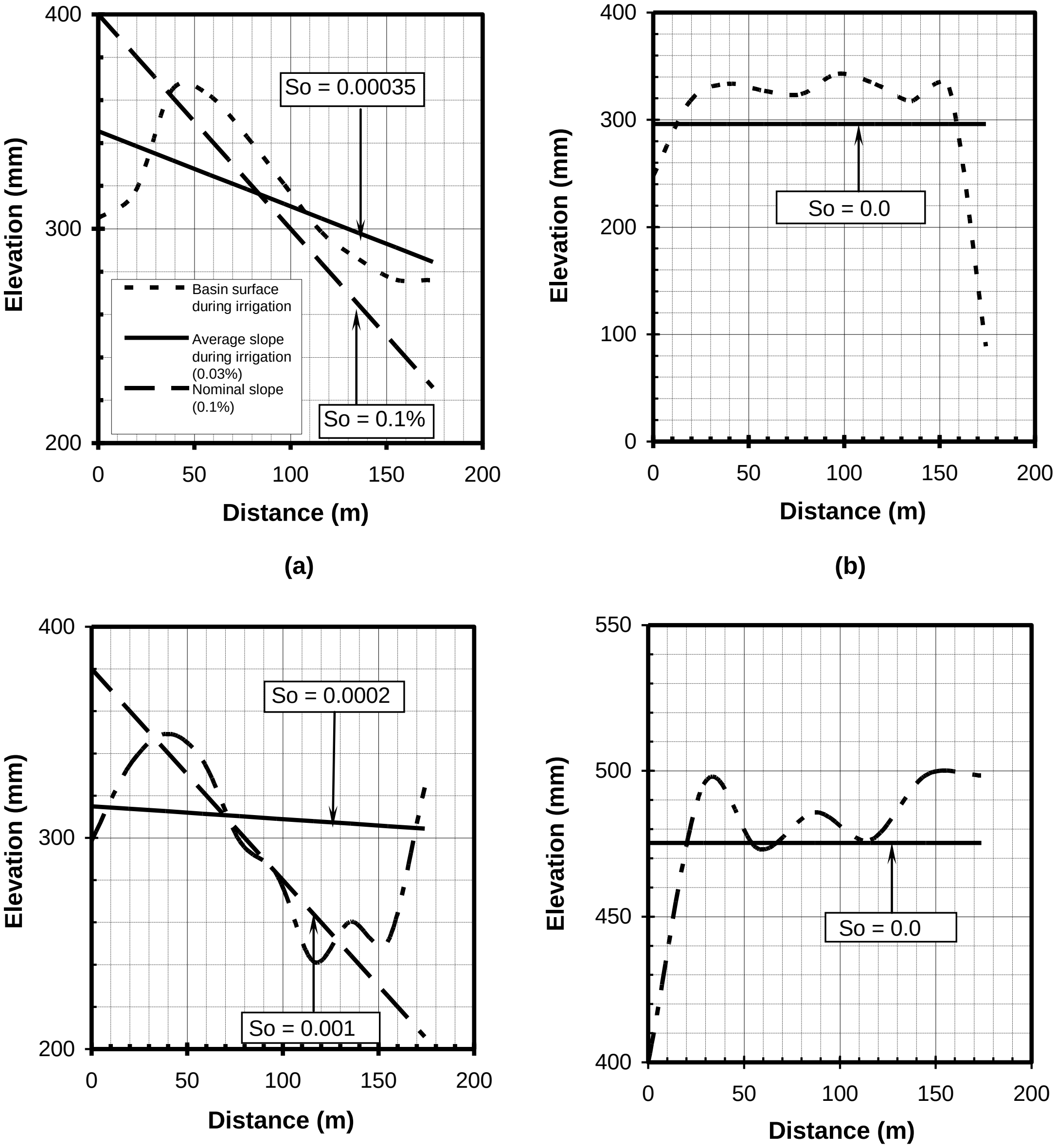
Figure 8 (a) The effect of changing Manning *n* and intake family at the same time on E_a, Z_{min}, and range of t_{50} (L = 200m, S_o = 0.0003, and Z_{Req} = 50mm) and (b) the effect of increasing t_{50} by 20% (equivalent to applying a safety factor of 20% to the measured t_{50}) on ranges of attainable E_a and corresponding Z_{min} (same data as in Figure 7a)



(a) (b)

(c) (d)

