Chapter 12. IRRIGATION COMPONENT

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12.1 Introduction

The use of irrigation has greatly increased agricultural productivity. This is reflected in the following statistic: 18 percent of the cultivated land is irrigated but accounts for one-third of the world's food production (Stewart and Nielsen, 1990). Use of irrigation systems, however, may cause serious erosion on a significant portion of the irrigated land.

Erosion from areas irrigated using stationary sprinkler or furrow irrigation systems can be estimated using the irrigation component of the WEPP hillslope/watershed model. Rainfall, snowmelt, or irrigation events may cause erosion. The contribution of each of these events to runoff and soil loss from an area can be identified by the the hillslope/watershed model. The purpose of this chapter is to present the governing equations and methodology used in the development of the irrigation-induced erosion model.

12.2 Sprinkler Irrigation Systems

Stationary sprinkler systems considered by the model include solid-set, side-roll, and hand-move systems. Stationary sprinkler systems are assumed to provide water simultaneously to all locations within an overland flow element (OFE). Sprinkler irrigation water additions are simulated within the WEPP model using the same calculations as for water additions from rainfall. An additional user input allows modification of the effective sprinkler nozzle impact energy on the interrill detachment computed by the model (see Chapter 11). For the fixed-date scheduling option (section 12.4.3), any combination of OFE's can be irrigated on a particular day. The depletion-level scheduling algorithms, described in section 12.4.2, have the limitation of irrigating only one OFE on a particular day. The OFE irrigated is that which is most severely depleted.

12.2.1 Concurrent Events

If a rainfall event occurs on a day on which stationary sprinkler irrigation is required, the events are assumed to have identical starting times. Thus, the rainfall and irrigation hydrographs are combined. For an irrigation event with a duration less than or equal to the duration of rainfall, the model first disaggregates the rainfall into 10 intensity-duration blocks of equal volume (see Chapter 2). Starting with the first block, each intensity is then increased by the irrigation rate until the block including the time at which the irrigation stops is encountered. For this block, the intensity is increased by the average irrigation intensity for duration of the block. The final disaggregated hydrograph has 10 intensity-duration blocks with volumes that may not be equal.

For an irrigation event of duration greater than the rainfall duration, the model first disaggregates the rainfall into 9 equal volume intensity-duration blocks. The intensity of each of these blocks is then increased by the irrigation rate. A 10th intensity-duration block is established having an intensity equal to the irrigation rate. The duration of this block is defined by the irrigation duration and the time at which the 9th intensity-duration block ends. The final disaggregated hydrograph has 10 intensity-duration blocks with volumes that may not be equal.

12.3 Furrow Irrigation Systems

Erosion on furrow irrigated areas has been long recognized as a serious problem. Isrealson et al. (1946) and Mech and Smith (1967) reported erosion of up to 10.2 cm/yr near head ditches on some furrow irrigated fields. The long term effect of irrigation-induced erosion on the upper end of a field and deposition on the lower portion is vividly described by Carter (1990). Several other researchers have measured soil loss from furrow irrigated areas (Berg and Carter, 1980; Aarstad and Miller, 1981; Berg, 1984; Dickey et al., 1984; Brown, 1985; Sojka et al., 1992). Kemper et al. (1985) found that, in general, reasonable soil loss estimates could be obtained by relating erosion to a power function of flow rate and slope gradient. The empirical constants used in these equations limit their utility to a very specific set of conditions.

12.3.1 Governing Equations and Methodology

12.3.1.1 Hydrology

Infiltration into an irrigated furrow is a three-dimensional process. This process can be simplified into a two-dimensional form if infiltration opportunity time at each location within the furrow is known. Numerous models are available for estimating infiltration. The Green and Ampt (1911) equation is frequently used to predict one-dimensional flow. Considerable work has been performed to improve the original Green and Ampt equation and to predict appropriate parameters from physical characteristics of the soil (Rawls et al., 1983).

