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Simple Model of Border Irrigation

By D. B. Jaynes[1]

Abstract: This paper describes a numerical model for irrigation of sloping and level borders. The model solves the differential form of the combined equations for the conservation of mass and momentum with the acceleration terms removed. A finite difference scheme is used with the depth gradient term expressed explicitly and averaged over the entire wetted border. The model is stable and inexpensive to run. Model results compare well with measured advance and recession times. Predicted ponding depths during infiltration and total water infiltrated over the border also agree well with observed behavior. The model gives results equivalent to those of other existing zero-inertia and fully dynamic models but is much simpler to program and requires less computer code.

Introduction

One of the first priorities in agriculture today is the development of irrigation designs that are more efficient in the use of both water and energy resources for a variety of crops and farming practices. An integral part of this research is the development of mathematical models for the accurate description of the irrigation process. These models can be used to develop and refine new irrigation technologies, rapidly and inexpensively test new designs for a wide range of conditions, and prepare economic assessments of different designs. However, to be useful, models must accurately represent the interplay between soil hydraulic properties, irrigation system design, and surface water hydraulics.

Border irrigation systems, including level basins, represent an important class of irrigation systems widely used in agriculture today. These systems are flexible and their simulation has been the objective of an extensive modeling effort in recent years. Border irrigation can be considered a problem of non-steady water flow in one dimension. Treating the border as a wide channel, we can accurately describe the flow with the Saint-Venant equations (4). These equations consist of an equation describing the conservation of mass

$$-\frac{\partial q}{\partial x} - w = \frac{\partial h}{\partial t} \quad \text{(1)}$$

and a second equation describing the conservation of momentum

$$\frac{1}{g}\frac{\partial v}{\partial t} + \frac{v}{g}\frac{\partial v}{\partial x} + \frac{\partial h}{\partial x} = S_0 - S_f + \frac{vw}{gh} \quad \text{(2)}$$

In these equations h = the water depth (L); t = time (T); q = the flux per unit width (L^2T^{-1}); x = distance down the reach (L); w = the infil-

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tration rate (LT^{-1}); g = the acceleration of gravity (LT^{-2}); v = the velocity (LT^{-1}) where $q = vh$; S_0 = the slope of the border (LL^{-1}); and S_f = the friction slope (LL^{-1}). Current models for border irrigation can be grouped into four classes: volume balance, full dynamic, kinematic, and zero-inertia. Details of these approaches can be found in a review by Bassett et al. (2), as well as in other places and will not be reviewed in detail here. Briefly, volume balance approaches solve Eq. 1 by assuming predetermined shape factors for the surface and infiltration profiles (9). These methods give satisfactory results for many problems but can be applied to only a narrow range of conditions (16). Full dynamic models (3,10) solve the complete Saint-Venant equations. These models are accurate over a wide range of conditions but require considerable computation time (16). Both kinematic and zero-inertia methods simplify the momentum equation by assuming that the acceleration (inertial) terms are negligible and therefore can be ignored. For most border systems, where Froude values are below 0.3 (5), this is a reasonable assumption (11). Kinematic solutions (13,14,18) further simplify the equations by assuming that the water depth gradient, $\partial h/\partial x$, is also negligible in Eq. 2 and thus set the bottom slope equal to the friction slope. Although both procedures give acceptable results for a wide range of conditions, kinematic solutions are not applicable to level or blocked borders and may not be adequate during the initial stages of recession because of the steep depth gradients developed then. Zero-inertia methods (16) therefore seem to be the best approach for modeling border irrigation over a wide range of conditions.

In this paper a method for solving the conservation of mass equation and the zero-inertia form of the momentum equation is described. The model (designated Z.I.D.) solves the differential form of the combined Eqs. 1 and 2. Results of the model are compared to earlier models and to field data for typical border irrigation conditions.