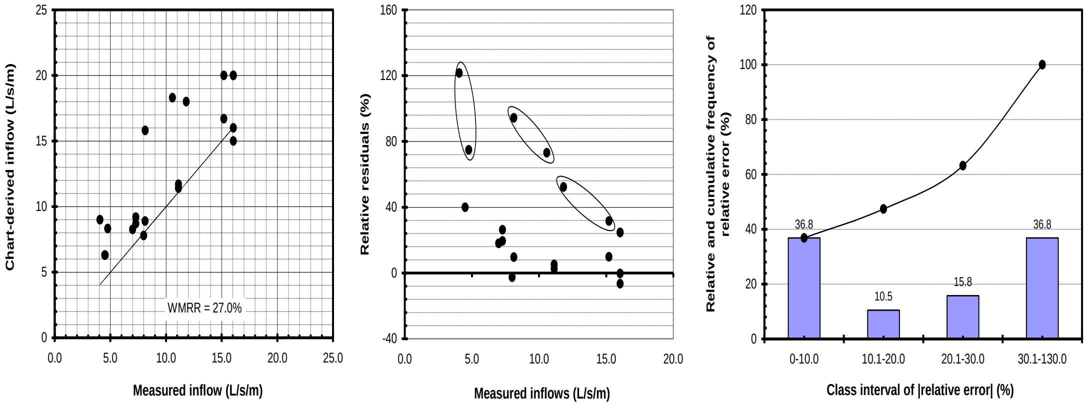
Figure 9 Cutoff time, t_{co}, unit inlet flow rate, q_o, and application efficiency, E_a, as a function of advance time to mid-field, t_{50}: (a) I_f =0.8, S_o = 0.001, n =0.08, L = 183m, Z_{Req} = 37.5mm (b) I_f = 1.5, S_o = 0.0, n = 0.08, L =206m, Z_{Req} = 34.0mm; (c) I_f = 1.5, S_o = 0.001, n = 0.2, L = 177m, Z_{req} = 34mm, and (d) I_f = 2.0, n = 0.08, S_o = 0.0, L = 183m, Z_{Req} = 30mm



(a) (b)

(c) (d)

Figure 10 Longitudinal profile along the central transect of four test basins at the UA Mesa farm: (a) Basin C, (b) basin G, (c) Basin F, and (d) basin D



(a) (b) (c)

Figure 11 (a) A comparison of measured and chart derived unit inflow rate, q_o, UA data, (b) Relative residuals between measured and chart derived q_o, UA data, (Ovals encompass outlier data points obtained from the same farms) and (c) Relative and cumulative frequency of relative residuals between measured and chart derived q_o, UA data

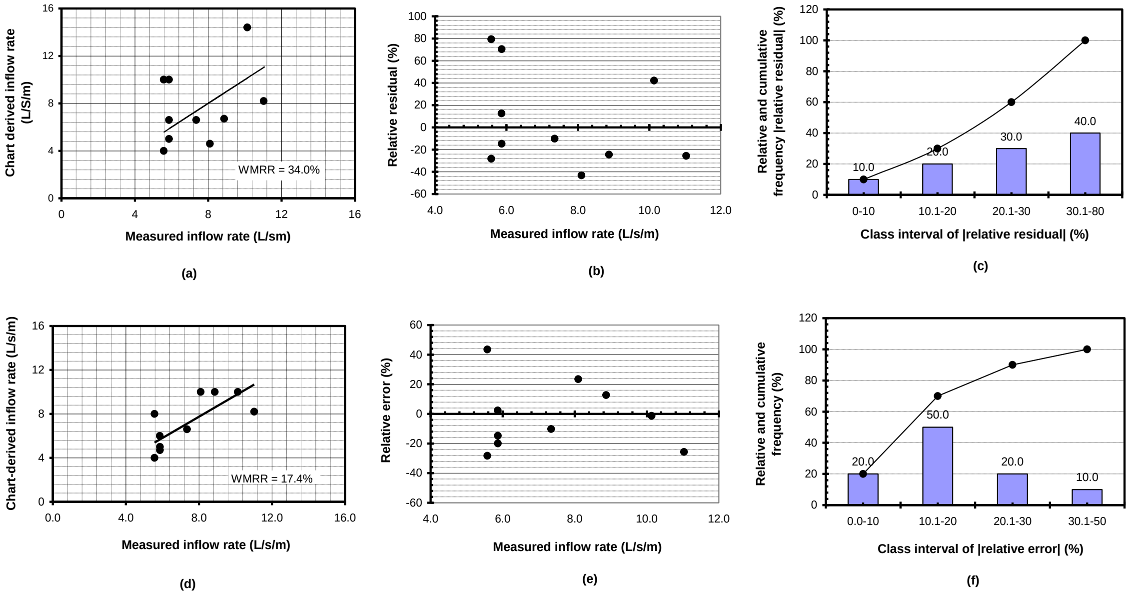


Figure 12 (a) A comparison of measured and chart derived unit inflow rate, q_o, BR data, (b) Relative residuals between measured and chart derived q_o, BR data, (c) Relative frequency histogram and cumulative frequency of residuals between measured and chart derived q_o, BR data, (d) A comparison of measured and chart derived q_o, revised parameter estimates BR data, (e) Relative residuals between measured and chart derived q_o, revised parameter estimates, BR data, (f) Relative frequency histogram and cumulative frequency of residuals between measured and chart derived q_o, revised parameter estimates, BR data