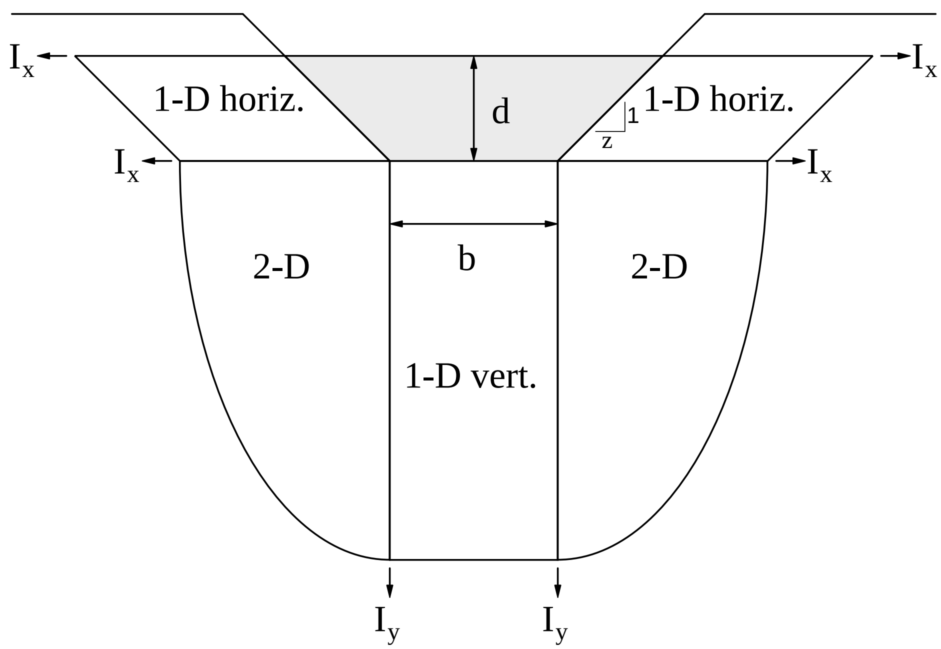

Figure 12.3.1. Two-dimensional infiltration pattern.

Fok and Chiang (1984) presented a two-dimensional infiltration function useful for furrow irrigated conditions. To use their function, Green and Ampt infiltration parameters must be known. The function assumes two regions of one-dimensional horizontal infiltration, one region of one-dimensional vertical infiltration, and two regions of two-dimensional infiltration as shown in Fig. 12.3.1. The two-dimensional regions are assumed to be quarter ellipses. Using these assumptions, cumulative infiltrated volume per unit furrow length, *Z*, is given by

$$Z = \left[2dI_x + bI_y + \left(\frac{\pi}{2}\right)I_xI_y\right]\Delta\theta \qquad [12.3.1]$$

where d = depth of flow; I_x = horizontal advance distance of the wetting front; b = bottom width of the furrow; I_y = vertical advance distance of the wetting front; and $\Delta\theta$ = net change in soil moisture content.

The equation of Green and Ampt (1911), the basis for estimating vertical advance distance, is given as

$$\frac{K_e\tau}{\Delta\theta h_y} = \frac{I_y}{h_y} - \ln\left(1 + \frac{I_y}{h_y}\right) \qquad [12.3.2]$$

where K_e = effective hydraulic conductivity; τ = infiltration opportunity time; and h_y = total head loss in the vertical direction. The equation for horizontal advance distance is given by Fok and Chiang (1984) as

$$I_x = \left(\frac{2K_eh_x}{\Delta\theta}\right)^{0.5}\tau^{0.5} \qquad [12.3.3]$$

where h_x = total head loss in the horizontal direction. The value of h_x is assumed to be equal to h_y.

Because the hydraulic model component described below must be solved numerically, it is not computationally efficient to use the Green and Ampt infiltration function which also requires a numerical solution. To improve efficiency, parameters for the Kostiakov-Lewis infiltration function are calibrated to a set of time-cumulative infiltration pairs. The Kostiakov-Lewis infiltration function, which is often used in computer models, is given as

$$Z = k\tau^a + f_o\tau \qquad [12.3.4]$$

where k, a, and f_o are empirical parameters. The value of f_o is assumed to be equal to the minimum infiltration rate over the duration of the irrigation.

The largest infiltration opportunity time used for the time-cumulative infiltration pairs is the summation of all inflow durations. The numerical solution of the Green and Ampt infiltration function is used to identify vertical advance distance for this opportunity time. This vertical advance distance is then divided by the number of time-infiltration pairs. The resulting value is used to incrementally increase vertical infiltration distance. The time required for the wetting front to advance a given distance can be determined directly using a form of Eq. [12.3.2]. From the calculated time it is possible to identify the horizontal advance distance of the wetting front and cumulative infiltration using Eq. [12.3.3] and [12.3.1], respectively. In this manner, all time-cumulative infiltration pairs can be determined from only one numerical solution of the Green and Ampt function.