Model Description

In the zero-inertia form of the momentum equation, we assume that the acceleration terms and the term representing the dynamic effects of infiltration are negligibly small and can be set equal to zero. Eq. 2 then becomes

$$\frac{\partial h}{\partial x} = S_0 - S_f \qquad (3)$$

where the depth, h, depends on time as well as distance. The friction slope, S_f, is defined by (4)

$$S_f = \frac{q^2}{C^2 h^3} = \frac{q^2 n^2}{C_u^2 h^{10/3}} \qquad (4)$$

where C = the Chezy C ($L^{1/2}T^{-1}$); C_u = a units conversion factor ($L^{1/3}T^{-1}$); and n = the dimensionless Manning roughness factor. Substituting Eq. 4 into Eq. 3 and solving for q gives:

$$q = \left(S_0 - \frac{\partial h}{\partial x}\right)^{1/2} \frac{C_u}{n} h^{5/3} = C_t h^{5/3} \qquad (5)$$

which is in the form of the Manning equation with the depth gradient retained in the Manning coefficient, C_t ($L^{1/3}T^{-1}$). Substituting Eq. 5 into Eq. 1 gives a single, nonlinear, partial differential equation for border irrigation with C_t spatially dependent as defined in Eq. 5

$$-\frac{\partial(C_t h^{5/3})}{\partial x} - w = \frac{\partial h}{\partial t} \quad (6)$$

In this model we solve Eq. 6 by dividing the border into r reaches of arbitrary length [Fig. 1(a)]. By letting the water depth for each reach equal the average of the depths at the ends of each reach and by taking the backward derivative of both the time and space derivatives, we can write Eq. 6 in a finite difference form for reach i

$$\frac{C_{t_{i-1}} h_{i-1}^{*5/3} - C_{t_i} h_i^{*5/3}}{\Delta x_i} - w_i = \frac{h_{i-1}^* + h_i^* - h_{i-1} - h_i}{2\Delta t} \quad (7)$$

where the flux into (q_{i-1}^*) and out of (q_i^*) reach i is represented by $C_{t_{i-1}} h_{i-1}^{*5/3}$ and $C_{t_i} h_i^{*5/3}$ respectively, Δx_i is the length of the reach, and h_i and h_{i-1} are the depths of water at the outlet and inlet ends of the reach, respectively. The starred depth terms are for the end of the time step Δt and the unstarred terms are for the beginning of the time step. If we use an explicit form for C_t and solve for each reach successively, starting at the border inlet and progressing down the flow path, the only unknown in Eq. 7 is h_i^* which is solved for iteratively:

$$h_i^* = \frac{2\Delta t C_{t_{i-1}} h_{i-1}^{*5/3} - 2V_i + \Delta x_i(h_{i-1} + h_i - h_{i-1}^*)}{\Delta x_i + 2\Delta t C_{t_i} h_i^{*2/3}} \quad (8)$$

where V_i = the volume infiltrated per unit width during Δt which equals $\Delta t \Delta x_i w_i$ and is described later.

The solution scheme represented by Eq. 8 is possible because we assume the water moves across the border in only one direction, away from the inlet. Thus, the flow is not affected by downstream conditions except through the C_t term. Therefore, reversals in the direction of flow cannot be handled by the model described here, and conditions where this may occur such as the arrival of the advancing stream to the end of a blocked border must be handled in a different manner described below.

Manning Coefficient

From Eq. 5, the Manning coefficient, C_t, depends on the bottom slope, Manning roughness coefficient, and depth gradient. Assuming that only the depth gradient is a function of time, we can calculate the time dependent Manning coefficient, C_t, by using an explicit form of Eq. 5

$$C_{t_i} = \frac{C_u}{n_i}\left(S_0 - \frac{h_m - h_d}{l}\right)^{1/2} \quad (9)$$

where h_d and h_m are two known depths at the beginning of the time step separated by distance l. In this model h_d = the depth of water at the inlet end of the first water covered reach and h_m = the water depth at the advancing front or at the end of the border once the advance phase is completed. This averaging of the depth gradient is used to avoid stability problems caused by using explicit values of the gradient found from local differences in the water depth (14). If the Manning roughness coefficient, n_i, does not vary over the border, Eq. 9 gives the same Manning coefficient for each reach. In effect, we are replacing the Manning coefficient which we would expect to vary over the border, increasing near the wetting front, with an average value for all reaches. Eq. 9 shows that the depth gradient term will make a dominant contribution to C_i at the start of irrigation but will become less important as the wetting front advances (l increases).