Title:

Evaluation of basin inflow cutoff criterion in the irrigation districts of southwest Arizona

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EVALUATION OF BASIN INFLOW CUTOFF CRITERION IN THE IRRIGATION DISTRICTS OF SOUTHWEST ARIZONA

Abstract: Low irrigation efficiencies persist in irrigated areas near Yuma, Arizona due to poorly designed irrigation systems, poor condition of existing systems, inaccurate delivery of flow rates, and inadequate criteria for determining irrigation cutoff to individual basins. In farms where growers lack adequate control over the water supplied to individual basins, conventional irrigation cutoff criteria, based on precise measurement of inflow rates, are ineffective. A joint research project, involving the USDA-ARS-ALARC, University of Arizona, and the USBR, is exploring the management of these systems using the time of advance to half the field length as a criterion for cutoff when inflow rates are not know accurately. Preliminary simulation studies have shown the potential benefits and limitations of such a strategy. This strategy is being tested in the field, to assess its sensitivity to uncertain system properties. This article describes the general research methodology and some of the initial simulation and field results.

Introduction

The Yuma Mesa Irrigation and Drainage District (YMIDD) and the Unit B Irrigation and Drainage District (UBIDD) of southwest Arizona supply Colorado River water to more than 8000 ha of irrigated land (Yuma Ag Council, 2008). Large basins, both level and graded, are widely used to irrigate citrus and alfalfa crops grown on the sandy soils of these irrigation districts.

Irrigation application efficiencies in the YMIDD and UBIDD have been low, averaging less than 40% (USDA-NRCS, 1987). Because deep percolation losses contribute to drainage problems and elevated nitrate-nitrogen levels in the shallow groundwater of the adjacent lower Colorado and Gila River valleys (United States Bureau of Reclamation, 1991), there is strong interest in improving irrigation practices in the area.

Basin irrigation management packages (performance charts, tables, and guidelines) were developed for the YMIDD and UBIDD (Sanchez and Zerihun, 2000a,b, 2004). These technologies were developed assuming controlled inflows and, therefore, cannot be applied to farms where inflows are inadequately measured and controlled, a prevalent problem in the area. Cutoff criterion not explicitly dependent on inflow rate may help improve the management of irrigation systems in the area.

With support from the Lower Colorado Region of the USBR, the University of California (Bali et al, 2000) developed practical inflow cutoff guidelines based on measured advance over the cracking soils of the Imperial Valley. There, flow rates are measured with satisfactory precision, but infiltration properties, needed for optimal management, are difficult to quantify *a priori* because of the cracks. Following this successful effort, Niblack (United States Bureau of Reclamation, 2005) proposed an alternative approach that does not require flow rate measurements, and instead use a real-time measurement of t_{50}, the advance time to mid-field, to estimate basin inflow cutoff in the YMIDD and UBIDD. Niblack envisioned a chart or slide-card for basins in the Yuma area such that, given t_{50}, it would provide an appropriate cutoff time, t_{coReq}, that ensures that the irrigation requirement is met in the post-irrigation infiltration distribution without excess.

Irrigation practices in the YMIDD and UBIDD are relatively uniform, in terms of the crops irrigated (alfalfa and citrus), field lengths (between 183 and 215 m), field slopes (either 0.001 or 0.0003), available inflow rate (between 7 and 12 l/s/m), and soil textures (the area is dominated by soils described as Superstition-Rosita's association [Hendricks, 1985]). Hence there is a reasonable expectation that most or all of the basins in these districts could be managed using one or two slide-card options.

The work reported here is part of a larger study, the main objective of which is to evaluate the t_{50}–t_{coReq} inflow-cutoff criteria under field conditions covering the range encountered in the YMID and UBIDD. This paper briefly describes the theoretical bases for the t_{50} –t_{coReq} criterion, related assumptions and limitations, and presents the research methodology. Also described are initial simulation and field experimental results.