The use of horizontal advance distance in equations derived by Fok and Chiang (1984) requires appropriate adjustments if horizontal wetting fronts meet prior to the completion of irrigation. Horizontal wetting fronts are assumed to meet when I_x equals a maximum horizontal distance, $(I_x)_{\max}$, given by

$$(I_x)_{\max} = \frac{W - b}{2} \qquad [12.3.5]$$

where W = distance between the center lines of irrigated furrows. A consequence of basing the definition of $(I_x)_{\max}$ on b is that, for a trapezoidal furrow, some overlapping of the horizontal wetting fronts occurs.

The water contained in the overlapping regions is assumed to move upward into ridges located between furrows. The volume of water in the overlapping regions is small compared to the total infiltrated volume. Thus, the effect of this assumption on cumulative infiltration is small. If horizontal wetting fronts are found to meet, the incremental vertical advance distance is assumed to occur over a representative width equal to *W*. This assumption is demonstrated graphically in Fig. 12.3.2.

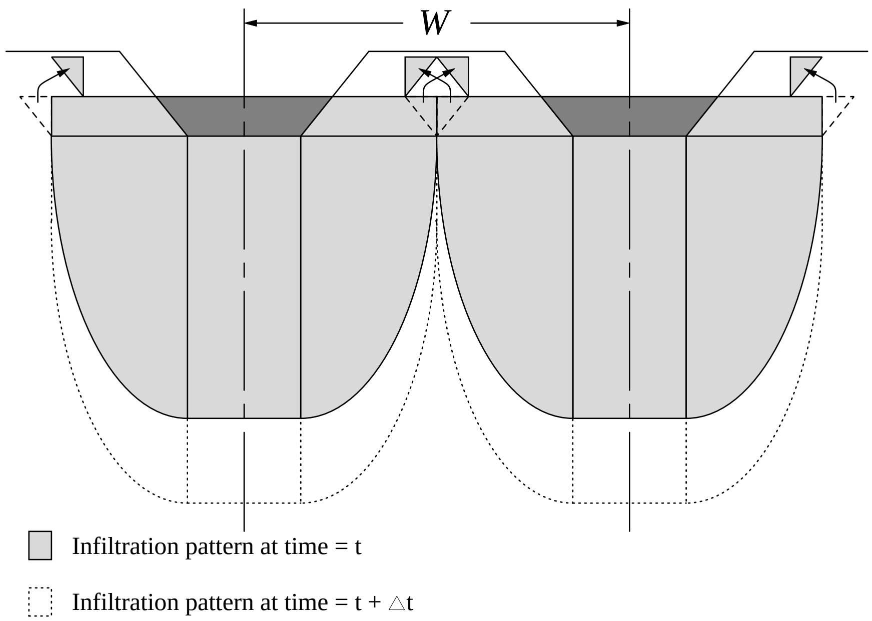

Figure 12.3.2. Infiltration after wetting fronts meet.

The Kostiakov-Lewis infiltration parameters are estimated using a least squares regression analysis of time-cumulative infiltration pairs. The technique is similar to that used for exponential functions as described by James et al. (1985). This procedure properly weights errors obtained during the least-squares analysis.

12.3.1.2 Hydraulics

The hydraulics of furrow irrigation have been modeled using a variety of approaches. Elliott et al. (1982) used a zero-inertia procedure with a specified time step to model the advance phase of an irrigation event. Kinematic wave theory with a specified time step was employed by Walker and Humpherys (1983) to simulate the entire irrigation event including surged inflow. Wallender and Rayej (1985) used a non-linear zero-inertia procedure with an adjustable time step to model irrigation events including surged inflow. Volume balance analysis with specified space intervals was employed by Wallender (1986) to simulate the advance phase of an irrigation event. Rayej and Wallender (1987) used a cumulative solution of the volume balance equation with specified space intervals to model irrigation events. A volume balance and Muskingum type storage-discharge relation with a specified time step was employed by Singh and He (1988) to simulate irrigation hydraulics. SIRMOD (Utah State University, 1989) and SRFR (Strelkoff, 1990) are computer models that use the complete hydrodynamic, zero-inertia, or kinematic wave approaches. These two computer models simulate the entire irrigation event including surge flow.

