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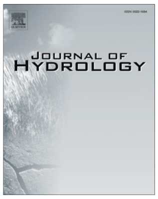

Research papers

Controlled laboratory experiments and modeling of vegetative filter strips with shallow water tables

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ABSTRACT

Natural or planted vegetation at the edge of fields or adjacent to streams, also known as vegetative filter strips (VFS), are commonly used as an environmental mitigation practice for runoff pollution and agrochemical spray drift. The VFS position in lowlands near water bodies often implies the presence of a seasonal shallow water table (WT). In spite of its potential importance, there is limited experimental work that systematically studies the effect of shallow WTs on VFS efficacy. Previous research recently coupled a new physically based algorithm describing infiltration into soils bounded by a water table into the VFS numerical overland flow and transport model, VFSMOD, to simulate VFS dynamics under shallow WT conditions. In this study, we tested the performance of the model against laboratory mesoscale data under controlled conditions. A laboratory soil box (1.0 m wide, 2.0 m long, and 0.7 m deep) was used to simulate a VFS and quantify the influence of shallow WTs on runoff. Experiments included planted Bermuda grass on repacked silt loam and sandy loam soils. A series of experiments were performed including a free drainage case (no WT) and a static shallow water table (0.3–0.4 m below ground surface). For each soil type, this research first calibrated VFSMOD to the observed outflow hydrograph for the free drainage experiments to parameterize the soil hydraulic and vegetation parameters, and then evaluated the model based on outflow hydrographs for the shallow WT experiments. This research used several statistical metrics and a new approach based on hypothesis testing of the Nash-Sutcliffe model efficiency coefficient (NSE) to evaluate model performance. The new VFSMOD routines successfully simulated the outflow hydrographs under both free drainage and shallow WT conditions. Statistical metrics considered the model performance valid with greater than 99.5% probability across all scenarios. This research also simulated the shallow water table experiments with both free drainage and various water table depths to quantify the effect of assuming the former boundary condition. For these two soil types, shallow WTs within 1.0–1.2 m below the soil surface influenced infiltration. Existing models will suggest a more protective vegetative filter strip than what actually exists if shallow water table conditions are not considered.

1. Introduction

A commonly used method for reducing sediment, nutrient, and pesticide loadings from agricultural fields is the edge-of-field vegetative filter strip, VFS (Popov et al., 2005; Reichenberger et al., 2007; Fox et al., 2010, 2011; Muñoz-Carpena et al., 2010; Lacas et al., 2012). A VFS reduces sediment, nutrient, and pesticide movement to streams by decreasing runoff volumes through infiltration into the soil profile, allowing contact between dissolved phase solutes and vegetation, and/or by reducing flow velocities to the point where sediment and sorbed solutes can settle out of the water.

Commonly VFS are placed adjacent to streams in riparian floodplains or adjacent to drainage ditches at the edge of an agricultural field, where shallow groundwater tables can be present (Lacas et al., 2005; Dosskey et al., 2011; Carluer et al., 2016). While it is commonly recognized that a shallow groundwater table may limit infiltration into a soil profile, there is a lack of controlled, experimental data available for demonstrating when this limitation becomes important.

Various strategies have been used to model shallow groundwater tables in hydrologic models. It is generally well known that shallow groundwater tables can significantly affect infiltration

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Abbreviations: bgs, below ground surface; VFS, vegetative filter strip; VFSMOD, Vegetative Filter Strip Modeling System.
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rates and therefore surface runoff during rainfall events. For example, Salvucci and Entekhabi (1995) and Chu (1997) proposed approximate non-uniform Green-Ampt solutions for infiltration with ponded soils bounded by a water table. However, this effect is often ignored or handled simplistically in many common simulation models. Specifically, as an example for vegetative filter strips or riparian buffers, the Riparian Ecosystem Management Model (REMM) simulates water movement and storage through a riparian buffer including subsurface lateral flow, upward flux from the water table, and deep seepage (Lowrance et al., 2000; Tilak et al., 2014). However, water storage and movement in REMM and other models is based on simplistic mass balance, rate controlled approaches, and operates on a daily time scale. A widely used watershed model (SWAT, Arnold and Fohrer, 2005) that contains a VFS component derived empirically from other model simulations (White and Arnold, 2009) does not account for shallow water table effects. A more robust and mechanistic modeling package is needed that is capable of operating at the event time scale.

