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Approach to Control the Depth of Water in Basin Irrigation and Wetland Flooding

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Abstract: The controlled ponding of water over level terrain in basin irrigation or wetland flooding is described quantitatively as a three-phase process. During the first phase, water is applied at a known rate until ponding emerges at the time of ponding initiation. In the second phase, water continues to be applied at the same rate until a desired ponded depth is attained. In the third phase, water is applied to maintain the desired ponded depth during an arbitrarily long period. The desired ponded depth is maintained by adjusting the water-application rate to equal the infiltration rate plus the evaporation rate. The time of ponding, the ordinary differential equations (ODEs) governing cumulative infiltration during the second and third phases, and the water-application rate during the third phase are derived in this work using an extended Green-and-Ampt formulation of infiltration. Computational examples illustrate the solutions of the derived ODEs and their application in the control of basin irrigation and wetland flooding.

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Introduction

Ponding of water over level fields is a common practice in basin irrigation. It is widely used in rice paddies, where the control of the depth of ponding during the growing season is important in obtaining high crop yield (Booher 1974; Yoshida 1977). The controlled ponding of water has other applications; one case in point being wetland flooding for restoration purposes (see for example, Loáiciga and Huang 2005; Hammer 1997). In the latter case, the area of flooding is surrounded by levees of suitable height, and water is applied to create suitable habitat and moisten soils to achieve predefined objectives. The situation with rice paddies is similar in approach, although different in scope. Specifically, small parcels of level terrain—featuring levees in their perimeters to contain lateral drainage—are flooded to achieve a desired depth of ponding. The depth of ponding is maintained during a specified period following planting, the duration of the period depending on the variety of rice and local climatic conditions (Yoshida 1977). Artificial flooding as described herein is practical on level terrain underlain by soils of low hydraulic conductivity.

The controlled flooding of level terrain is envisioned as a three-phase process. In the first phase, water is applied at a constant rate r (units of length over time) until ponding is initiated at time t_p over the entire area to be flooded. The net water input rate, $r-e$, in which e denotes the (known) evaporation rate, is equal to the infiltration rate in the preponding phase when water is applied uniformly with sprinklers, a situation that emulates rainfall wetting. Otherwise, the net water input is only approximately equal to the infiltration rate because a finite depth of water is needed to allow the spreading of water over the area undergoing flooding. The error committed in the approximation is inconsequential in small flooded areas (tens to a few hundred m^2) underlain by low permeability soils, the situation considered in this work. In the second phase, water continues to be applied at the same rate (r) until a desired ponded depth (Y^*) is reached at time t^*. In the third and last phase, water is applied to maintain the desired ponded depth during an arbitrarily long period. The desired ponded depth is maintained by adjusting the water-application rate r^* to equal the infiltration rate (f) plus the evaporation rate (e).

The time of ponding initiation (t_p), the ordinary differential equations (ODEs) governing cumulative infiltration (F) during the second and third phases, and the water-application rate during the third phase are derived in this article using an extended Green-and-Ampt formulation of infiltration. The ODE for the second phase, in particular, is solved to obtain the time (t^*) to reach the desired ponded depth (Y^*). Thereafter, the rate of water application (r^*) during the third phase of controlled irrigation is calculated by setting it equal to infiltration plus evaporation and solving for r^*. Fig. 1 depicts a conceptual representation of the evolution of cumulative infiltration (F), the depth of ponding (Y), and cumulative evaporation (E), all in units of length, during the three-phase flooding process just described.

Ponding Initiation according to the Green-and-Ampt Formulation of Infiltration

The Green-and-Ampt (G&A) method (Green and Ampt 1911) has been widely used to calculate infiltration in hydrologic studies in general, and irrigation planning in particular (Philip 1993).