Infiltration

The infiltration term for each reach, V_i, represents a value averaged over both the reach distance, Δx, and the time increment, Δt, since the reach is not wetted uniformly but from the inlet end first. In this model, a derivation for V similar to the scheme described by Clemmens (7) and Strelkoff (15) is followed. For the initial wetting of the first reach, the infiltrated volume per unit width, V_1, is found from

$$V_1 = \int_0^{x_1} I_1(\tau)dx = \int_0^{\Delta x_1} I_1(\tau)dx \quad \text{(10)}$$

where I_1 = the depth infiltrated (L).

Here we will assume that I_1 can be represented by the modified Kostiakov equation (8)

$$I_i = S_i\tau^{b_i} + A_i\tau \quad \text{(11)}$$

where τ represents infiltration opportunity time. We will also assume that the wetting front moves across the reach at a uniform linear rate expressed by

$$\left.\frac{dx}{d\tau}\right|_{\Delta x_i} = c_1 \quad \text{(12)}$$

Substituting Eqs. 11 and 12 into Eq. 10 gives

$$V_1 = \int_0^{t_1} c_1(S_1\tau^{b_1} + A_1\tau)d\tau \quad \text{(13)}$$

where t_1 = the time for the advancing front to reach x_1. Integrating and factoring out $x_1 = \Delta x_1 = c_1\tau_1$ gives for the infiltration volume in reach 1

$$V_1 = \Delta x_1\left(\frac{S_1}{b_1 + 1} t_1^{b_1} + \frac{At_1}{2}\right) \quad \text{(14)}$$

In general, the infiltration volume per unit width can be found for any time increment and reach. The wetting front first arrives at reach i at t_{i-1} and travels Δx_i in Δt_i where $t_i = t_{i-1} + \Delta t_i$. For any time increment, $\Delta t_j = t_j - t_{j-1}$, after t_{i-1}, the volume of water that infiltrates reach i during this time can be found from

$$V_i|_{\Delta t_j} = \int_{t_j - t_{i-1} - \Delta t_j}^{t_j - t_{i-1}} c_i(S_i\tau^{b_i} + A_i\tau)d\tau - \int_{t_j - t_i - \Delta t_j}^{t_j - t_i} c_i(S_i\tau^{b_i} + A_i\tau)d\tau \quad (15)$$

which can be written as

$$V_i|_{\Delta t_j} = \int_{t_j - t_i}^{t_j - t_{i-1}} c_i(S_i\tau^{b_i} + A_i\tau)d\tau - \int_{t_j - t_i - \Delta t_j}^{t_j - t_{i-1} - \Delta t_j} c_i(S_i\tau^{b_i} + A_i\tau)d\tau \quad (16)$$

Integrating Eq. 16, substituting Δx_i for $c_i\Delta t_i$, and recognizing that the second term on the right-hand side of Eq. 16 is equal to the total volume of water infiltrated into the reach from the start of irrigation to t_{j-1} and is known from the previous time steps, we thus have

$$V_i|_{\Delta t_j} = \Delta x_i \left[\frac{S_i}{b_i + 1}\left(\frac{t_j - t_{i-1}}{\Delta t_i}\right)^{b_i+1} \Delta t_i^{b_i} + \frac{A_i}{2}\left(\frac{t_j - t_{i-1}}{\Delta t_i}\right)^2 \Delta t_i \right.$$
$$\left. - \frac{S_i}{b_i + 1}\left(\frac{t_j - t_i}{\Delta t_i}\right)^{b_i+1} \Delta t_i^{b_i} - \frac{A_i}{2}\left(\frac{t_j - t_i}{\Delta t_i}\right)^2 \Delta t_i\right] - \sum_{\xi=0}^{j-1} V_i|_{\Delta t_\xi} \quad (17)$$

which is used to calculate the value of V_i in Eq. 8.

