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Author
Loáiciga, Hugo A

Publication Date
2006-05-19

DOI
10.1061/40856(200)143

Peer reviewed

The Life Cycle of Vernal Pools: Hydrologic Principles

Hugo a. Loáiciga[1]

[1]Department of Geography, University of California, Santa Barbara, California 93106; PH (805) 893-8053; FAX (805) 893-3146; email: hugo@geog.ucsb.edu

Abstract

This paper reviews the hydrologic principles governing the life or flooding-drying cycle of vernal pools. A quantitative method for describing the ponding hydrograph in a vernal pool formed by rainfall or by artificial flooding is proposed. This method can be used for predicting the flooding-drying phases of a vernal pool, and also to achieve desired ponding hydrograph in vernal-pool restoration work.

Introduction

Vernal pools are seasonal wetlands that are occasionally flooded as a result of intense storms (usually –but not always- occurring December through March). They are of relatively small dimension, ranging from tens to a few thousands of square meters. Yet, they occupy an estimated 276,800 hectares in California and Oregon, where they serve important habitat functions for migratory birds and other organisms. The geormorphological processes leading to the creation of vernal pools are not well understood. Many vernal pools were created by the action of surface waters that have effected erosion and deposition differentially at a spatial micro-scale. In other instances vernal pools appear to have been created, unintendedly, by human action (say, by the removal of buildings and their foundations). Figure 1 shows a typical cross section of a vernal pool. The subsurface characteristics of vernal pools are integral for their development. They are usually underlain low permeability clay and silt soils that become saturated during intense storms but do not give rise to laterally continuous phreatic aquifers. In some instances the hydric soil responsible for ponding may be a thin layer of sediments. The soil stratigraphy beneath the vernal pool can vary considerably. Deep soil moisture may in some cases percolate and create perched water tables over bedrock that drain as groundwater flow, as shown in Figure 1. Generally, however, rising water tables do not cause vernal-pool flooding, as is the case with perennially wet or saturated wetlands (Hammer, 1997; Kent, 2001). Vernal pools in some cases receive water from upland tributary slopes, in addition to rainfall input. This paper focuses on vernal pools with negligible later drainage whose water balance is determined by rainfall, evaporation and infiltration within the boundaries of the vernal pool as shown in Figure 1. Cyclonic storm systems move in a westward direction bringing heavy precipitation to

California and Oregon. These storms initiate the flooding-drying cycle in vernal pools. This cycle features a series of typical phases.

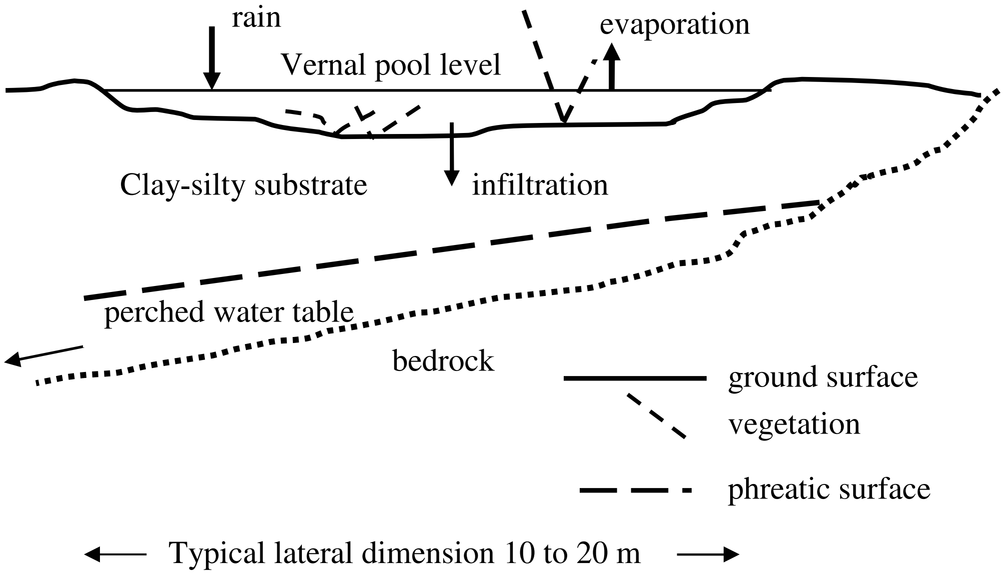

Figure 1. Schematic vertical cross-section of a generic vernal pool. Figure not drawn at scale.