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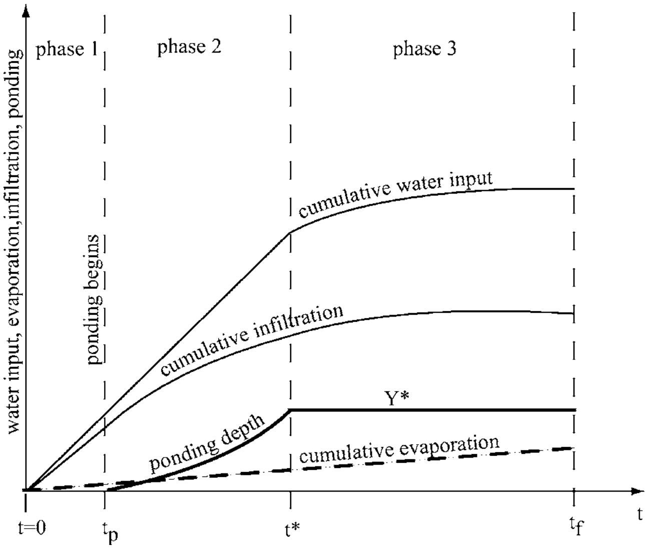

Fig. 1. Conceptual description of cumulative water input, evaporation, infiltration, and ponded depth; the evaporation rate was assumed constant in drawing the graph; t_p=time when ponding starts; t_f marks the end of flooding control

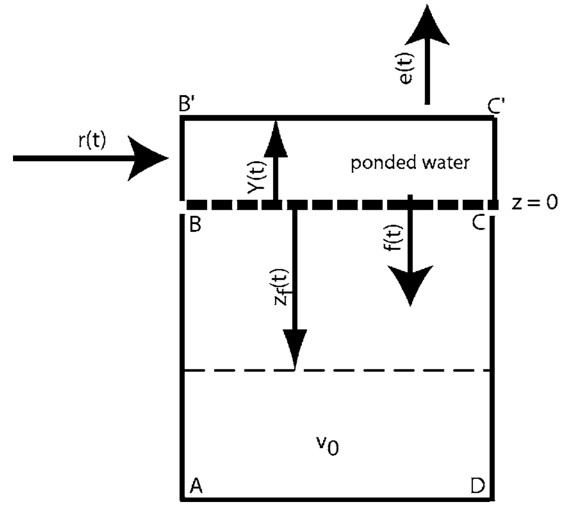

Fig. 2. Cross-sectional view of a soil column with ponded water of depth $Y(t)$, wetting-front depth $z_f(t)$, water-input rate $r(t)$, evaporation rate $e(t)$, and infiltration rate $f(t)$, all at time t. The soil surface is at $z=0$. The initial water content (shown below the wetting-front depth) is ν_0. The soil-water tension at the depth $z_f(t)$ is denoted by h_f.

The method is physically based in the sense that it incorporates Darcy's law to calculate the actual infiltration rate (f) in a vertical column of a homogeneous soil with (1) an initial moisture deficit (equal to the soil porosity minus the initial volumetric water content, $n-\nu_0$); (2) a constant soil-water tension at the downward-advancing saturation front (h_f, where $h_f>0$, a soil property); and (3) a saturated hydraulic conductivity (K_0). Thus, a well-accepted empirical law and basic soil-textural and hydraulic parameters enter in the formulation of the G&A infiltration model. A detailed description of the classical G&A method can be found in Chow et al. (1988), among others. In the classical G&A method, the effect of ponding on infiltration is considered negligible. This work, following Loáiciga and Huang (2006), extends the classical method to account for the interactions among infiltration, evaporation, and ponding, and develops the equations to control the depth of ponding.

