System-Dependent Boundary Conditions – Atmospheric Boundary Condition

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In many applications neither the flux across nor the pressure head or gradient along a boundary is known a priory, but follows from interactions between the vadose zone and its surroundings (e.g., the atmosphere or deeper subsurface). The boundary representing the soil-air interface, which is exposed to atmospheric conditions, is one example of the system dependent boundary. The potential fluid flux across this interface is controlled exclusively by external conditions (precipitation, evaporation). However, the actual flux depends also on the (transient) moisture conditions in the soil. Soil surface boundary conditions may change from prescribed flux to prescribed head type conditions (and vice-versa). This occurs, for example, when the precipitation rate exceeds the infiltration capacity of the soil, resulting in either surface runoff or accumulation of excess water on top of the soil surface, depending upon the soil conditions. The infiltration rate in that case is not controlled any more by the precipitation rate, but instead by the infiltration capacity of the soil. A system-dependent boundary condition also occurs when the potential evaporation rate as calculated from meteorological conditions (the evaporative demand of the atmosphere), exceeds the capability of the soil to deliver enough water toward the soil surface. In this case the potential evaporation rate can be significantly reduced to an actual evaporation rate that is again controlled by the soil.

System-dependent atmospheric boundary conditions can be implemented mathematically using an approach of Neuman et al. (1974) which limits the absolute value of the flux such that the following two conditions are satisfied:

$$\left| -K(h)\left(\frac{\partial h}{\partial x}+1\right)\right| \le E \tag{1}$$

and

$$h_A \le h \le h_S \tag{2}$$

where E is the maximum potential rate of infiltration or evaporation under the current atmospheric conditions [LT^{-1}], h is the pressure head at the soil surface [L], and h_A and h_S are, respectively, minimum and maximum pressure heads allowed under the prevailing soil conditions [L]. The value for h_A is determined from the equilibrium conditions between soil water and atmospheric water vapor, whereas h_S is usually set equal to zero (which would initiate instantaneous surface runoff) or results from the accumulation of excess water in the surface ponding layer, in which case its value must be calculated from the difference between the infiltration and precipitation (or irrigation) rates. When one of the limits of (2) is reached, a prescribed head boundary condition will be used to calculate the actual surface flux. Methods for calculating E and h_A on the basis of atmospheric data have been discussed by Feddes et al. (1974).

An example application of the atmospheric boundary condition for infiltration from a rainfall event is demonstrated in Figures 1, 2 and 3, which shows infiltration during and following rainfall at a large but constant intensity (50 cm/d) and of short duration (0.25 d) into a loamy soil. Calculations were carried out using HYDRUS-1D (Šimůnek et al., 2008) assuming that water can either pond at the soil surface or is immediately removed by surface runoff. Plots of both the pressure head (Figure 1) and the infiltration rate (Figure 2) show that surface ponding occurred after 0.0176 d. After this time the infiltration rate decreases continuously as time proceeds, with the reduction being smaller for the case with surface water build-up since the water level exerts a hydrostatic pressure at the soil surface. Infiltration ceased at the end of the infiltration event for the case that considered surface runoff. However, when water was allowed to accumulate on top of the soil surface, a 4.64-cm thick water layer developed at the end of the precipitation event, which subsequently served as a source for further infiltration until 0.425 d when all water had infiltrated. The third scenario assumes that ponding is limited by a surface water layer of 2.5 cm (Figure 1), after which surface runoff starts (Figure 2). In this case less water accumulates at the soil surface and some water is removed by surface runoff. This simple application clearly demonstrates that neither the pressure head nor the water content could be specified at the boundary a priori, and that the actual flux depended on the interaction between the applied flux and the degree of saturation of the soil system.