In the first phase, rainfall begins with a (variable) rate that is less than the infiltration capacity of its underlying soils. All the rainfall infiltrates and there is no ponding during this phase. The second phase begins with the initiation of ponding. The rainfall rate exceeds infiltration in the second phase. Ponding increases over time and reaches a maximum (Y_{max}) when the rainfall rate in the recession limb of its hyetograph becomes equal to the infiltration rate. Thereafter, the rainfall rate falls below the infiltration rate and the depth of ponding decreases and might vanish altogether prior to the end of rainfall. In the latter case, the extinction time of ponding $-t_f$ -, which marks the end of the flooding cycle- can be calculated from water-balance equations. Otherwise, the third, and last, phase begins with the end of rainfall. Evapotranspiration of ponded water begins at the start of the third phase. Loss of ponded water (besides that caused by infiltration) is dominated by evaporation when vegetation is dormant or dead during the rainy (cold) season, as is the case in vernal pools of northern mid-latitudes. Note that transpiration removes water from the root zone, but not ponded water. Infiltration and evaporation combine to deplete persisting ponding until it vanishes, marking the end of a wetland's flooding-drying cycle. The extinction time of ponding can be calculated from infiltration and evaporation during the third phase, and from the ponding depth at the beginning of the third phase. This last case, that in which ponding outlasts the end of rainfall is the one pursued in this work. The duration of ponding is of interest from ecological and recreational viewpoints. The maximum depth of ponded water, Y_{max}, is used for determining flooded area and the degree of lateral containment needed to achieve optimal water retention in wetland restoration or in irrigation by flooding. The calculation of infiltration is useful in assessing groundwater recharge potential. It is plausible that a new storm may arrive to replenish the vernal pool prior to its drying. In this case, the depth of ponding and the cumulative infiltration at the time the storm's arrival become the boundary initial conditions that drive the subsequent water balance in the vernal pool.

Prediction Method for the Flooding-Drying Cycle of Vernal Pools

The Green-and-Ampt (G&A) method (Green and Ampt, 1911; Philip, 1993) 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 an initial moisture deficit (equal to the soil porosity minus the initial volumetric water content, $n - v_0$), a constant soil-water tension at the downward-advancing saturation front (h_f, where $h_f > 0$, a soil property), and a saturated hydraulic conductivity (K_{sat}). Thus, a key empirical law and basic soil-textural and hydraulic parameters enter in the formulation of the G&A infiltration model. The infiltration phases of the Green-and-Ampt model in the context of a wetland's flooding cycle are depicted in Figure 2.