Boundary Conditions

The solution of Eq. 8 depends on the irrigation phase. During advance the inlet or upper boundary condition is (from Eq. 5):

$$q_0 = C_{t_0} h_0^{*5/3} \quad (18)$$

$$\text{or} \quad h_0^* = \left(\frac{q_0}{C_{t_0}}\right)^{3/5} \quad (19)$$

where q_0 = the water application rate per unit width of border (L^2T^{-1}). Each successive water depth can then be found from Eq. 8. The lower boundary condition during advance is $h_m^* = 0.0$; however, the length of the end reach is unknown. The length is found by rearranging Eq. 7 to solve for Δx_m. Since $h_m^* = h_m = h_{m-1} = 0.0$ for this reach we have

$$\Delta x_m = \frac{2\Delta t C_{t_{m-1}} h_{m-1}^{*5/3}}{(h_{m-1} + 2\Delta t w_m)} \quad (20)$$

A slight modification on this scheme is used for calculating the initial advance across the first reach. For this case, Eqs. 19 and 9 are solved iteratively for h_0^* with $h_m = 0$ and $h_d = h_0^*$, in effect using an implicit representation for C_{t_0} at this time step. This method affords greater stability in the solution when the boundary condition undergoes a rapid change due to the start of water application.

During the storage and recession phases, the lower boundary condition is no longer zero water depth. Instead, we allow the depth gradient at the end of the border to go to zero, making the runoff rate proportional to the slope (Eq. 5). This method of handling the lower boundary is somewhat arbitrary since it depends on conditions beyond the border's limits which are seldom specified (e.g., sudden drop in elevation into a conveyance ditch) and precludes significant runoff from un-

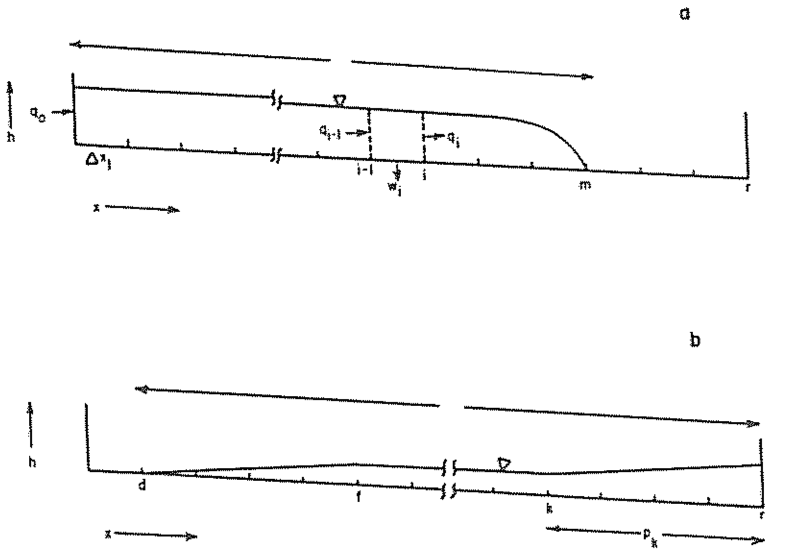

FIG. 1.—Idealized Profile of Irrigated Border: (*a*) Advance Phase; (*b*) Recession Phase. Parameters Defined in Test

blocked level borders. However, for most sloping borders, this approach is a good approximation to the lower boundary condition, and unblocked level borders are seldom found in practice.

For blocked borders, a zero flux boundary condition is used at the end of the border during storage and recession. However, Eq. 8, with C_t found explicitly from the previous time step, is unsatisfactory for calculating the water depth in the lower reaches where water is backing up. This is because the water depth increases rapidly at the border end, causing a reversal in the surface water elevation gradient, and thus, direction of flow which cannot be handled by this simple model. To account for blocked borders we instead assume that for the lower portion of the border where water is backing up [reaches k through r, Fig. 1(*b*)] the surface water elevation has a zero gradient, and thus, the water is no longer flowing. A volume balance is maintained for these reaches where the volume of water flowing into the stagnant reaches equals the change in surface and infiltrated water volumes for the reaches over any time increment. In effect, this approach is analogous to letting C_t decrease to zero as the water backs but letting the surface water redistribute instantly to maintain a zero surface water elevation gradient.