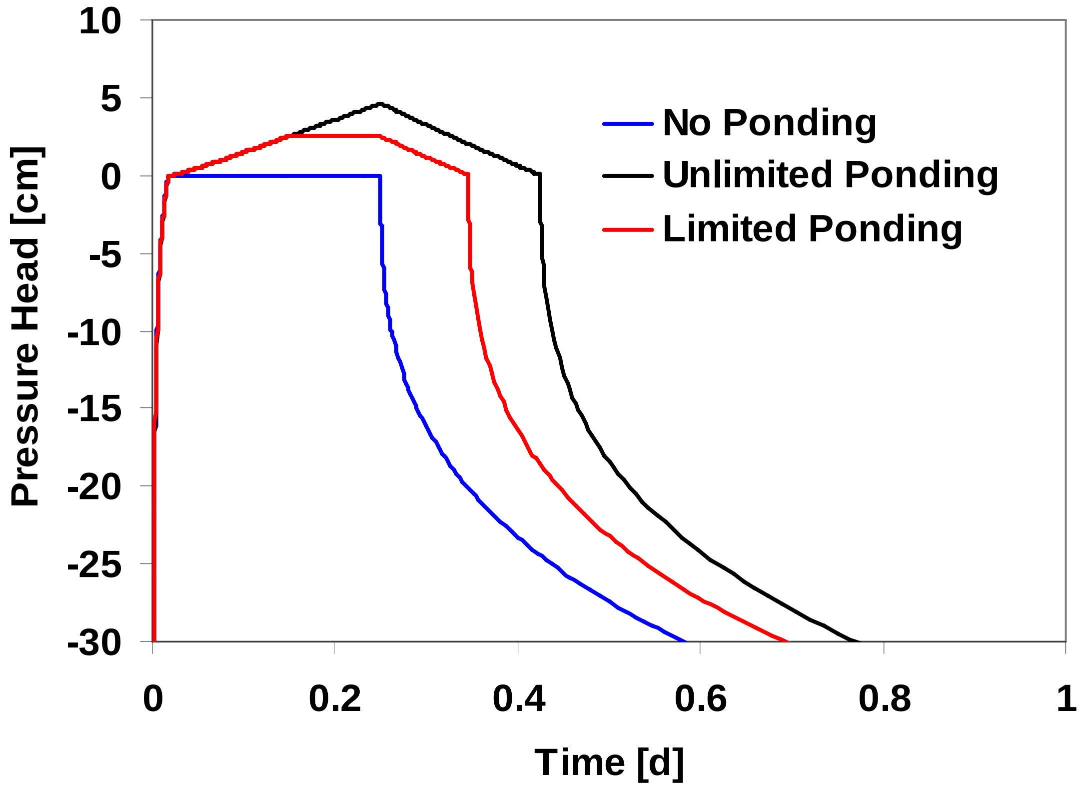

Figure 1. Pressure heads in the surface node for three scenarios of infiltration from a high-intensity rain rainfall event in a loamy soil with (unlimited or limited) and without surface ponding.

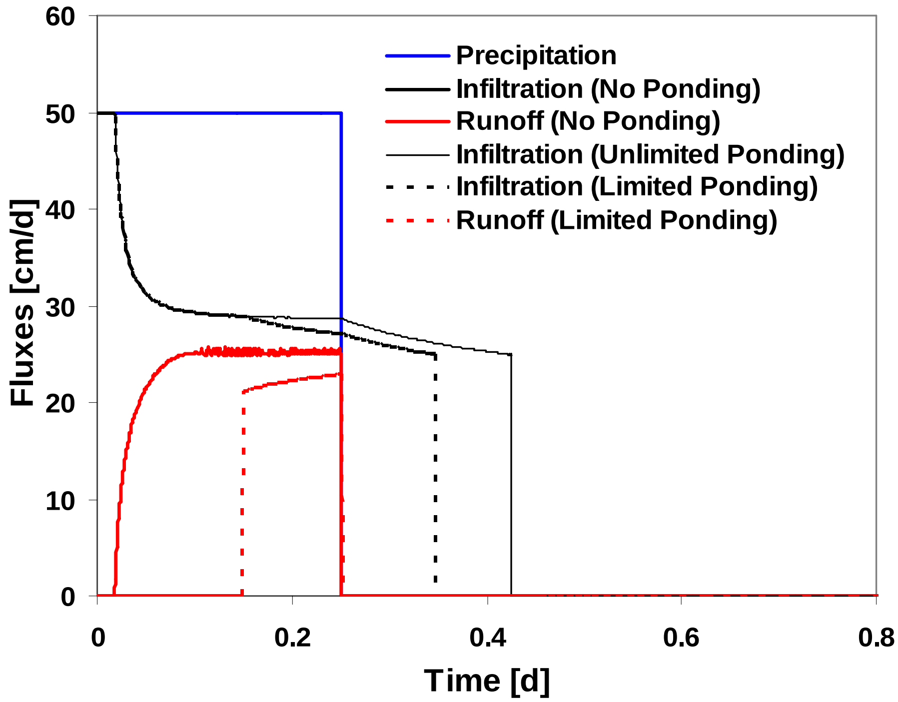

Figure 2. Infiltration fluxes and surface runoff for three scenarios of infiltration from a high-intensity rainfall event in a loamy soil with (unlimited or limited) and without surface ponding.