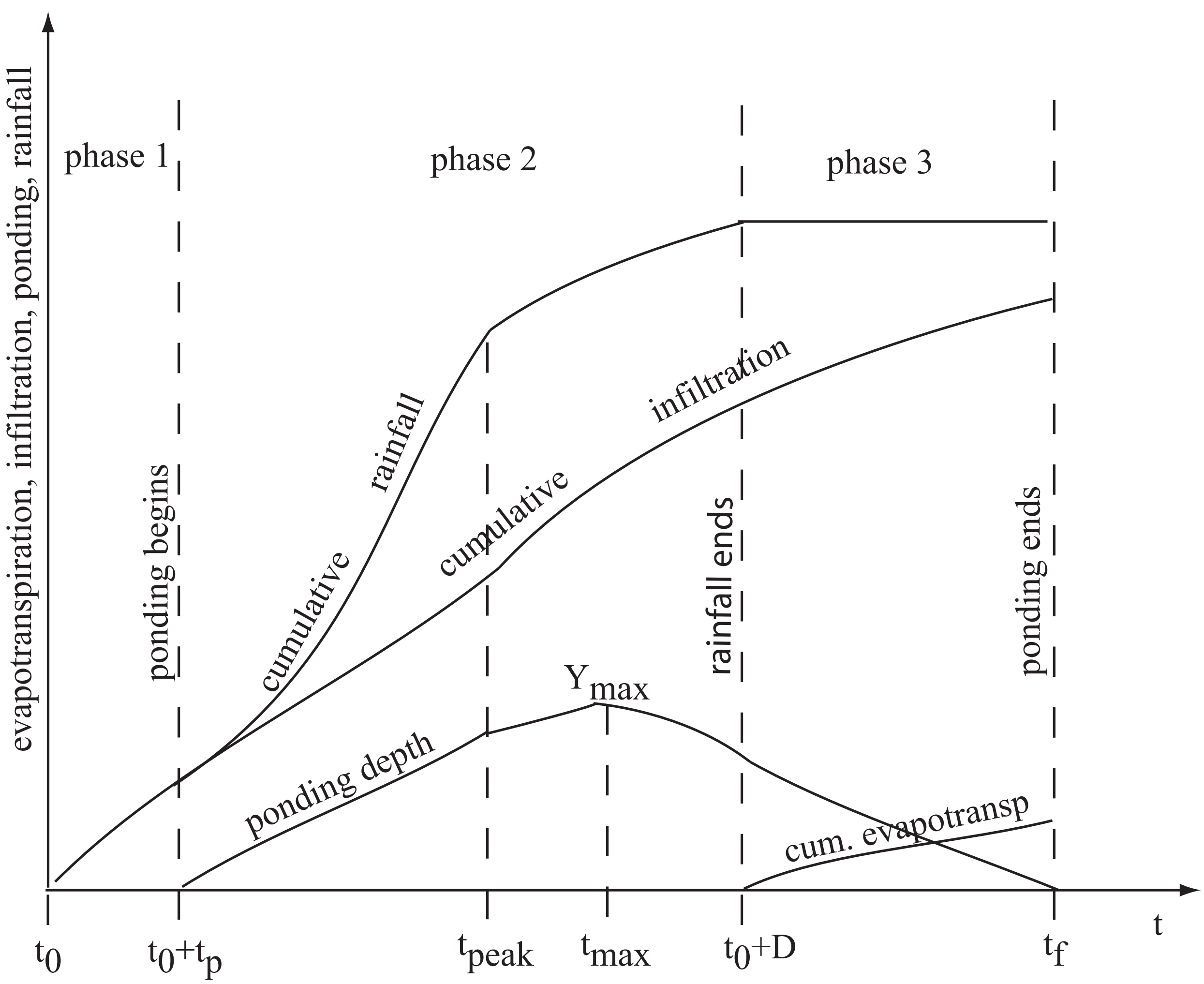

Figure 2. The phases of the flooding-drying cycle triggered by intense storms in vernal pools.

The first important variable to determine in the implementation of the G&A infiltration model is the time to ponding. First note that a saturation front at a depth z_f (measured vertically from the ground surface, $z_f < 0$) in a soil column of unit cross-sectional area implies a cumulative infiltration equal to $F(t_0, t) = |z_f(t_0 + t)|(n - v_0))$. During the pre-ponding phase the rainfall rate (w) equals the infiltration rate (f), so that cumulative infiltration equals cumulative rainfall, $F(t_0, t) = W(t_0, t)$. This is expressed in the following integral equation (in which $t_0 + t_p$ denotes the time at which ponding begins, i.e., the time to ponding): $W(t_0, t_0 + t_p) = |z_f(t_0 + t_p)|(n - v_0)$, in which $W(t_0, t_0 + t_p)$ is the cumulative rainfall from time t_0 to the time to ponding, $t_0 + t_p$. The magnitude of the depth of the saturation front at the initiation of ponding, $|z_f(t_0 + t_p)|$,is unknown in the previous integral equation. To obtain it one writes Darcy's law between the ground surface (i.e., at z = 0, where the hydraulic head is zero) and $z_f(t_0 + t_p)$ (where the hydraulic head equals $z_f(t_0 + t_p) - h_f$) and sets the magnitude of the Darcian flux equal to the rainfall rate at time $t_0 + t_p$ (i.e., equal to $w(t_0, t_0 + t_p)$). Solving for $|z_f(t_0 + t_p)|$ one obtains that $|z_f(t_0 + t_p)| = K_{sat} h_f / (w(t_0, t_0 + t_p) - K_{sat})$, with $w(t_0, t_0 + t_p) > K_{sat}$ required, otherwise ponding does not occur. Substitution of the latter expression for $|z_f(t_0 + t_p)|$ in the integral equation for the time to ponding presented a few lines earlier produces the equation for $t_0 + t_p$:

$$W(t_0, t_0 + t_p) = \frac{K_{sat} h_f}{w(t_0, t_0 + t_p) - K_{sat}}(n - v_0) \qquad (1)$$

Since the function $w(t_0, t_0 + t_p)$ for the rainfall rate is known, equation (1) can be solved for $t_0 + t_p$. In general, this solution must be achieved numerically.