In our notation, the volume balance for these reaches can be written as:

$$C_{t_{k-1}} h_{k-1}^{*5/3} = \sum_{i=k}^{r} \frac{\Delta x_i[h_i^* + h_{i-1}^* - (h_i + h_{i-1})]}{2\Delta t} + \sum_{i=k}^{r} w_i \Delta x_i \quad \ldots\ldots\ldots\ldots\ldots (21)$$

Remembering that the surface water elevation is horizontal over these reaches, we can express all unknown water depths in terms of h_r^*, the depth at the end of the border. Eq. 21 can then be rearranged and solved explicitly for h_r^*.

$$h_r^* = \frac{2\Delta_t C_{I_{k-1}} h_{k-1} - 2s_V + s_h - s_p}{a} \quad \text{(22)}$$

$$\text{with} \quad s_V = \sum_{i=k+1}^{r} V_i \quad \text{(23)}$$

$$s_h = -\Delta x_k h_{k-1} + \sum_{i=k}^{r} \Delta x_i (h_i + h_{i-1}) \quad \text{(24)}$$

$$a = \Delta x_k + \sum_{i=k+1}^{r} 2\Delta x_i \quad \text{(25)}$$

$$\text{and} \quad s_p = \sum_{i=k+1}^{r} S_0 p_i (\Delta x_i + \Delta x_{i-1}) \quad \text{(26)}$$

where p_i = the distance from reach i to the end of the border.

Since no backward flow is allowed in the model, the position of the first ponding reach, k, is determined by checking that the surface-water elevation at k is less than or equal to that at $k - 1$ and decreasing k when this is no longer true. For the rest of the border, during the recession phase, Eq. 8 is used to calculate the water depths. However, the upper boundary condition changes at this point since $q_0 = 0.0$ and Eq. 19 is no longer valid. Instead, the surface-water elevation at the head of the border is assumed to become horizontal while the volume balance is maintained, requiring the volume of water leaving the first reach to equal the change in surface and infiltrated water in the reach for any time increment. This condition can either propagate down the border or dissipate, depending on the hydraulic conditions of the irrigation. While a horizontal surface-water elevation condition exists near the inlet, the water depth over this portion of the border [reaches d through f, Fig. 1(b)] is found in a manner similar to that for a blocked border. The depth, h_f^*, is calculated from a volume balance equation, and the position of f is found by requiring that the surface-water elevation at f be higher than or equal to that at $f + 1$. This method allows for a smooth draining of the border after a sudden change in the boundary condition.

Results

Four aspects of a border irrigation model can be readily tested: the predicted advance and recession times, infiltration and runoff volume, and surface water depth. Ideally, we would like to test the model against observed irrigation behavior over a wide range of conditions. However, this kind of data is rarely available in the literature. Instead, we will compare the model with measured results and several earlier models for four well documented border irrigations.

In the first example the irrigation of a blocked border described by Clemmens (6) was simulated (McDonnell Farm, #6, irrigated on 6/9/

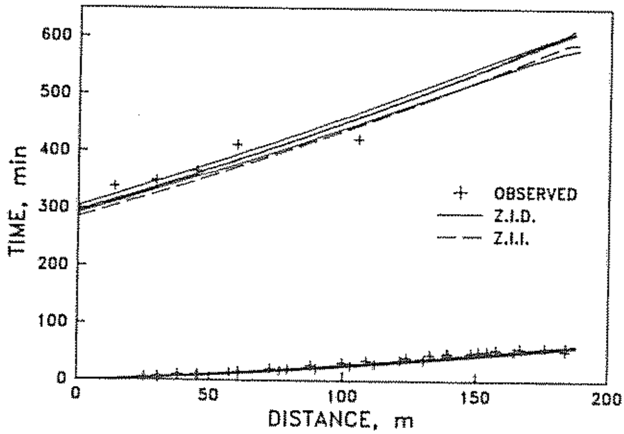

FIG. 2.—Calculated and Observed Advance and Recession Times for McDonnell Farm Border #6. Calculated Curves Are from Model Described in this Paper, Z.I.D., and Zero-Inertia Model Described by Katopodes and Strelkoff (16), Z.I.I. During Recession, Upper Z.I.D. Curve Is for Δx = 11.6 m, Lower Curve Is for Δx = 1.45 m, and Intermediate Curve Is for Δx = 1.45 and 2.9 m

77). The border was 610-ft (185.9-m) long with a slope of 0.00033 and a Manning roughness coefficient, $n = 0.15$. The inflow rate was measured at 0.0871 sq ft sec^{-1} (0.00809 $m^2\ s^{-1}$) and lasted for 58 min. Eq. 11 was used to describe the infiltration rate with $S = 0.00260$ ft sec^{-b} (0.0791 cm s^{-b}), $b = 0.52$, and $A = 0.0$. To demonstrate the sensitivity of the model to the size of Δx, four simulations were run for this irrigation with Δt in Eq. 20 chosen so that Δx was approximately 1.45, 2.9, 5.8, and 11.6 m.