The basis for the t_{50}-t_{co} inflow-cutoff criterion: assumptions and potential limitations

In 2005, an extensive (unpublished) simulation study with the SRFR model (Strelkoff et al, 1998) at the USDA-ARS Arid Land Agricultural Research Center showed that, given an irrigation requirement, Z_r, a basin length, L, and soil and crop hydraulic-parameter set (bed slope S_0, Manning roughness n, and infiltration properties, SCS intake family, I_F), the cutoff time needed to make the minimum infiltrated depth, Z_{min}, just equal to Z_r is uniquely related to the advance time to mid-field, over the feasible range of the basin inflow rate. As can be seen from Figure 1, both t_{coReq} and t_{50} are monotonic functions of unit inflow rate, q_o. With q_o eliminated between them, a functional relationship is established between t_{coReq} and t_{50}, resulting in a cutoff criterion without explicit dependence on q_o. However, the application of this cutoff criterion to any given irrigation event is predicated on the assumption that actual field conditions at the time of the irrigation event match the conditions assumed in its formulation. Figures 2a and 2b exemplify the variation in the criterion under different field conditions. The figures also show the variation of application efficiency - in anticipation of a future study aimed at optimal inflow rate recommendations.

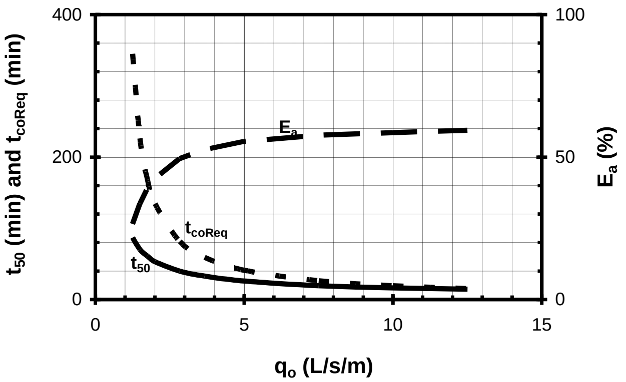
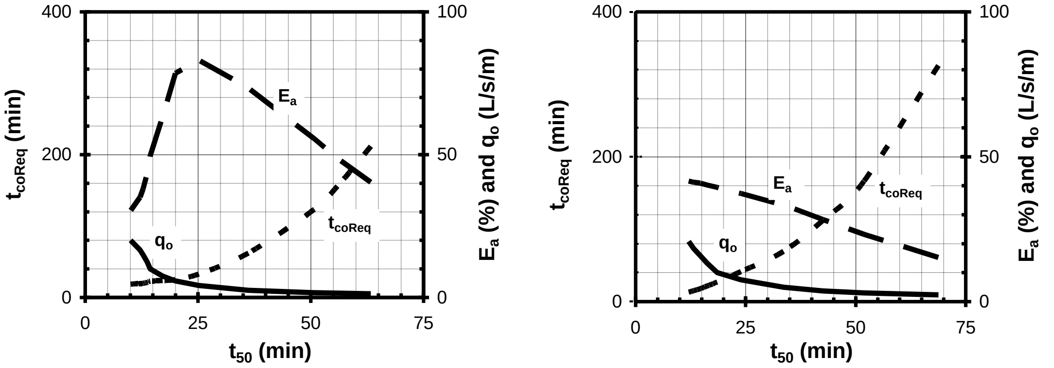


Figure 1 Example showing the relationship between basin inflow cutoff time, when $Z_{min} = Z_r$, (t_{coReq}), application efficiency, E_a, and advance time to 0.5L, t_{50}, expressed as a function of unit inflow rate, q_o,



(a) (b)

Figure 2 Example t_{50}-t_{co} charts for (a) graded basin and (b) level basin

Evaluation methodology

With the Yuma basins divided into discrete groupings of slope, roughness, and infiltration, as well as basin length and irrigation requirement, charts are prepared for each unique combination. The inflow rates in each chart vary from a minimum – that can reach field end (considering a soil of finite steady state intake rate) -- to a maximum, for which $t_{50} \leq t_{coReq}$. Field evaluation of the chart is accomplished in one or, possibly, two stages.

In the field, a chart appropriate to the particular grouping of irrigation parameters for a test basin is selected, an irrigation is initiated, and inflow is cutoff in accord with the measured t_{50} (provided the measured t_{50} is in the range of the chart's t_{50} and $t_{coReq} > t_{50}$). Measurements of stream advance and recession determine infiltration opportunity times. The minimum depth in the post-irrigation infiltration distribution, compared to the requirement, discloses the efficacy of the chart-selected cutoff time. In a corollary comparison, measured inflow is compared to the chart value corresponding to the measured t_{50}. This evaluation completes the first stage.

The optional, diagnostic second stage, aims at establishing reasons for inadequate performance of the cutoff criterion in the first stage. The most likely reason is that conditions on the ground are not reflected in the assumed conditions of the particular chart in use. This diagnostic test requires an evaluation of the extant field conditions. This, in turn, requires that the test basin be instrumented in accord with standard protocols for parameter estimation (USDA-NRCS 1997). The diagnostic stage is completed with the preparation and application of a revised chart, based on the measured field conditions.