The kinematic wave approach executes rapidly and provides reasonable results for slopes greater than or equal to 0.1% (Walker and Humpherys, 1983). Rayej and Wallender (1985) decreased computer processing time and the amount of required memory by using variable time steps. In the WEPP hillslope/watershed model, the hydraulics of a complete irrigation event are modeled using principles of conservation of mass (continuity) and kinematic wave theory. A specified space interval is used to reduce processing time and the required computer memory.

The continuity equation is given as

$$\frac{\partial Q}{\partial x} = \frac{\partial A}{\partial t} = \frac{\partial Z}{\partial t} = O \qquad [12.3.6]$$

where Q = flow rate; x = downslope distance; A = cross-sectional flow area; and t = time. A kinematic wave approximation of the momentum equation is used, resulting in the assumption that

$$S_f = S_o \qquad [12.3.7]$$

where S_f = friction slope and S_o = furrow slope.

A first order Eulerian integration of Eq. [12.3.6] yields

$$\begin{aligned} &\left\{ \left[\theta\, Q_{i,\, j-1} + (1-\theta)\, Q_{i,\, j} \right] - \left[\theta\, Q_{i-1,\, j-1} + (1-\theta)\, Q_{i-1,\, j} \right] \right\} \delta t \\ + &\left\{ \left[\phi\, A_{i-1,\, j,} + (1-\phi)\, A_{i,\, j} \right] - \left[\phi\, A_{i-1,\, j-1} + (1-\phi)\, A_{i,\, j-1} \right] \right\} \delta x \\ + &\left\{ \left[\sigma\, Z_{i-1,\, j} + (1-\sigma)\, Z_{i,\, j} \right] - \left[\sigma\, Z_{i-1,\, j-1} + (1-\sigma)\, Z_{i,\, j-1} \right] \right\} \delta x = 0 \end{aligned} \qquad [12.3.8]$$

where θ = time averaging coefficient for Q; i = distance indicator for the computational grid; j = time indicator for the computational grid; δt = time increment; ϕ = space averaging coefficient for A; δx = distance increment; and σ = space averaging coefficient for Z. A simplified computational grid where δx is held constant is shown in Fig. 12.3.3.

A relationship between Q and A is given by the Chezy equation which is written as

$$Q = cAR^{1/2} S_o^{1/2} \qquad [12.3.9]$$

where c = Chezy roughness coefficient and R = hydraulic radius. An approximating power function relationship between Q and A, used in previous studies (Elliott et al., 1982; Walker and Humpherys, 1983; Rayej and Wallender, 1987), is given as

$$Q = \alpha A^m \qquad [12.3.10]$$

where α and m are empirical coefficients. The values for α and m depend on c, S_o, and the shape of the furrow (Walker, 1989). The procedures for determining α and m are similar to those used to identify the Kostiakov-Lewis infiltration parameters k and a.

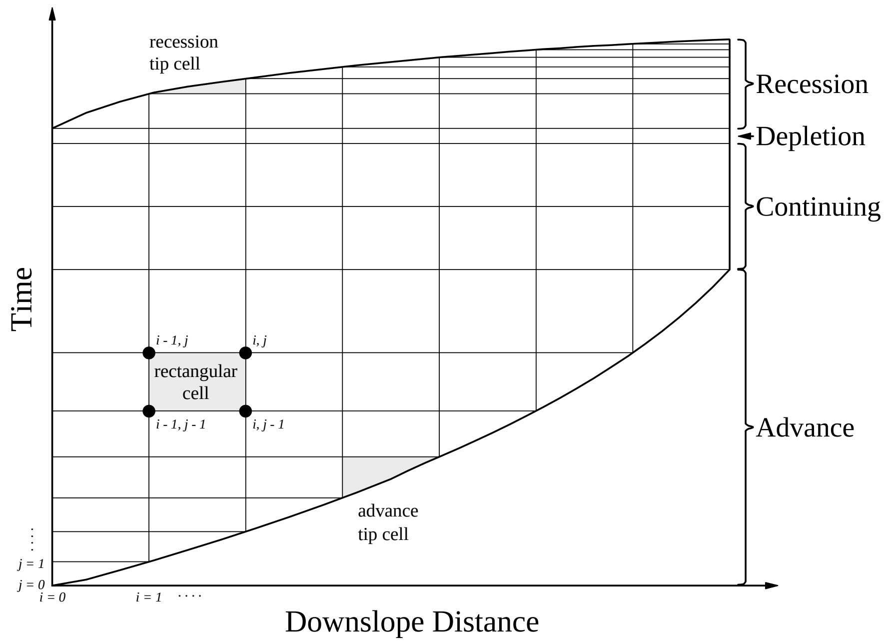

Figure 12.3.3. Typical advance curve showing time-distance computation cells.