Advance and recession times for the simulations are shown in Fig. 2. Also shown are the measured values and the results found by Clemmens (6) using the zero-inertia model (Z.I.I.) described by Katopodes and Strelkoff (16) with a spacing of approximately 2.9 m/reach. Agreement between the four simulations of the Z.I.D. model, the Z.I.I. model, and measured advance times is excellent with the five simulations forming a single line in Fig. 2. During recession, the reach size had an effect on the calculated recession front. Results for Δx = 1.45 and 2.9 m are virtually identical, but a Δx of 5.8 m increased the recession times by less than 10 min, while a Δx of 11.6 decreased the times by less than 10 min. All four recession times are slightly larger than those calculated with the Z.I.I. model, but all fit the observed data well. The discrepancy between the observed and modeled recession times is not surprising considering the difficulty of measuring recession and that constant, spatially uniform values for n, S, b, and S_0 were used in the models.

A second simulation was run using data from Atchison (1) presented in Clemmens (7) for the border V-5, irrigated at the Univ. of Arizona. The unblocked border was 300-ft (91.44-m) long with an average slope of 0.0011 and $n = 0.089$ and was divided into reaches of 2.2 m average length. The inflow rate was 0.0156 sq ft sec^{-1} (0.00145 $m^2\ s^{-1}$) and lasted for 140 min. The infiltration parameters used were $S = 0.00109$ ft sec^{-b}

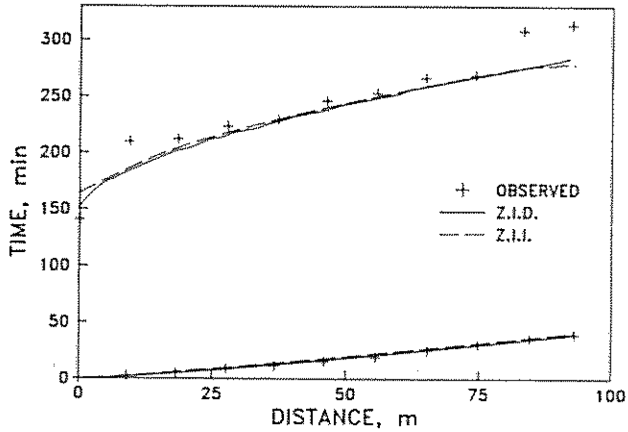

FIG. 3.—Observed Advance and Recession Times for Border V-5 and Simulated Values Calculated with Z.I.D. and Z.I.I. Models

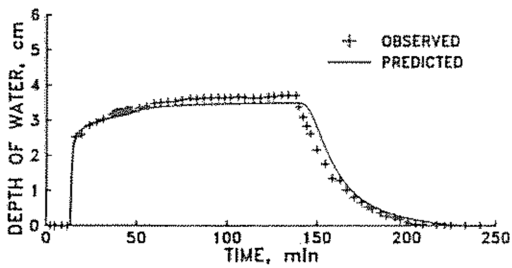

FIG. 4.—Calculated and Observed Ponding Depth versus Time from Start of Irrigation for Point 36.6 m below Head of Border

(0.0332 cm s^{-b}), b = 0.444, and A = 0.0. Fig. 3 shows the advance and recession times for the border where again the measured values and the results of the Z.I.D. and Z.I.I. models are shown. As in the first example, agreement is good between the models and the measured data during both phases of irrigation.

Predicted and measured surface-water depths as a function of time were compared for three locations along this border; 27.7, 111.6, and 195 ft (9.1, 36.6, and 64.0 m). Results were similar at the three positions and are shown in Fig. 4 for the 111.6-ft (36.6-m) location only. The Z.I.D. model predicts the depth well, especially during the first 50 min of irrigation when the gradual increase in depth following the initial rapid jump is accurately predicted.