The first variable to determine in the implementation of the extended G&A infiltration model is the time of ponding initiation (t_p). Referring to Fig. 2, notice that the saturation front at time t ($z_f(t)$, a depth measured vertically from the ground surface, $z_f<0$) in a soil column of unit cross-sectional area implies a cumulative infiltration at time t equal to $F(t)=|z_f(t)|(n-\nu_0)$). Prior to t_p the (constant) water application rate r equals the infiltration rate (f) plus the evaporation rate (e), that is $r=f+e$. Therefore, at time t, cumulative infiltration ($F(t)$) plus cumulative evaporation ($E(t)$) equals cumulative water application ($R(t)=r\times t$). It is then clear that at the time of ponding initiation, the following water-balance equation holds:

$$F(t_p) = r \times t_p - E(t_p) = |z_f(t_p)|(n-\nu_0) \tag{1}$$

The magnitude of the depth of the saturation front at the initiation of ponding $|z_f(t_p)|$ is unknown in Eq. (1). To obtain it, one writes Darcy's law between the ground surface (i.e., at $z=0$, where the hydraulic head is approximately 0) and the wetting-front depth $z_f(t_p)$ (where the hydraulic head equals $z_f(t_p)-h_f$) and sets the magnitude of the Darcian flux equal to the water-application rate minus the evaporation rate at time t_p (i.e., $f(t_p)=r-e(t_p)$. Solving for $|z_f(t_p)|$, one obtains

$$|z_f(t_p)| = \frac{K_0 h_f}{[r-e(t_p)-K_0]} \tag{2}$$

in which $r-e(t_p)>K_0$ is required, otherwise ponding does not occur. Substitution of the latter expression for $|z_f(t_p)|$ in Eq. (1) produces the equation for the time of ponding t_p

$$r \times t_p - E(t_p) = \frac{K_0 h_f}{r-e(t_p)-K_0}(n-\nu_0) \tag{3}$$

Eq. (3) is nonlinear with respect to t_p and must be solved numerically. It simplifies to its well-known form when the evaporation rate is constant during the preponding phase

$$t_p = \frac{K_0 h_f}{(r-e)(r-e-K_0)}(n-\nu_0) \tag{4}$$

where $r-e>K_0$.

ODE for the Second Phase: Buildup of Ponding until Reaching the Target Depth Y^*

At any time following the onset of ponding, the cumulative water input ($R(t)$) is partitioned into cumulative infiltration ($Y(t)$), evaporation ($E(t)$, and ponding ($Y(t)$), or $R(t)=F(t)+E(t)+Y(t)$. To obtain the cumulative infiltration $F(t)$, or its derivative with respect to time, the infiltration rate, $f(t)=F'(t)$, Darcy's law is written between the ground surface (i.e., at $z=0$, where the hydraulic head equals $Y(t)=R(t)-F(t)-E(t)$) and $z_f(t)$ (where the hydraulic head equals $z_f(t)-h_f$). The magnitude of the Darcian flux equals the infiltration rate. Next, the established relation $F(t)=|z_f(t)|(n-\nu_0)$ is combined with Darcy's law to produce the following (nonlinear) ODE for the cumulative infiltration $F(t)$ after the initiation of ponding [F and F' are functions of time in Eq. (5)]

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$$FF' - \nu F - c \times [r \times t - E(t) + h_f] = 0 \quad t_p < t \leqslant t^* \tag{5}$$

in which $c = K_0 \times (n - \nu_0)$ and $\nu = K_0 \times (1 - (n - \nu_0))$ are constant coefficients, and the initial condition of Eq. (5) is $F(t_p) = r \times t_p - E(t_p)$.

Eq. (5) can be solved accurately using Runge-Kutta numerical solvers (Carnahan et al. 1969). Commercial software, such as MATLAB or MATHEMATICA, feature solvers for ODEs of the type written in Eq. (5). Once $F(t)$ is calculated using Eq. (5), the infiltration rate can be computed as follows [by solving for $f(t)$ in Eq. (5)]:

$$f(t) = F'(t) = \frac{\nu F(t) + c \times [rt - E(t) + h_f]}{F(t)} \tag{6}$$

The ODE (5) simplifies when the evaporation is constant

$$FF' - \nu F - c^* \times (t + d) = 0 \quad t_p < t \leqslant t^* \tag{7}$$

with $c^* = K_0 \times (r - e)(n - \nu_0)$, $\nu = K_0(1 - (n - \nu_0))$, $d = h_f/(r - e)$, and initial condition $F(t_p) = (r - e)t_p$, t_p given by Eq. (4). Eq. (7) can be shown to have the following implicit solution (letting $w = r - e$, and $\delta = \sqrt{\nu^2 + 4c^*}$):