Replacing $Q_{i,\,j}$ in Eq. [12.3.8] with the expression in Eq. [12.3.10] and rearranging yields

$$A^m_{i,\,j} + C_l A_{i,\,j} + C_2 = 0 \qquad [12.3.11]$$

where the values of C_1 and C_2, collections of variables used to simplify the kinematic wave equation, are given by

$$C_1 = \frac{(1-\phi)\delta x}{(1-\theta)\alpha\delta t} \qquad [12.3.12]$$

and

$$C_2 = -\frac{Q_{i-1,\,j}}{\alpha} + \frac{\theta}{(1-\theta)\alpha}(Q_{i,\,j-1} - Q_{i-1,\,j-1}) + \frac{\delta x}{(1-\theta)\alpha\delta t}\Big[\phi(A_{i-1,\,j} - A_{i-1,\,j-1}) - (1-\phi)A_{i,\,j-1} + \sigma(Z_{i-1,\,j} - Z_{i-1,\,j-1}) + (1-\sigma)(Z_{i,\,j} - Z_{i,\,j-1})\Big] \qquad [12.3.13]$$

Bassett et al. (1983) identify four phases for a typical irrigation event: advance, continuing, depletion, and recession. Advance is that portion of the irrigation event during which water is supplied to the furrow but has not yet progressed to the end of the field. The continuing phase begins when water reaches the end of the furrow and concludes when inflow ceases. The period between cessation of inflow and the time at which the flow area at the upper end of the furrow decreases to zero is the depletion phase. The recession phase is defined by the end of the depletion phase and the disappearance of water from the soil surface. If water does not reach the end of the furrow, the continuing phase does not occur and water may continue to progress downslope during the depletion and recession phases. The solution procedure for each phase of an irrigation event is discussed below.

Advance

The solution to Eq. [12.3.11] for each cell of the advance phase (Fig. 12.3.3) is determined using the Newton-Raphson technique. The upper end of the furrow provides boundary conditions for the left column of cells. The solution begins by estimating δt for a row of computational cells and solving for $A_{i,j}$ for each rectangular cell, starting at the upstream cell. The tip cell is analyzed after all rectangular cells in the row have been processed. For a tip cell $Q_{i-1,\, j-1}$, $Q_{i,\, j-1}$, $A_{i-1,\, j-1}$, $A_{i,\, j-1}$, and $A_{i,\, j}$ are all equal to zero and $Z_{i,\, j} = Z_{i,\, j-1}$ so $C_2 = 0$ (Eq. [12.3.11]) and Eq. [12.3.13] becomes

$$\delta t = \frac{\delta x \left[\phi A_{i-1,\, j} + \sigma (Z_{i-1,\, j} - Z_{i-1,\, j-1}) \right]}{(1-\theta) Q_{i-1,\, j}} \qquad [12.3.14]$$

This value of δt is compared to the estimate used for the rectangular cells. If the two values differ by more than an allowable amount, calculations for the row of computational cells are repeated using the new value of δt. This procedure continues until the change in δt is less than or equal to the allowable limit. By not assuming that $Z_{i-1,\, j-1} = 0$ in Eq. [12.3.14], the procedure can be applied to surge irrigated fields.

Continuing

For the continuing phase, there are no tip cells. Consequently, the model must determine a reasonable time step. The model divides the remainder of the inflow period into equal increments. These increments are as large as possible but no greater than the largest time step of the advance phase (Fig. 12.3.3). The solution technique for $A_{i,\, j}$ for each rectangular cell is the same as for the advance phase.