Worthy of note, continued poor performance of the criterion, even under revised conditions, suggests that the cause lies in the spatial variability of conditions over the length of the basin, particularly the field elevations. Figure 3, for instance, shows the measured profile of the soil surface along with assumed and actual average slopes in an example basin.

Field studies

The YMIDD and UBIDD are characterized by four different soil groups identified by the USDA-NRCS intake families, 0.8, 1.0, 1.5, and 2.0. Within each soil subdivision, the two prevalent crops in the area, citrus and alfalfa, were characterized by Manning n values of 0.08 and 0.2, respectively (Sanchez and Zerihun, 2000a,b). In the future, the influence of crop growth stage and surface conditions on the Manning *n* will be taken into account via parameter-estimation techniques applied to field experiments under prevailing conditions. Two grades (0.03% and 0.1%), are standard in the YMIDD and UBIDD and were included in this study (noting that in the Yuma area, the 0.03% grade is described as a level basin).

The selected basins in each of the test sites were instrumented for the experiments. A level survey was conducted along the central transect of each test basin a day prior to the irrigation event. In addition, advance and recession trajectories, advance time to mid-field, t_{50}, cutoff time, $t_{co} = t_{coReq}$, obtained from the pertinent chart, and corresponding advance distance, L_{co}, were recorded during each irrigation event. Basin inflow was measured using long throated flumes located at the off-take from the main canal (noting the potentially high seepage losses) or using the velocity-area method, based on measured average cross-sectional velocity in the supply canal near the inlet to a basin.

Results and Discussion

Data description: So far, 26 test irrigations were conducted in citrus and alfalfa basins characterized by three of the four USDA-NRCS intake families identified in the project area: 0.8, 1.5, and 2.0. The dimensions of the test basins, measured inflow rates, Manning *n*, assumed average bed-slopes, and required depth of applications are summarized in Table 1.

In addition to the 26 data sets referred to as University of Arizona (UA) data in Table 1, 10 more (labeled BR) were obtained from the US Bureau of Reclamation Yuma Area Office. Since the BR data contain both advance and recession trajectories, they can be used to accurately estimate intake parameters. Hence, they are amenable to the more complete, two-stage, evaluation of the t_{50}-t_{coReq} cutoff criterion. The UA

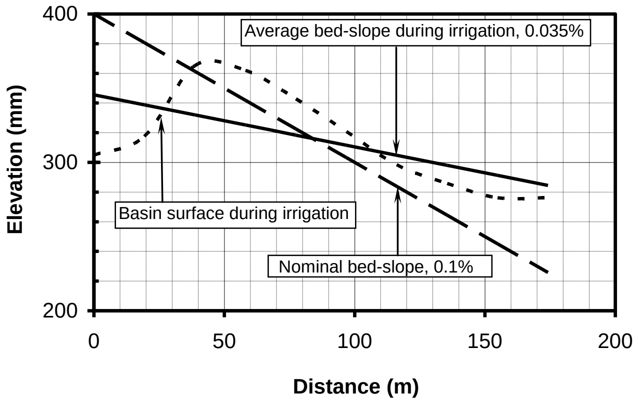


Figure 3 A comparison of longitudinal profile, assumed average bed-slope, and actual average bed-slope along the central transect of a test basin at the UA Yuma Mesa farm (Basin C, 11/08/06)

data sets, on the other hand, do not contain recession trajectories and thus are used in the descriptive evaluation phase only.

Descriptive evaluation:

A t_{50}-t_{coReq} chart was prepared for each unique combination of field condition and basin length. The 36 field trials covered by this report required a total of 17 different charts, three for basins in the 0.8 intake family, seven each for basins in the 1.5 and 2.0 USDA-NRCS intake families. Typical t_{50}-t_{coReq} charts for two basins with different lengths and soil and crop hydraulic parameters are shown in Figure 2a (I_F= 0.8, S_o = 0.001, n = 0.08, L = 183m, and Z_r = 37.5mm) and Figure 2b (I_F = 1.5, S_o = 0.0, n = 0.08, L =206m, and Z_r = 34.0mm). The field conditions assumed in preparing the 17 charts are given in Table 1.

As noted earlier, basin bed-slopes (0.0% and 0.1%) are nominal estimates based on standard grades, constructed in the last land grading operation in the basin. The values of Manning roughness coefficient used in developing the t_{50}-t_{coReq} charts were 0.08 for citrus basins and 0.2 for alfalfa basins.