$$\frac{F(t)}{w \times t_p} = \frac{\left| \dfrac{t_p + d}{w \times t_p} - \left(\dfrac{-\nu + \sqrt{\nu^2 + 4c^*}}{2c^*} \right) \right|^{1/2 + \nu/2\delta}}{\left| \dfrac{t + d}{F(t)} - \left(\dfrac{-\nu + \sqrt{\nu^2 + 4c^*}}{2c^*} \right) \right|^{1/2 + \nu/2\delta}} \times \frac{\left| \dfrac{t_p + d}{w \times t_p} - \left(\dfrac{-\nu - \sqrt{\nu^2 + 4c^*}}{2c^*} \right) \right|^{1/2 - \nu/2\delta}}{\left| \dfrac{t + d}{F(t)} - \left(\dfrac{-\nu - \sqrt{\nu^2 + 4c^*}}{2c^*} \right) \right|^{1/2 - \nu/2\delta}} \tag{8}$$

$F(t)$ in Eq. (8) can be calculated for any specified t with any of several iterative search techniques, such as those coded in numerical software (MATHEMATICA, MATLAB, and EXCEL are software that contain equation-solving routines of the type needed to solve Eq. (8)). A sufficiently large number of pairs $(t, F(t))$ is obtained to characterize the temporal characteristics of the cumulative infiltration. Once $F(t)$ is calculated, the infiltration $f(t)$ can be obtained after solving for it in Eq. (7)

$$f(t) = F'(t) = \frac{\nu F(t) + c^*(t + d)}{F(t)} \tag{9}$$

Upon calculation of $F(t)$ from either Eq. (5) or using Eq. (8), the ponded depth follows from water balance, namely, $Y(t) = r \times t - F(t) - E(t)$. Eventually, at some time t^*, the desired depth Y^* is attained. This ends the second phase and initiates the third phase, during which the ponded depth is maintained at level Y^*. Details follow in the next section.

Third Phase and the Water-Application Rate to Maintain Y^*

The ODE for cumulative infiltration in the third (control) phase is a variant of Eq. (5), in which the ponded depth (Y^*) is kept constant

$$FF' - K_0 F - c(Y^* + h_f) = 0 \quad t \geqslant t^* \tag{10}$$

where $c = K_0(n - \nu_0)$, with initial condition $F(t^*) \equiv F^*$ from the solution of the second-phase ODE. Recall that t^* = time at which the ponded depth reaches the target value Y^*. Notice that, from Eq. (10), the infiltration rate is given by the following expression:

$$f(t) = F'(t) = K_0 + \frac{c(Y^* + h_f)}{F(t)} \tag{11}$$

The cumulative infiltration $F(t)$ is obtained using separation of variables and integration of Eq. (10). This produces the following implicit solution for cumulative infiltration (where $b = (n - \nu_0)(Y^* + h_f)$):

$$t - t^* = \frac{1}{K_0} \left\{ [F(t) - F^*] - b \, ln \left(\frac{F(t) + b}{F^* + b} \right) \right\} \quad t \geqslant t^* \tag{12}$$

The implementation of Eq. (12) is expeditious if an infiltration $F(t)$ larger than F^* is specified, and then the time t at which it occurs is solved for from Eq. (12). Any number of such pairs $[t, F(t)]$ can be obtained in the control interval $t \geqslant t^*$. Once $F(t)$ is calculated, the infiltration rate is calculable via Eq. (11).