Depletion

When inflow is stopped, the flow rate at the upper end of the furrow goes to zero instantaneously. The flow area, however, decreases over an unknown but finite amount of time. The procedure for determining the duration of the depletion phase is based on three assumptions. The first assumption is that flow depth at the second node (Fig. 12.3.4) does not change during the depletion phase. It is next assumed that flow depth at the first node has an upper limit equal to the elevation of the upper end of the furrow minus the elevation of the first node (a horizontal profile). Finally, flow depth at the first node is assumed to not increase during the depletion phase. The smaller of the flow depths resulting from the second and third assumptions controls the hydraulic process. The two possible outcomes are presented grapically in Fig. 12.3.4.

The depletion phase is modeled using a single time step. Referring to Eq. [12.3.8], $Q_{0,\, j}$ and $A_{0,\, j}$ are equal to zero at the end of this time step. All variables with a subscript that includes $j-1$ are known from previous calculations. The assumptions given above provide values for $Q_{1,\, j}$ and $A_{1,\, j}$. Inspection of Eq. [12.3.8] shows that values for $Z_{0,\, j}$, $Z_{1,\, j}$, and δt are not known. An iterative procedure can be used to solve Eq. [12.3.8] by assuming a value for δt, calculating $Z_{0,\, j}$ and $Z_{1,\, j}$, and then determining a new value of δt. This procedure is repeated until the change in δt is less than or equal to an allowable limit. The solution procedure for the remaining rectangular cells is the same as that used for the advance phase. The model can estimate lower end advance or recession during the depletion phase. If advance occurs, Eq. [12.3.14] can be used to determine the advance distance. The nearest calculation grid boundary is shifted to this new location.

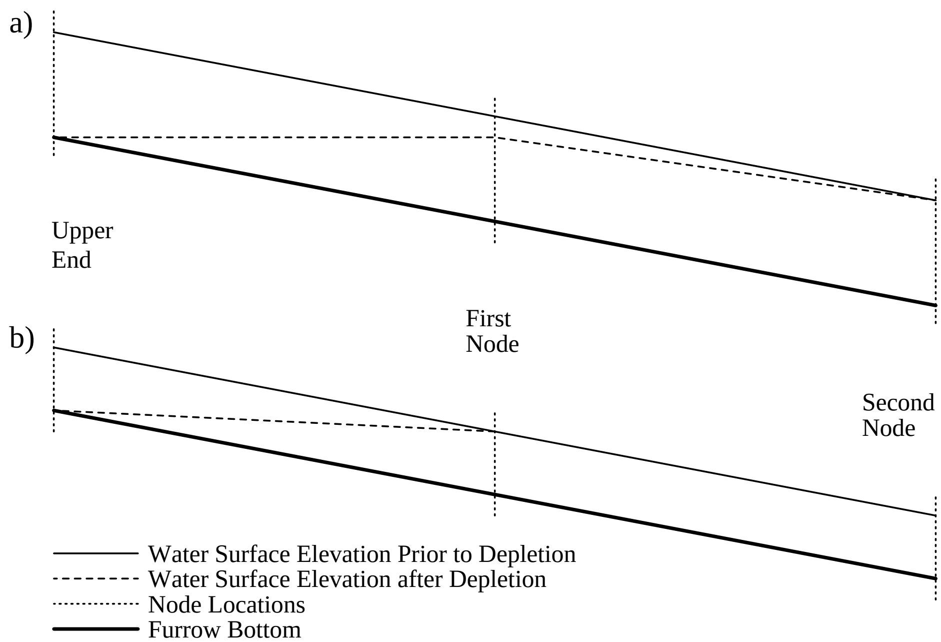

Figure 12.3.4. Limiting factors for flow depth at the first node: a) horizontal water surface profile, b) previous flow depth.

Recession

The recession process results in a tip cell configuration for the first cell being analyzed (Fig. 12.3.3). This means that $Q_{i-1,\,j-1}$, $Q_{i-1,\,j}$, $Q_{i,\,j}$, $A_{i-1,\,j-1}$, $A_{i-1,\,j}$, and $A_{i,\,j}$ are all equal to zero and $Z_{i-1,\,j} = Z_{i-1,\,j-1}$. Inspection of Eq. [12.3.8] shows that $Z_{i,\,j}$ and δt are unknown. An iterative procedure, similar to that of the depletion phase, can be used to solve for δt. The solution procedure for the rectangular cells is the same as that used for the advance phase. The model can estimate lower end advance or recession during the recession phase.