Feasibility tests were conducted on all the data sets with the results summarized in Table 1. These confirm that the t_{50}-t_{coReq} charts could be used with all of the BR data sets. However, in 27% of the UA data sets, i.e., in 7 out of the 26, the measured t_{50} was less than the corresponding chart minimum and could not be assessed. Thus, 19 data sets from the UA data pool (73 percent of the total) and all 10 BR sets were considered further, in the next step of the descriptive evaluation process. Although a diagnostic evaluation could, in principle, establish reasons for the failure of 7 of the 26 UA data sets to meet the feasibility requirements, it may be, simply, that inflow rates were too high to meet the feasibility criterion. In any event, without data for estimating infiltration and roughness parameters, a diagnostic evaluation could not be performed.

Further descriptive evaluation, comparing measured and chart-derived inflow rates (based on measured t_{50}) was conducted on the data sets that were deemed feasible in the preceding analysis. The results are summarized in Figures 4a-4c for the UA data sets and in Figures 5a-5f for the BR data sets.

Figure 4a shows a comparison of measured and chart-derived unit inflow rates. A straight line with y-intercept = 0.0 and slope ≈ 1.0 is fitted to the (q_{om}, q_{oc}) data, where q_{om} = measured q_o and q_{oc} = chart-derived q_o. The low r^2 value, only 0.41, and the relatively high Weighted Mean Relative Residual (*WMRR*, Eq. 1), at 25.0%, indicate a significant discrepancy between q_{om} and q_{oc} data. This suggests that either inflow rates were inaccurately measured, or actual field conditions at the time of irrigation were significantly different from those assumed in developing the charts.

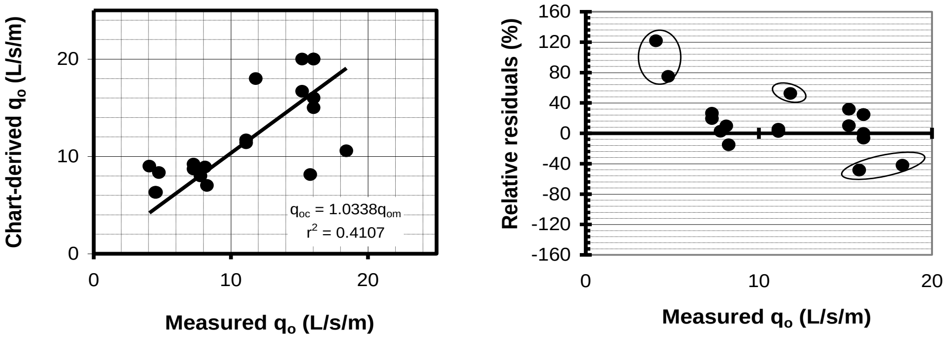
Table 1 Data used to generate t_{50}-t_{coReq} charts

	Variable and parameter Types	Units	USDA-NRCS intake family		
			0.8	1.5	2.0
			UA data set		
Ranges of variables and parameters, number of test irrigations, feasibility test	L	m	183	177-205	161-195
	W	m	33.5	35-63	51-112
	q_o	L/s/m	11.8-16	7.8-10.6	4.1-11.1
	S_o	-	level/0.001	level/0.001	level/0.001
	Z_r	mm	37.5	34	30
	n	-	0.08/0.2	0.08/0.2	0.08/0.2
	Number of test irrigations	-	13	5	8
	Is $t_{50min} \leq t_{50m} \leq t_{50max}$?	-	7	4	8
			BR data sets		
	L	m	164	183-198	183-198
	W	m	75	34-75	24-61
	q_o	L/s/m	5.6	5.6-10.1	5.9-11
	S_o	-	level/0.001	level/0.001	level/0.001
	Z_r	mm	37.5	34	30
	n	-	0.08/0.2	0.08/0.2	0.08/0.2
	Number of test irrigations	-	1	5	4
	Is $t_{50min} \leq t_{50m} \leq t_{50max}$?	-	1	5	4

UA = university of Arizona, BR = Bureau of Reclamation, L = basin length, W = basin width, q_o = unit inflow rate used in the field experiment, S_o = basin bed slope, Z_r = required depth of application, and n = Manning roughness coefficient (n = 0.2 and 0.08 are used for alfalfa and citrus basins, Sanchez and Zerihun, 2000a,b), t_{50min} = minimum t_{50} in chart, t_{50m} = measured t_{50}, and t_{50max} = maximum t_{50} in chart. Data has not yet been collected in a 1.0 intake family soil

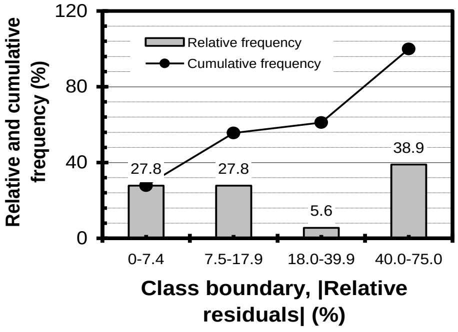
$$WMRR = \frac{1}{N}\sum_{i=1}^{N}\frac{\left|q_{oci} - q_{omi}\right|}{q_{omi}}\frac{q_{omi}}{q_{oav}}100 \qquad (1)$$

where i = data set index, N = number of data sets used in the analysis, and q_{oav} = the average of the measured inflow rates for the N data sets.



