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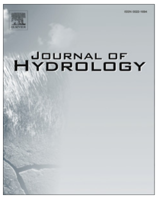

Research papers

Modeling hourly subsurface drainage using steady-state and transient methods

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ABSTRACT

Computer models have been frequently used to simulate the hydrologic and environmental processes in subsurface-drained cropland. The widely-tested steady-state Hooghoudt (*ssH*) equation, implemented in the Root Zone Water Quality Model (RZWQM2, version 2.94.00), serves in simulating subsurface drainage. However, transient methods such as the integrated Hooghoudt (*inH*) and van Schilfgaarde (*vanS*) equations have seldom been implemented in models. In the present study, RZWQM2's hydrologic component was modified to initiate the soil water redistribution process when rainfall occurred. The three drainage equations (*ssH*, *inH* and *vanS*) were tested in each of two versions of RZWQM2 (original and modified). Field data from Iowa (2007–2008) and Ontario (2009–2010) were used to evaluate different model version × equation combinations' simulation accuracy at both daily and hourly scales, evaluated using the percent of bias (*PBIAS*), Nash-Sutcliffe efficiency coefficient (*NSE*), and the Index of Agreement (*IoA*). On a daily scale and across equations, for the Iowa data the original model ($PBIAS \leqslant 14.96, NSE \geqslant 0.40, \geqslant 0.69$) was outperformed by the modified model ($PBIAS \leqslant 6.48, NSE \geqslant 0.70, IoA \geqslant 0.76$). Similarly, for the Ontario data, the original model ($PBIAS \leqslant 8.87, NSE \geqslant 0.19, IoA \geqslant 0.65$) was outperformed by the modified model ($PBIAS \leqslant 3.59, NSE \geqslant 0.31, IoA \geqslant 0.67$). However, based on a parity of *PBIAS*, *NSE* and *IoA* values, hourly scale tile drainage computed using the modified model equipped with transient equations did not improve model performance compared with the original *ssH* equation.

1. Introduction

As an important physical component in agricultural systems, subsurface drainage is implemented to improve field trafficability and crop yield. Tied to factors such as drain layout, weather, soil texture and irrigation rates and methods, tile drainage flow rates from agricultural lands influence water table levels as well as nutrient and pesticide losses to groundwater (Stämpfli and Madramootoo, 2006; Baker and Johnson, 1981). The development of computer technology has provided the capacity to accurately simulate agricultural and hydrologic processes rather than time- and cost-inefficient field experimentation. Generally used in simulating cropping systems and predicting the effects of different agronomic operations, such soil-water-crop-climate system models (*e.g.* RZWQM2, DRAINMOD, SWAT, GLEAMS) almost invariably include a hydrologic module. Such models have been shown to provide acceptable simulations in subsurface drainage flow (Qi et al., 2011; Ma et al., 2007a,b; Wang et al., 2006; Singh et al., 2006; Moriasi et al., 2013; Gowda et al., 2012; Sogbedji and McIsaac, 2002; Ritzema et al., 2008; Sharma and Gupta, 2006).

The Root Zone Water Quality Model (version 2.94.00) is a widely-used agricultural system model first developed in 1992, and subsequently coupled with other models such as DSSAT and SHAW. Compared with other models, RZWQM2 provides a more comprehensive simulation of agricultural systems, including the interactions between hydrology, agricultural management practices, crop growth and fate and transport of chemicals (Ahuja et al., 2003). A subsurface drainage component was incorporated into RZWQM2 in 1994, enabling the model to simulate tile drainage flow (Singh and Kanwar, 1995). Different from other agro-hydrological models such as DRAINMOD, SWAT and GLEAMS, which include a drained-to-equilibrium based soil water dynamic component (Skaggs et al., 2012; Arnold et al., 2012; Knisel and Douglas-Mankin, 2012), the soil water redistribution in RZWQM2 is based on Richards equation which determines soil water movement using soil water potential for every soil node and each simulation time step. That facilitates RZWQM2 in testing different

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subsurface drainage modeling methods as it provides update in water table fluctuation under precise time step. Furthermore, it is the first time to modify the timing of soil water redistribution and drainage in a Richards equation based hydrologic model. The hydrologic component is the core of RZWQM2, which coordinates with other components in modeling crop, chemicals transportations and management practice. Therefore, improving subsurface drainage simulation in RZWQM2 can lead to robust model performance in other related functionalities.

The performance of RZWQM2's hydrologic component was tested on different scenarios of subsurface drain flow data, and the overall performance was deemed acceptable (Kanwar et al., 1997; Akhand et al., 2003). Simulations of hydrologic process under a corn-soybean rotation with different winter land cover treatments in north central Iowa, found simulated annual subsurface drainage to closely match observed data; the percent of bias (*PBIAS*) was within 11%, the Nash Sutcliffe Efficiency coefficient (*NSE*) exceeded 0.84, and the ratio of the root mean square error to the standard deviation (*RSR*) was below 0.40 (Qi et al., 2011). However, some delays in simulated (vs. actual) drainage were observed for extended rainfall events in this study, and the high drainage peaks were underestimated in this scenario. These problematic simulations may be due to inadequate methods of subsurface drainage calculation in RZWQM2, and alternative approaches should be tested to improve the model.