12.3.1.3 Erosion

Methods of predicting erosion on croplands using process-based models have progressed gradually since mathematical descriptions were given by Meyer and Wischmeier (1969). Foster and Meyer (1972) presented a relationship between detachment rate and the ratio of sediment load to transport capacity. Meyer et al. (1975) were the first to evaluate detachment and transport on rill and interrill areas, a critical step in the prediction of erosion due to furrow irrigation.

In this model, erosion is estimated using the approach identified in Chapter 11. This procedure uses a steady-state sediment continuity equation to describe the movement of suspended sediment. Two hydrologic variables, peak runoff rate and effective runoff duration, are required input parameters. Effective runoff duration is the ratio of runoff volume to peak runoff rate.

12.3.1.4 Inflow Management

Several approaches to furrow inflow management exist. Each inflow management technique has a unique set of advantages and disadvantages that must be considered in the selection or evaluation process. Inflow management approaches the furrow erosion model is capable of simulating are constant inflow, cut-back inflow, and surge inflow.

Constant inflow, the simplest of the three methods, is the continuous application of a single flow rate. Cut-back inflow management may also be utilized. This option uses a continuous supply of water to the furrow but the flow rate is reduced either when the water reaches the end of the field or after a selected delay period.

Surge irrigation is the most complicated of the three inflow management practices. Surge irrigation consists of a series of intermittent inflows to a furrow (Stringham and Keller, 1979). The surges may be of constant or variable duration (Israeli, 1988). During the advance surges, the final advance distances seldom correspond with the uniform space intervals initially established. This difficulty is resolved by shifting the nearest grid boundary to the location corresponding to the final advance distance. Overlapping advance and recession waves of successive surges are not considered by the model.

12.3.2 Concurrent Events

Furrow irrigation and rainfall processes are much different. Therefore, the hillslope/watershed model generally does not allow furrow irrigation to take place on a day in which rainfall occurs. The exception occurs for rainfall events with depths less than 0.001 m and peak intensities less than the effective hydraulic conductivities of all soil layers. For this situation, the rainfall event is not simulated and the furrow irrigation occurs.

12.4 Irrigation Scheduling Options

A large variety of approaches are used by irrigators for scheduling irrigation. Four scheduling alternatives are incorporated into the model to provide the user considerable flexibility in simulating these approaches. These alternatives are described below.

12.4.1 No-irrigation Option

The no-irrigation option is included so that the model may also be used for non-irrigated conditions. Also, the irrigation component is structured such that, after completion of all irrigation events, model flags are assigned values indicating the no-irrigation option is in effect.

12.4.2 Depletion-Level Scheduling

Depletion-level scheduling results when the decision to irrigate is based on soil water depletion exceeding some critical, predetermined value. Before performing calculations to determine whether irrigation is necessary, the simulation date is compared to the beginning and end of the irrigation period. If the simulation date is prior to the specified irrigation period, no irrigation will occur. If the simulation date corresponds with the last day of the irrigation period, the hillslope/watershed model checks for additional irrigation periods. When no additional irrigation periods are identified, the hillslope/watershed model then operates under a no-irrigation condition. Multiple irrigation periods are allowed for a single growing season. A potential use of this feature is to adjust the critical soil water depletion-level during a growing season to allow greater protection from water stress during periods that are critical to crop development.

If the simulation date falls within the irrigation period, calculations are performed to determine if irrigation is necessary. Current and maximum available soil water values are calculated for both the current rooting depth and for the entire soil profile. The ratio of current to maximum available soil water defines the depletion level. An irrigation will occur if either the depletion level for current rooting depth or the entire soil profile is greater than the critical value supplied by the user. The irrigation requirement, that amount of water necessary to fill the soil profile to field capacity for the appropriate rooting depth, is then calculated.

For sprinkler irrigation systems, the user specifies minimum and maximum irrigation depths as well as the percentage of the irrigation requirement to be applied. The minimum irrigation depth is necessary to prevent the frequent application of small quantities of water. This may especially be a concern at the beginning of a cropping season when a very shallow rooting depth may be present. Specifying a maximum irrigation depth can help the user prevent irrigation depths larger than a preferred amount. The percentage of the irrigation requirement to be applied allows the user to simulate the practice of leaving room in the soil profile for natural precipitation that might occur within a few days of the irrigation.