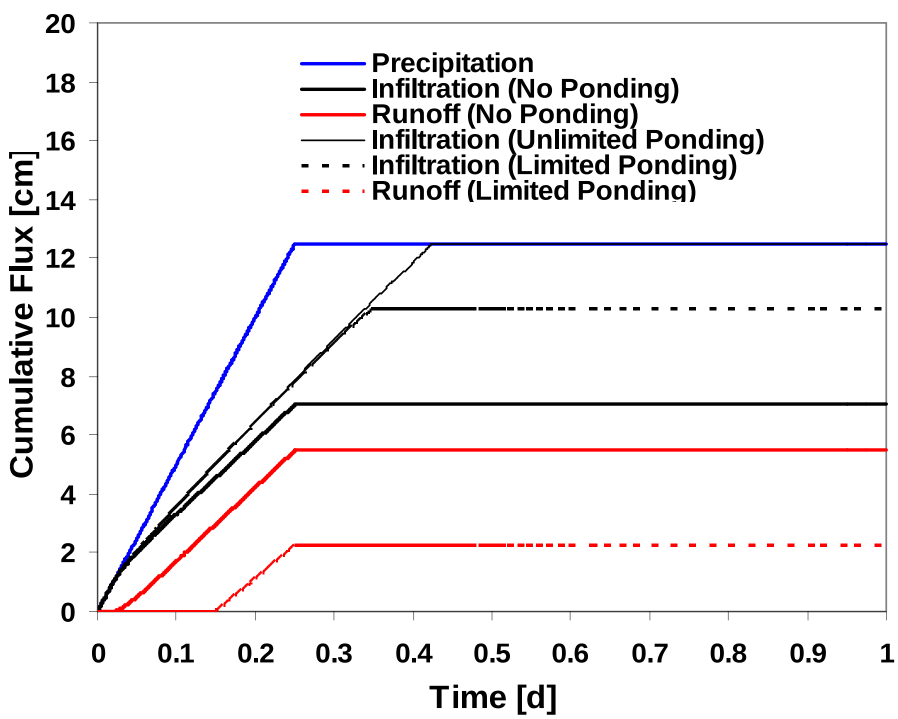

Figure 3. Infiltration fluxes and surface runoff for three scenarios of infiltration from a high-intensity rain rainfall event in a loamy soil with (unlimited or limited) and without surface ponding.

Feddes, R. A., Bresler, E., and Neuman, S. P., Field test of a modified numerical model for water uptake by root systems, *Water Resour. Res., 10*(6), 1199-1206, 1974.

Neuman, S. P., Feddes, R. A. and Bresler, E. Finite element simulation of flow in saturated-unsaturated soils considering water uptake by plants, *Third Annual Report*, *Project No. A10-SWC-77*, Hydraulic Engineering Lab., Technion, Haifa, Israel, 1974.

Šimůnek, J., M. Šejna, H. Saito, M. Sakai, and M. Th. van Genuchten, The HYDRUS-1D Software Package for Simulating the Movement of Water, Heat, and Multiple Solutes in Variably Saturated Media, Version 4.0, *HYDRUS Software Series 3*, Department of Environmental Sciences, University of California Riverside, Riverside, California, USA, pp. 315, 2008.

Test examples:

Project	Description
Pond1	Atmospheric boundary with the high precipitation rate exceeding the soil infiltration capacity and causing the **surface runoff**.
Pond2	Atmospheric boundary with the high precipitation rate exceeding the soil infiltration capacity and resulting in the development of the **surface water layer,** thickness of which is **not limited**.
Pond3	Atmospheric boundary with the high precipitation rate exceeding the soil infiltration capacity and resulting in the development of the surface water layer, thickness of which is **limited**. Once the limit is reached, surface runoff starts.
Pond4	Atmospheric boundary with **multiple** pulses of precipitation exceeding the soil infiltration capacity and resulting in the development of the **surface water layer,** thickness of which is **not limited**.
Pond5	**Infiltration from the surface water layer** that was initially at the soil surface.