In the original RZWQM2, the onset of a rainfall or irrigation event would activate the simulation of infiltration processes using the Green-Ampt model. As Richards equation is not applied to the redistribution of soil moisture in the profile during infiltration, infiltrated water is held above the wetting front. It is not distributed to the unsaturated soil profile below the wetting front and not used to raise the water table until the rainfall ceases. A constant drainage rate which begins when rain starts and is calculated using a constant water table height above the drain, along with unit gradient flow in an unsaturated soil matrix are used to accumulate drain outflow over this period (Ahuja et al., 2003). At the onset of the current infiltration event this outflow is calculated using the steady-state Hooghoudt (*ssH*) equation. During infiltration this constant drainage rate will be updated only if the wetting front reaches the water table, resulting in ponding conditions. For extended rainfall events, which usually also coincides the periods of elevated drainage, drainage would occur with a delay of at most one day. This delay could be critical for agricultural contaminants modeling, as many pesticides and herbicides have short degradation half-lives, and the fate and subsurface transport of these contaminants are highly related to subsurface drainage (Malone et al., 2004). The high concentration of the contaminants in the leachate is usually accompanied by intensive drainage (Kumar et al., 1998). Therefore, higher accuracy in drainage peak simulations also benefits the prediction in the fate of agricultural contaminant. To simulate soil water movement more appropriately and solve the drainage delay problem, redistribution of water in the soil profile must be assumed to occur simultaneously with rainfall.

In addition, the appropriateness of using the *ssH* drainage equation to compute subsurface drainage has been questioned in a number of studies which attempted to identify alternative drainage equations offering better simulation accuracy (Shokri and Bardsley, 2014; Mishra and Singh, 2007; Pali et al., 2014). Drainage equations can be classified into two principal categories: steady-state equations and non-steady-state (transient) equations (Oosterbaan, 1994). Steady-state equations, rather quasi-steady state equations, assume that drainage outflow is equal to the net recharge over a given period of time, with the water table remaining at the same depth during this period (Darzi-Naftchally et al., 2014), but changing between the time periods. Common steady-state equations include the Hooghoudt, Kirkham, Ernst, and Dagan equations. Comparatively, in the case of transient equations recharge and discharge differ: (i) when recharge exceeds discharge, the water table rises, resulting in a rise in discharge rate until it reaches the inflow rate, (ii) when discharge exceeds recharge, both the water table and drainage rate drop. As a result, under transient conditions the water table fluctuates around an average depth during a given period.

The objectives of this study were therefore: 1) to modify RZWQM2's hydrologic component and to improve drainage flow simulation by allowing soil moisture redistribution and drainage to occur simultaneously with rainfall, and 2) to compare the accuracy of RZWQM2 in simulating daily and hourly tile drainage using the transient *inH* and *vanS* equations to that using the standard *ssH* equation. The comparisons in this study are based on precise hourly data which is seldom used in drainage simulation. Hourly data can be used to more precisely evaluate the accuracy of a model (Kohler et al., 2001), since a peak drainage event usually last for only a few hours. The subsurface drainage hydrograph on a daily scale are vague, while hourly hydrograph can provide much more detailed information about the timing of drainage peaks.

2. Materials and methods

2.1. Modification of the approach in simulating tile drainage

In order to solve the delayed drainage peaks due to inappropriate soil water redistribution method in the original RZWQM2, we modify the model to better represent the situation observed in experimental plots. Redistribution of water in the soil profile and subsurface drainage are assumed to occur simultaneously with rainfall. To achieve this modification, we reset the starting time step of soil water redistribution as the first time step of the rainfall event. During the rainfall, the constant drainage rate will be replaced with a dynamic drainage rate computed using *ssH* and changing water table (the modifications to the RZWQM2 code are provided in Appendix). Drainage flow data during 2007 and 2008 from Iowa, and during 2009 and 2010 from Ontario were used to evaluate the accuracy of simulations. Information regarding measured data is presented in the "Observed data and parameterization" section below.

2.2. Different equations to simulate tile drainage

In RZWQM2's basic hydrology module the steady state Hooghoudt equation (*ssH*) is used to calculate the subsurface drainage rate *R*. This equation assumes that the water table is unchanged during the drainage period (Fig 1A):

$$R = \frac{8K_e d_e m + 4K_e m^2}{S^2} \tag{1}$$

where R is the subsurface drainage rate (m d^{-1}), m is the depth from the midway water table to the drains (m), d_e is the effective depth of the soil profile (m), K_e is the effective hydraulic conductivity (m d^{-1}), and S is the drain spacing (m)

The value of K_e is calculated as:

$$K_e = \frac{\sum_{i=1}^{i=n} D_i K_i}{\sum_{i=1}^{i=n} D_i} \tag{2}$$

where n is the number of soil layers (set by model user), D_i is the thickness of layer I (m), and K_i is the lateral hydraulic conductivity of layer i (m h^{-1}).