Similar calculations are performed for furrow irrigation systems. A minimum irrigation depth is used to prevent frequent applications of small irrigation amounts. A required ponding time at the lower end of the furrow must also be calculated. The required ponding time is related to the infiltration function parameters and a user-specified ratio of desired application depth at the lower end of the furrow to the irrigation requirement. Additional calculations are described below.

For constant inflow management (section 12.3.1.4), the model performs advance phase calculations until water reaches the end of the furrow. Continuing phase calculations are performed for a number of uniform time periods until the required ponding time at the lower end of the furrow is satisfied. The model then assumes water is turned off and depletion and recession phase calculations are performed.

The cut-back option also performs advance phase calculations until water reaches the end of the furrow. The second inflow event, or cut-back, begins immediately and has a duration equal to the required ponding time at the lower end of the furrow. The flow rate for the cut-back event is set equal to the infiltration rate of the furrow, 60 seconds after the time of advance, integrated over the length of the furrow.

For the surge option, the irrigation component develops the sequence of surges for the advance and cut-back phases using algorithms that mimic those in commercially available surge valve controllers. The user specifies the number of surges typically required for water to reach the end of the furrow.

12.4.3 Fixed-Date Scheduling

The fixed-date scheduling option uses known irrigation dates and amounts. This alternative is especially useful in situations where irrigation is provided at predetermined dates during the growing season or for applications using historical data. An irrigation will occur when the date of simulation is equal to the date specified for the fixed-date irrigation. Operating parameters and the date of the next irrigation are read from the input file. If no additional fixed-date irrigation events are identified, the model then moves into the no-irrigation mode.

12.4.4 Combination of Fixed-Date and Depletion-Level Scheduling

A combination of depletion-level and fixed-date scheduling is included in the model primarily to allow for pre-planting irrigation and for leaching of salts from the root zone. When this scheduling alternative is used, the model checks on a daily basis for a fixed-date irrigation. If a fixed-date irrigation is indicated, the effects of the irrigation application are identified. If a fixed-date irrigation is not indicated, then the need for irrigation using depletion-level scheduling is evaluated.

If, on the last day of a depletion-level scheduling period, no additional periods are identified, the model moves into the fixed-date scheduling mode and proceeds as described in section 12.4.3. If, after performing a fixed-date irrigation, the model finds no additional fixed-date irrigations, the model will move into a depletion-level scheduling mode and proceed as described in section 12.4.2.

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12.6 List of Symbols

Symbol	Definition	Units
A	cross-sectional flow area	m^2
a	empirical parameter for the Kostiakov-Lewis infiltration function	none
b	bottom width of the furrow	m
c	Chezy roughness coefficient	$m^{0.5} \cdot s^{-1}$
C_1	collection of variables used to simplify kinematic wave equations	$m^{(2m-2)}$
C_2	collection of variables used to simplify kinematic wave equations	m^{2m}
d	depth of flow	m
f_o	empirical parameter for the Kostiakov-Lewis infiltration function	$m^2 \cdot s^{-1}$
h_x	total head loss in the horizontal direction	m
h_y	total head loss in the vertical direction	m
i	subscript indicating distance for a space-time grid	none
I_x	horizontal advance distance of the wetting front	m
$(I_x)_{\max}$	maximum horizontal advance distance of the wetting front	m
I_y	vertical advance distance of the wetting front	m
j	subscript indicating time for a space-time grid	none
k	empirical parameter for the Kostiakov-Lewis infiltration function	m^2/s^a
K_e	effective hydraulic conductivity	$m \cdot s^{-1}$
m	empirical exponent in flow rate - flow area relationship	none
Q	flow rate	$m^3 \cdot s^{-1}$
R	hydraulic radius	m
S_f	friction slope	$m \cdot m^{-1}$
S_o	furrow slope	$m \cdot m^{-1}$
t	time	s
W	distance between center lines of irrigated furrows	m
x	downslope distance	m
Z	cumulative infiltration per unit furrow length	m^2
z	furrow side slope	$m \cdot m^{-1}$
α	empirical coefficient in flow rate - flow area relationship	$m^{(3-2m)}/s$
$\Delta\theta$	net change in soil moisture content	$m^3 \cdot m^{-3}$
δt	time increment	s
δx	distance increment	m
θ	time averaging coefficient for flow rate	none
σ	space averaging coefficient for cumulative infiltration	none
τ	infiltration opportunity time	s
ϕ	space averaging coefficient for cross-sectional flow area	none