The predicted infiltration depths from the Z.I.D. and Z.I.I. models are shown in Fig. 5 for this irrigation. Agreement between the two models is excellent as expected since both used the same infiltration equation and the predicted opportunity times are nearly identical (Fig. 4).

The third irrigation modeled, AR-15, was presented in Bassett and

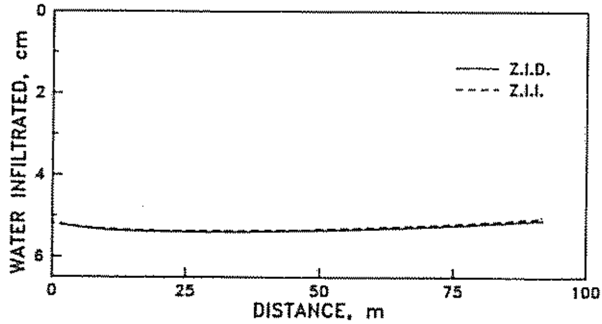

FIG. 5.—Infiltration Depths along Border as Calculated by Z.I.D. and Z.I.I. Models for Border V-5

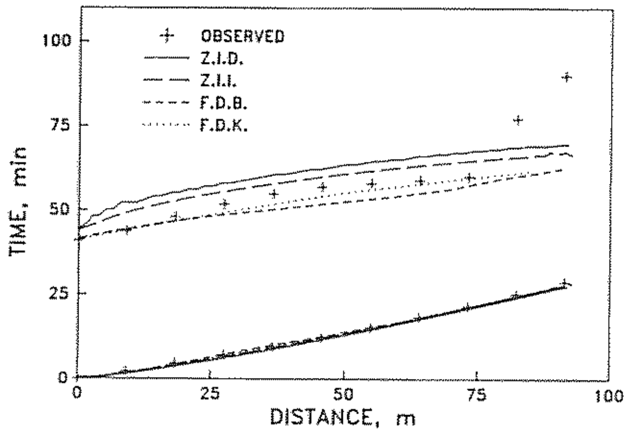

FIG. 6.—Observed Advance and Recession Times for Border AR-15 and Simulated Results Calculated with Z.I.D. and Z.I.I. Models and Full Dynamic Models of Bassett and Fitzsimmons (3), F.D.B., and Katopodes and Strelkoff (12), F.D.K.

Fitzsimmons (3) from data by Roth (12). The border was unblocked, 300-ft (91.44-m) long, had a Manning roughness factor of 0.024, and an average slope of 0.0010. The average reach was 1.7 m long. Water was applied at a rate of 0.053 sq ft sec^{-1} (0.00328 m^2 s^{-1}) for 38 min. The infiltration parameters used were S = 0.0199 ft sec^{-b} (0.067 cm s^{-b}), b = 0.2716, and A = 0.0. Fig. 6 shows the measured advance and recession times for this irrigation. Also shown are the predicted times from the Z.I.D. and Z.I.I. models and the full dynamic models of Katopodes and Strelkoff (10) and Bassett and Fitzsimmons (3), F.D.K. and F.D.B., respectively. All models predicted the advance phase very well. During recession, predicted times were not as good nor do the models agree with each other exactly. Both fully dynamic models predict the recession to occur sooner than observed, while the Z.I.D. and Z.I.I. models predict slower recession times. The average overestimation of opportunity

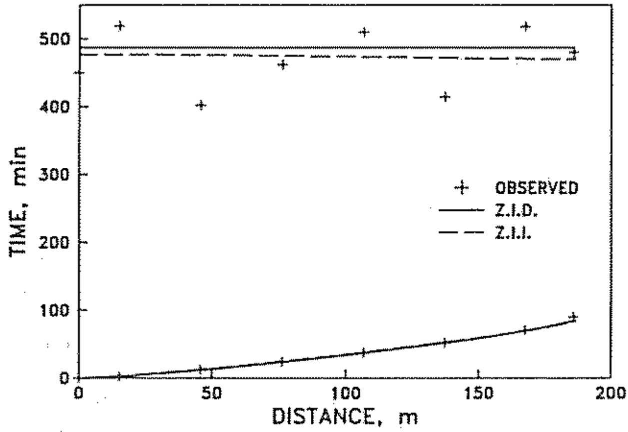

FIG. 7.—Observed Advance and Recession Times for Border CRC-1 and Calculated Values Using Models Z.I.D. and Z.I.I.

time by the Z.I.D. model for the first 75 m of the border was 7 min or 17% of observed opportunity time.

