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A numerical experiment to determine the soil water contents in the unsaturated zone and the water table response under transient ponding conditions

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Abstract

A model based on analytical solutions derived from the 2-phase flow theory for infiltration and drainage processes under transient supply conditions is presented here. The mathematical derivations are based on the knowledge of unsaturated flow in porous media, on the continuity equation and Darcy equation. The main assumption concerns the rectangular shape of the water content profile with depth which leads to an abrupt change of the water contents as the front goes by. A sequence of infiltration and drainage fronts are analysed and the results are presented. New is the approach of combining the saturated and the unsaturated zones in one efficient methodology using analytical solutions.

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Keywords: unsaturated zone; water content; aquifer recharge; analytical solutions; two-phase flow theory

1. Introduction

In soil sciences, hydrology and agricultural sciences, water content plays an important role regarding groundwater recharge, agriculture, soil chemistry and ecology. The interest in modeling soil water dynamics in the unsaturated zone has been increased in the last 30 years [1] [2] [3].

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Scientific efforts have aimed towards a predictive approach for the soil water distribution over space and time for different purposes such as a better assessment of fire risk or a more comprehensive understanding of the seasonal dynamics of the water dependent terrestrial ecosystems or an accurate simulation of the groundwater recharge process. Laboratory experiments have given insight into the front morphology [4]. Mathematical models have given evidence of the accuracy of the current approaches for mildly unsaturated flow in the vadose zone [5] and for saturated aquifer recharge [6]. Techniques for field estimation of the water content have been improved and their accuracy tested [7].

The purpose of this study is to describe the evolution in time of the soil water content and to offer a tool to interpret the field values of water contents under transient water supply conditions at the surface. The approach is based on soil water balance, averaged values of the water content below and behind the fronts which are assumed to be rectangular shaped. New is the approach of combining the saturated and unsaturated zones in one efficient methodology using analytical solutions.

2. Methodology

A methodology previously applied for the interpretation of the water table levels at an artificial groundwater recharge plant in Fresno, California [8] has been used for determining the soil water contents and the aquifer response. Based on the theory of multi-phase flow and the current understanding of unsaturated flow in porous media, approximate equations for the evolution of water content with time were derived. The basic approximation consists of assimilating the water content profile to a rectangle. The water content is assumed to be uniform from the surface to the descending front downstream which propagates further into the assumed initially uniform water content. This approximation for the rectangular profile is especially valid down into the column once the wetting front has passed it and previous studies have shown that this approximation is realistic [9]. The water content in the upper rectangular zone (see Fig.1) is calculated both with a "mass balance "approach and with a "dynamic" approach. The first one is based on conservation of mass and the second one is based on the two-phase flow theory and on the definition of total velocity. Given that at early times capillary dominates, the dynamic estimate is used when the front first starts to proceed down. Beyond that time a weighted average of the two estimates is used.

3. Mathematical derivations

3.1. Infiltration phase

Let i_{sr} denote the infiltration rate associated with the supply rate. The water content between the surface and the descending front is θ. Below the descending front and above the water table the water content has a uniform value denoted θ_{rech} (the subscript referring to recharge). The flow associated with that water content is the recharge rate to the water table. At the beginning of the simulation the water content is assumed to be uniform. Let z_f denote the depth of a descending front and z_{rf} denote the height of the current water table (Fig. 1). D_{wt} is the depth to the initial position of the water table and $\tilde{\theta}$ is the water content at natural saturation. Let q_{rech} designate the recharge rate into the current water table. The cumulative net infiltration water depth since time zero must fill the available pore space under the rectangular water content profiles, thus the relation:

$$W = \int_0^t \left\{ \left[i_{sr}(\tau) - q_{rech}(\tau) \right] d\tau \right\} = z_f(\theta - \theta_i) + (\theta_{rech} - \theta_i)(D_{WT} - z_f - z_{rf}) + (\tilde{\theta} - \theta_i) z_{rf} \qquad (1)$$