To maintain the depth Y^*, one must adjust the application rate (r^*) so that it equals the evaporation rate [$e(t)$] plus the infiltration rate [$f(t)$] at time t. The infiltration rate equals the Darcian flux into the soil, in this case expressed by Eq. (11). The water-application rate is then

$$r^*(t) = e(t) + f(t) = e(t) + K_0 + \frac{c(Y^* + h_f)}{F(t)} \quad t \geqslant t^* \tag{13}$$

in which the evaporation $e(t)$ is known and $F(t)$ is calculated from Eq. (12) for any time t. It is evident from Eq. (13) that the water-application rate is variable during the control period. The total water application at time $t \geqslant t^*$ equals

$$R(t) = r \times t^* + \int_{t^*}^{t} r^*(s) ds = r \times t^* + E(t) - E(t^*) + F(t) - F(t^*) \tag{14}$$

in which the cumulative evaporation [$E(t)$] is a known function and the cumulative infiltration (F) is calculated with Eq. (12).

Specification of Hydraulic and Soil Parameters

Three parameters and one specified field variable enter the G&A infiltration model. The soil parameters are (i) porosity (n), (ii) saturated hydraulic conductivity (K_0), and (iii) the soil-water tension at the downward-advancing saturation front (h_f, where $h_f > 0$). Porosity and K_0 can be estimated by standard laboratory analysis of soil cores (see standard test methods D4404 and D2434/D5084 by the America Society for Testing and Materials (ASTM) for the determination of porosity and saturated hydraulic conductivity, respectively). The tension h_f is estimable from charts that graph it as a function of the well-known United States Department of Agriculture soil textural triangle (Rawls and Goldman 1996). To this end, the grain-size distributions of tested soils are determined using standard laboratory procedures on soil cores (see, e.g., ASTM, 2002). Alternatively, Neuman (1976) derived h_f by integrating the hydraulic conductivity versus soil-water tension [$K(h)$] function over the entire range of tension for a given soil

$$h_f = \frac{1}{K_0} \int_0^{h_{\max}} K(h) dh \tag{15}$$

The $K(h)$ function is determined experimentally and can be supplemented by curve fitting of the Van Genuchten type

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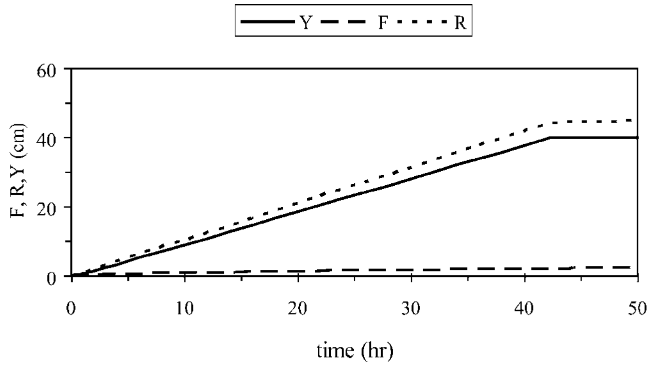

Fig. 3. Graphs of calculated cumulative infiltration (F), cumulative water input (R), and ponded depth (Y) in the Sorrento-clay example. The water-application rate $r=1.05$ cm/h until the time when the desired ponded depth ($Y^*=40.00$ cm) is reached at time $t^*=42.27$ h. Ponding starts at $t_p=0.0472$ h. The evaporation rate $e=0.05$ cm/h is constant, implying a linear graph for the cumulative evaporation (E, not shown).

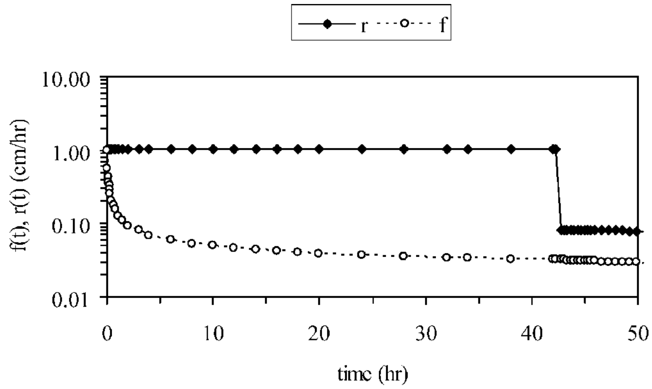

Fig. 4. Water-input rate (r, or calculated r^*) and calculated infiltration rate (f) in the Sorrento-clay example. The water-input rate equals $r=1.05$ cm/h in the precontrol phase and approximately $r^*=0.08$ cm/h during the control phase. The evaporation rate $e=0.05$ cm/h is constant. The control phase starts at $t^*=42.27$ h, once the desired ponded depth $Y^*=40.00$ cm is reached.