The last irrigation simulated (CRC-1) was on a level border located at the Cotton Research Center in Phoenix, Arizona, and was conducted by A. J. Clemmens (personnal communication). The blocked border was 610-ft (185.9-m) long, had a Manning roughness factor of 0.183, and had water applied at a rate of 0.067 sq ft sec^{-1} (0.00627 m^2 s^{-1}) for 53 min. The infiltration parameters used were $S = 0.00194$ ft sec^{-b} (0.059 cm s^{-b}), $b = 0.511$ and $A = 0.0$. The average reach was 2.4 m long. Fig. 7 shows the observed advance and recession times and the predicted results from the Z.I.D. model. Also shown are the results of the Z.I.I. model for the same conditions. Agreement between predicted and observed times is very good for both models on this level border.

The mass balance for the Z.I.I. simulation is also very good for this irrigation as well as the previously described irrigations with the calculated infiltrated plus runoff volumes being within ±0.5% of the applied volume. The simulations are also computationally fast. Table 1 compares the computation times for this model and the Z.I.I. model on an HP-1000 computer. The models were run with the same number of reaches for each simulation and yielded results of comparable accuracy. Although not a rigorous comparison of the two models, the computation times are of similar magnitude and are considerably faster than existing full dynamic models (16).

TABLE 1.—Computation Times Required on HP-1000 for Four Example Borders

Example borders (1)	Z.I.D. (sec) (2)	Z.I.I. (sec) (3)
McConnell #6	55.0	95.0
V5	21.0	31.8
AR-15	22.3	18.2
CRC-1	82.0	133.4

Conclusions

We have presented a model for describing the complete border irrigation cycle. The model is designed for blocked or unblocked sloping borders and for blocked level borders. The model can simulate irrigation on borders with variable slopes but cannot handle negative slopes or reversals in the direction of water flow. The model solves the combined equations for the conservation of mass and momentum with the acceleration terms removed. This model differs from earlier models in that the differential form of the combined Saint-Venant equations is solved. The model also simplifies the expression for the depth gradient by using an explicit value, averaged over the entire wetted border. Comparisons of results obtained with this model to other models and field data show the model to be very stable and to give equally accurate values for advance and recession times and thus total opportunity time for infiltration over a range of conditions including level slopes. Water depths during irrigation also appear to be closely reproduced despite the use of a very simple shape factor (a linear fit between successive reaches). This model is also conceptually very simple and easy to program, requiring approximately 450 Fortran statements and 40K bytes of memory, making it adaptable to many small computing systems.

Acknowledgments

The assistance of A. J. Clemmens in providing unpublished data for model comparisons and a Fortran program of the zero-inertia model of Katopodes and Strelkoff (16) is sincerely appreciated.

Appendix I.—References

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Appendix II.—Notation

The following symbols are used in this paper:

A = infiltration coefficient (LT^{-1});
a = sum of reaches (L);
b = infiltration power coefficient;
C = Chezy C ($L^{1/2}T^{-1}$);
C_i = effective Manning coefficient ($L^{1/3}T^{-1}$);
C_u = units conversion factor ($L^{1/3}T^{-1}$);
c = linear advance rate (LT^{-1});
g = acceleration of gravity (LT^{-2});
h = depth of water (L);
I = cumulative water infiltrated per unit area (L);
l = furthest distance between water-covered reaches (L);
n = dimensionless Manning roughness coefficient;
p = distance between reach and end of border (L);
q = flux rate per unit width (L^2t^{-1});
S = infiltration coefficient (LT^{-b});
S_f = resistance slope (LL^{-1});
S_0 = bottom slope (LL^{-1});
s_h = water volume per unit width at start of time step (L^2);
s_p = water volume per unit width at end of time step (L^2);
s_V = sum of infiltration volume per unit width (L^2);
t = time (T);
V = infiltration volume per unit width (L^2);
v = water velocity (LT^{-1});
w = infiltration rate (LT^{-1});
x = distance down border (L); and
τ = infiltration opportunity time (T).