(a)

(b)



(C)

Figure 4 (a) Comparison of measured and chart-derived unit inflow rate, q_o, UA data, (b) Relative residuals between measured and chart-derived q_o, UA data, and (c) Relative and cumulative frequency of relative residuals between measured and chart-derived q_o, UA data (Ovals encompass outlier data points obtained from the same farms)

Examination of Figure 4b, a plot of relative residuals, RR, defined as

$$RR = \frac{q_{oci} - q_{omi}}{q_{omi}} 100 \qquad (2)$$

shows that, in general, there is a systematic over-prediction of basin inflow rates by the charts compared to field measurements. The systematic behavior of the residuals about the zero-mean suggests one or more of the following factors as potential sources of error: (1) errors in inflow rate measurements, generally biased low in this case, (2) assumed infiltration rates higher than actual conditions at the time of irrigation, (3) actual hydraulic resistance lower than assumed, and (4) average basin bed-slope at the time of irrigation higher than nominal bed-slope.

As can be seen from Figure 4b, the *WMRR* (25.0%) is largely accounted for by five data points that can be grouped into three clusters (see ovals), each of which came from the same test farm (Figure 4b). The systematic nature of the residuals and the fact that residuals from the same farm show the same bias with respect to the zero-mean suggest that flow measurement errors played a more important role than differences in assumed and actual field conditions. However, a more definitive analysis will have to await the collection of additional data with enough detail to allow a diagnostic evaluation.

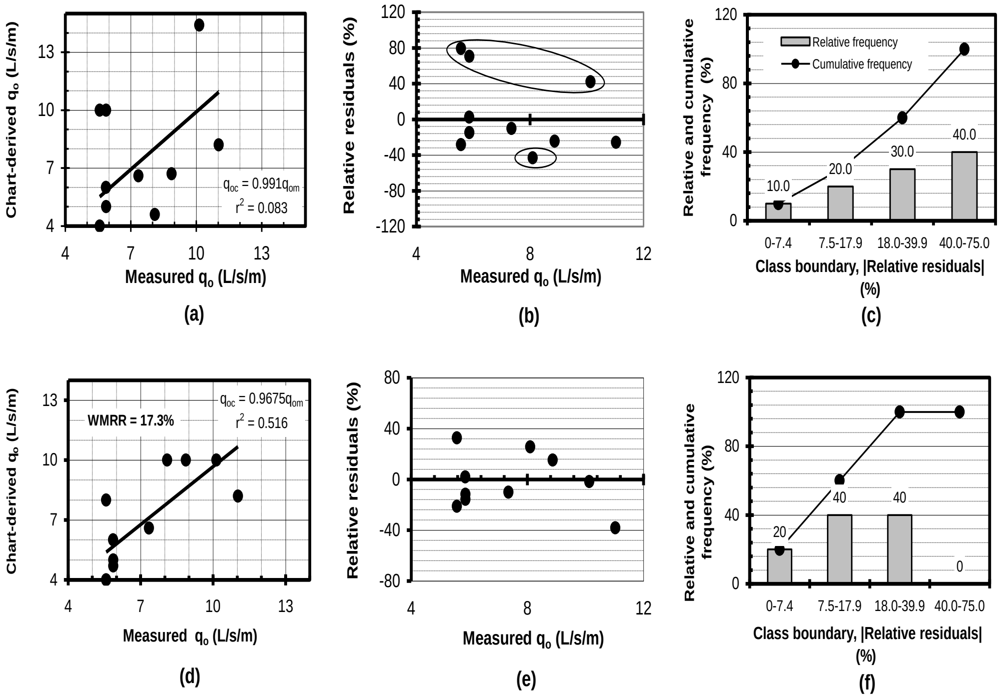


Figure 5 (a) Comparison of measured and chart-derived unit inflow rate, q_o, original BR data, (b) Relative residuals between measured and chart-derived q_o, original BR data, (c) Relative and cumulative frequency of relative residuals between measured and chart-derived q_o, original BR data, (d) Comparison of measured and chart-derived q_o, revised BR data, (e) Relative residuals between measured and chart-derived q_o, revised BR data, (f) Relative and cumulative frequency of relative residuals between measured and chart-derived q_o, revised BR data (Ovals encompass data used in diagnostic evaluation)