Following the onset of ponding and until the end of rainfall, the cumulative rainfall is partitioned into cumulative infiltration and cumulative ponding, $W(t_0, t) = F(t_0, t) + Y(t_0, t)$, for $t_0 + t_p \leq t \leq t_0 + D$. To obtain the cumulative infiltration $F(t_0, t)$, or its derivative, the actual infiltration rate, $f(t) = F'(t_0, t)$, Darcy's law is written between the ground surface (i.e., at z = 0, where the hydraulic head equals $Y(t_0, t) = W(t_0, t) - F(t_0, t)$) and $z_f(t)$ (where the hydraulic head equals $z_f(t) - h_f$), and the magnitude of the Darcian flux is set equal to the actual infiltration rate. Furthermore, $F(t_0, t) = |z_f(t)|(n - v_0)$, established above. This equation is combined with Darcy's law to produce the following ordinary differential equation (ODE) for the cumulative infiltration $F(t_0, t)$ in the interval $t_0 + t_p \leq t \leq t_0 + D$:

$$F F' - v F - c \cdot (W(t_0, t) + h_f) = 0 \qquad t_0 + t_p \leq t \leq t_0 + D \qquad (2)$$

whose initial condition is $F(t_0, t_0 + t_p) = W(t_0, t_0 + t_p)$, in which the cumulative rainfall $W(t_0, t)$ is a known function, and $c = K_{sat} \cdot (n - v_0)$, $v = K_{sat} \cdot (1 - (n - v_0))$. Equation (2) governs the evolution of infiltration from the onset of ponding until the end of rain. Its solution for constant rainfall, i.e., when $W(t_0, t) = w \cdot (t - t_0)$, has been obtained in closed-form by Loáiciga and Huang (2005). In the present case of variable rain, its solution is efficiently arrived at by sequential application of Loáiciga and Huang's solution to consecutive short time intervals (say, of six-minute duration each, the temporal resolution of the hyetographs corresponding to the well-known Soil Conservation Service rainfall storms specified for all the coterminous United States). The numerical solution method is based on the well-known Runge-Kutta algorithm.

Ponding is reduced by infiltration and evaporation (e_v) after rainfall. Evaporation (a known input function) starts at t = t_0 + D, i.e., at the end of rainfall. The water balance equation in the period t > t_0 + D is $W(t_0, t_0 + D) = Y(t_0, t) + F(t_0, t) + E(t_0 + D, t)$, t > t_0 + D, in which $E(t_0 + D, t)$ is the cumulative evaporation between t_0 + D and t. To obtain the cumulative infiltration $F(t_0, t)$, Darcy's law is written between the ground surface (i.e., at z = 0, where the hydraulic head equals $Y(t_0, t) = W(t_0, t_0 + D) - F(t_0, t) - E(t_0 + D, t)$) and $z_f(t)$ (where the hydraulic head equals $z_f(t) - h_f(t)$), and the magnitude of the Darcian flux is set equal to the actual infiltration rate. Furthermore, $F(t_0, t) = |z_f(t)|(n - v_0)$. This equation is combined with Darcy's law to produce the following ODE for the cumulative infiltration $F(t_0, t)$:

$$F\,F' - v\,F - c \cdot (W(t_0, t_0 + D) + h_f - E(t_0 + D, t)) = 0 \qquad t \geq t_0 + D \tag{3}$$

whose initial condition is $F(t_0, t_0 + D) \equiv F_D$ (from the solution of equation (2)), and $v = K_{sat} \cdot (1 - (n - v_0))$, $c = K_{sat} \cdot (n - v_0)$. Equation (3) is solved by the method of Loáiciga and Huang (2005) concatenating consecutive time intervals (say, of 6-minute durations) and solving equation (3) sequentially. The numerical solution method is based on the well-known Runge-Kutta algorithm.

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_{sat}), and (iii) the soil-water tension at the downward-advancing saturation front (h_f, where $h_f > 0$). Porosity and K_{sat} can be estimated by standard laboratory analysis of soil cores (see standard test methods by the America Society for Testing and Materials, ASTM, 2000, for example). The tension h_f is estimable from charts that graph it as a function of the well-known United States Department of Agriculture (USDA) soil textural triangle (Rawls et al., 1992; Rawls and Goldman, 1996). To this end, the grain-size distribution of tested wetland soils is determined using standard laboratory procedures on soil cores (see, e.g., ASTM, 2002). Neuman (1976) proposed a theoretical expression for h_f based on the tension vs. water content characteristic function of a soil. The field variable is the initial (volumetric) water content of the soil (v_0), which is determined by standard gravimetric measurement of undisturbed samples in the laboratory.