(Van Genuchten 1980). The field variable involved in the G&A method is the initial volumetric water content of the soil (ν_0), which is determined by standard gravimetric measurement of undisturbed samples in the laboratory.

Computational Example

The methodology derived in the previous sections is illustrated with a simulation of ponding and ponding control over a low-conductivity soil, the Sorrento clay, sampled in the Ojai Valley, California. The Sorrento clay's hydraulic parameters were determined by laboratory analyses on undisturbed samples. Its silt and clay contents are 38.57 and 61.43%, respectively. Other parameters are as follows: n (porosity)$=0.367$; ν_0 (initial water content)$=0.126$; $K_0=6.1\times10^{-7}$ cm/s$=2.2\times10^{-3}$ cm/h (saturated hydraulic conductivity); h_f (tension at the saturation front)=89 cm.

The water-application rate was set at $r=1.05$ cm/h starting at time $t=0$. The specified evaporation rate was constant, $e=0.05$ cm/h, throughout the entire simulation period. The net water-input rate over the Sorrento clay was set equal to $w=r-e=1.00$ cm/h during the preponding phase and during the second phase until the time t^* when the desired depth $Y^*=40.00$ cm was reached. The time of ponding was calculated using Eq. (4) and found to equal $t_p=0.0472$ h (2.83 minutes), a very short interval indeed, but hardly a surprising fact given the low capacity to the Sorrento clay to infiltrate water.

Fig. 3 shows graphs of calculated cumulative infiltration (F), cumulative water input (R), and ponded depth (Y). The cumulative infiltration was calculated using Eq. (8) in the period $t_p \leq t \leq t^*$ and using Eq. (12) in the control period $t \geq t^*$. The desired ponded depth ($Y^*=40.00$ cm) is reached at time $t^*=42.27$ h following the start of water application, at which time the calculated cumulative infiltration was $F^*=2.26$ cm. The evaporation rate $e=0.05$ cm/h is constant, implying a linear function for the cumulative evaporation (E, not shown in Fig. 3). It is seen in Fig. 3 that the ponded depth is maintained at the level $Y^*=40.00$ cm after time t^*. The simulation was terminated at time $t=50$ h.

Fig. 4 depicts the water-input and infiltration rates from time $t=0$ to time $t=50$ h. The water-input rate prior to time $t^*=42.27$ h equaled 1.05 cm/h. After t^*, the calculated water input r^* [using Eq. (13)] dropped abruptly to approximately 0.08 cm/h and remained at that approximate level thereafter. It is seen in Fig. 3 that the desired ponded depth $Y^*=40.00$ cm was kept at this level during the control phase. The infiltration rate shows a rapid decay in the early phases of simulation and converges to an approximate value of 0.03 cm/h during the control phase.

Conclusions

Water-balance equations describing the artificial wetting and flooding of level terrain were derived for the preponding and postponding phases using a Green-and-Ampt formulation of infiltration. The postponding phases include two sequential periods. During the first of these, the water-input rate is known and the ponded depth is allowed to rise until reaching a desired level. In the second, the water-input rate is adjusted to maintain the desired ponded depth during an arbitrarily long time. The water-balance equations were applied to illustrate the controlled flooding of level terrain underlain by low-conductivity, clayey soil. The methodology developed in this work was found to perform well, and appears well suited for basin-irrigation control and for use in the controlled flooding of wetlands.

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