Figure 4c shows the frequency distribution of residuals between measured and chart-derived q_o. For about 55.0% of the test cases, chart-derived inflows are within 18.0% of measured values. About 39.0% of the test irrigations show residuals exceeding 40.0% while the residuals for the remaining 6.0% of the test irrigations range between 18.0% and 40.0%. Comparisons of measured and chart-derived q_o for the BR data sets are summarized in Figures 5a-5f. A straight line with y-intercept = 0.0 and slope ≈ 1.0 is fitted to the (q_{om}, q_{oc}) data with an r^2 of 0.083, suggesting that there is almost no correlation between measured and chart-obtained inflow rates (Figure 5a). This observation is confirmed by the relatively high *WMRR* of 33.2%, Figure 5b.

In general, the low r^2 and the relatively high *WMRR* between q_{om} and q_{oc} indicate that either inflow measurements are inaccurate or actual field conditions at the time of irrigation are significantly different from values assumed in developing the charts. An examination of Figure 5b, a plot of relative residuals versus measured q_o, shows that residuals are randomly distributed about the zero-mean and exhibit no trend, indicating the absence of a systematic error. Although inflow measurement errors cannot be discounted altogether, at least in some of the test irrigations, this does suggest that the residuals between measured and field observed q_o may largely be explained by the discrepancies between assumed and actual field conditions. Thus, a revision of soil and crop hydraulic parameter estimates, based on data collected during test irrigation events, can perhaps significantly narrow the discrepancy between measured and chart-derived q_o. Figure 5c shows that in 30% of the test irrigations, the *WMRR* is less than 18.0% and in about 40% of the cases residuals are larger than 40%. As shown in Figures 5b and 5c (see data in ovals), four test irrigations with the largest residuals (a data set each from a 0.8 and a 1.5 intake family soil and two data sets from a 2.0 intake family soil) were selected for diagnostic evaluation.

Diagnostic results:

As explained in the preceding discussion, flow rate measurements in the BR data sets were generally considered accurate. Hence the diagnostic evaluation presented here is based on a revised estimate, using field measured data, of soil and crop hydraulic parameters only. Infiltration parameters for the four selected data sets were estimated via the event-analysis functionality of WinSRFR 2.05 (Bautista et al., 2008). This utilizes the Merriam-Keller approach, a post-irrigation mass balance, to select an appropriate intake family from the USDA-NRCS intake families or to determine the coefficient in alternate infiltration functions (Bautista et al., 2008). In addition, the average bed slope and Manning roughness coefficient were adjusted to obtain a satisfactory match between model-predicted and field-observed advance and recession trajectories; infiltration opportunity times and infiltrated depths follow. Average relative error between measured and fitted intake opportunity times and infiltrated depth profiles is generally < 2.0%. For three out of the four data sets investigated here, a Philip type equation gave a better fit to the field data than the USDA-NRCS infiltration function, suggesting that not only the infiltration parameters, but also the functional form is important in characterizing infiltration.

Using the revised parameter estimates, new t_{50}-t_{coReq} charts were generated for each of the four test irrigations considered for diagnostic evaluations. A comparison of the measured basin unit inflow rates against those obtained from the revised charts is summarized in Figures 5d-5f. A revision of the parameter estimates, in only four of the data sets, result in a significant increase in r^2, from 0.083 to 0.516, while *WMRR* fell from 33.2% to 17.3%, indicating a significant improvement in the accuracy of t_{50}-t_{coReq} chart-predictions. With the revised charts, predictions and measurements agree within 18% for about 60% of the data sets; the remaining 40% of the data sets show residuals ranging from 18.0% to 40% (Figure 5f), showing a dramatic improvement in the accuracy of the t_{50}-t_{cRreq} chart predictions.

Summary and Conclusions

The t_{50}-t_{coReq} inflow cutoff criterion has a sound theoretical basis and can be expressed in terms of a simple mathematical relationship with useful practical applications in real-time surface irrigation management. The criterion is however sensitive to inaccurate representation of irrigation variables and soil and crop hydraulic parameters. Although the t_{50}-t_{coReq} criterion is not explicitly dependent on inflow rate, its evaluation does require a precise measurement of inflow. Additional research is planned to establish the practicality of the criterion, which depends upon just *how* sensitive the controlled infiltration distributions are to mismatches of field conditions.

An inference stemming from this research is that surface irrigation management problems persist not for lack of novel management concepts, but mainly due to limitations in the tools available for characterizing soil and crop hydraulic properties.

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