Application Rate to Achieve a Desired Ponding Depth in Vernal Pools or in Flooded Crops

At times, water is artificially added to wetlands that are stressed by drought. Likewise, rice paddies are flooded to submerge nascent rice plants and to grow healthy crops. These two situations have in common that the land does not have any standing water on it, and that water is applied at a controlled rate to achieve a desired depth of ponding to be maintained during a specified period. The water-application rate, r, equals the volume of applied water per unit time divided by the area of the land to be flooded. Like rainfall and evaporation, r has dimensions of length over time. It is assumed herein that the application rate r is constant. At time zero (letting $t_0 = 0$ for the sake of simplicity) flooding of the land is initiated. The applied water is partitioned into infiltration and evaporation prior to the initiation of ponding. Once the application rate is chosen, the time to ponding t_p is fixed. The choice of application rate hinges on practical considerations, such as the available water and the area of the land being flooded. Also, large application rates can erode the flooded land. Once r is chosen, an argumentation analogous to that leading to equation (1) produces the following equation for the time to ponding (in which $e(t_p)$ and $E(t_p)$ denote the evaporation rate and the cumulative evaporation at time t_p, respectively):

$$r\,t_p - E(t_p) = \frac{K_{sat}\,h_f}{(r - e(t_p) - K_{sat})}(n - v_0) \tag{4}$$

Equation (4) must be solved numerically, given the evaporation function $e(t_p)$. The depth of ponding (Y) increases from zero after t_p. The governing ODE of cumulative infiltration in the post-ponding phase is similar to equation (2), the only difference being that the cumulative water input (r t) is reduced by the cumulative evaporation:

$$F\,F' - v\,F - c \cdot (r\,t - E(t)) + h_f) = 0 \qquad t \ge t_P \tag{5}$$

with $c = K_{sat} \cdot (n - v_0)$, $v = K_{sat} \cdot (1 - (n - v_0))$ and initial condition $F(t_p) = r\ t_p - E(t_p)$. Eventually, at time t*, the desired depth Y* is attained. To maintain the depth Y* one must adjust the application rate so that it equals the evaporation rate plus the infiltration rate. That is, letting the adjusted application rate be r* (a variable quantity):

$$r^*(t) = e(t) + f(t) = e(t) + K_{sat}\,\frac{R(t) - E(t) - (1 - (n - v_0))\,Y^* + (n - v_0)\,h_f}{R(t) - E(t) - Y^*} \qquad t \ge t^* \tag{6}$$

in which R(t) is the cumulative water application at time $t \ge t^*$.

Computational examples of the methodology developed in this work shall be presented in a follow-up technical session.

References

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ASTM (2000). "Standard test method for determining unsaturated and saturated hydraulic conductivity in porous media by steady-state centrifugation." *ASTM Standard Method D6527-00,* ASTM, West Conshohocken, Pennsylvania.

ASTM (2002). "Standard method for particle-size analysis of soils." *ASTM Standard Method D422-63,* ASTM, West Conshohocken, Pennsylvania.

Hammer, D.A. (1997). *Creating Freshwater Wetlands*. 2nd edn., Lewis Publishers, Boca Raton.

Kent, D.M. (2001). *Applied wetlands science and technology.*, 2nd ed., Lewis Publishers, Boca Raton.

Loáiciga, H.A., and Huang, A. (2005). "Flooding-cycle analysis in wetlands with negligible overland drainage." In *Dynamics and Biogeochemistry of River Corridors and Wetlands,* Intl. Assoc. Hydrological Sciences (IAHS) Publication 294, 122-129, Exeter, U.K

Neuman, S. (1976). "Wetting front pressure head in the infiltration model of Green and Ampt." *Water Resources Research,* 12*,* 564-566.

Philip, J.R. (1993). "Variable-head ponded infiltration under constant or variable rainfall." *Water Resources Research,* 29, 2155-2165.

Rawls, W.J., Lajpat R.A., Brakensiek,D.L., and Shirmohammadi, A. (1992). "Infiltration and soil water movement." In *Handbook of Hydrology*, Maidment, D.R., ed., p. 5.1-5.51, McGraw-Hill Inc., New York.

Rawls, W.J., and Goldman, D. (1996). "Infiltration." *Hydrology Handbook*, 75-124, American Society of Civil Engineers, New York.