Process-based models can predict VFS efficiency for pollutant removal and thereby allow site-specific design of VFS physical characteristics (length, width, slope, and type of vegetation). The design process is heavily dependent on being able to predict infiltration and sedimentation processes in the VFS. One such model, VFSMOD, is a field-scale, mechanistic, storm-based numerical model that estimates water and sediment retention for single storm or a time-series of storm events (Muñoz-Carpena et al., 1999; Muñoz-Carpena and Parsons, 2004, 2008). VFSMOD routes an incoming hydrograph and sedimentograph from an adjacent field through a VFS to calculate the resulting outflow, infiltration, and sediment trapping (Muñoz-Carpena et al., 1993a,b, 1999). Infiltration is modeled based on the Green-Ampt equation for unsteady rainfall. The model includes an automated and robust inverse calibration routine (Ritter et al., 2007) to optimize input parameters based on the Global Multilevel Coordinate Search algorithm (Huyer and Neumaier, 1999) in sequential combination with the local Nelder-Mead Simplex algorithm (Nelder and Mead, 1965). VFSMOD has been globally used to optimize filter placement and design (Kuo and Muñoz-Carpena, 2009; Balderacchi et al., 2016; Pan et al., 2017) and has been integrated into pesticide exposure assessment frameworks (e.g., Sabbagh et al., 2010; Bach et al., 2017).

A recently released version of VFSMOD considers the presence of a static, shallow water table (WT, hereon) in order to expand its applicability across a wide range of field conditions (Muñoz-Carpena et al., 2017; Lauvernet and Muñoz-Carpena, 2017). The SWINGO (Shallow Water table INfiltration alGOrithm) component in VFSMOD is a modified form of the integral solution to ponded infiltration for soils bounded by a water table proposed by Salvucci and Entekhabi (1995) and Chu (1997). The modification included making the solution numerically explicit in time and adding new integral formulae for calculation of the singular infiltration times: time of ponding and time to soil profile saturation. The new routine was validated against a numerical solution of Richards' equation for varying WT depths and rainfall intensities on five distinct soils (Muñoz-Carpena et al., 2017) and evaluated on two benchmark studies through global sensitivity and uncertainty analysis (Lauvernet and Muñoz-Carpena, 2017). These preliminary investigations demonstrated that the WT influenced infiltration and runoff for depths shallower than 1.0–1.5 m, but was negligible for deeper water tables. Also, soils that exhibited a marked (i.e., more definitive) air entry (bubbling pressure head) on their soil water characteristic curve were more prone to surface hydrology changes as quick saturation was reached when the wetting front reached the capillary fringe above the water table. Global sensitivity analysis of the modified model showed that WT depth was the first or second most important factor next to saturated hydraulic conductivity in controlling the changes in surface flow, sediment and pesticide trapping of the VFS (Lauvernet and Muñoz-Carpena, 2017). However, there remains a lack of experimental data for systematic validation of the updated model under controlled hydrologic conditions. Lauvernet and Muñoz-Carpena (2017) specifically call for laboratory and field research detailing the response of a VFS under both deep and shallow WTs.

Therefore, the research objectives were to (i) investigate the influence of shallow WTs on outflows from a VFS using meso-scale laboratory soil box, (ii) evaluate the performance of a new shallow WT algorithm in VFSMOD for simulating shallow WT effects, and (iii) utilize VFSMOD to determine the depth at which shallow WT conditions influence VFS effectiveness. The research evaluated the performance of VFSMOD for experiments without (free drainage) and with a shallow WT using several statistical metrics including a hypothesis testing approach recently proposed by Ritter and Muñoz-Carpena (2013).

2. Methods and materials

2.1. Brief description of the shallow water table Modeling component

The original infiltration component of VFSMOD was based on a modification of the Green-Ampt equation for unsteady rainfall with no restrictions due to the presence of a WT (Chu, 1978; Skaggs and Khaheel, 1982; Muñoz-Carpena et al., 1993b). Full details of the new WT algorithm within VFSMOD are provided in Muñoz-Carpena et al. (2017) and Lauvernet and Muñoz-Carpena (2017). Here we provide a brief description to ground the experimental setup and testing of the model performed in this study.

The new WT algorithm calculates the actual infiltration rate f (Eq. (1)) at the VFS soil surface for each time t [T] assuming the soil surface is not ponded at the beginning of the event:

$$f = \begin{cases} i & 0 < t < t_p \\ K_s + \frac{1}{z_f}\int_0^{L-z_f} K(h)dh & t_p < t < t_w \\ \min(f_w, i) & t \geqslant t_w \end{cases} \tag{1}$$

where $i = i(t)$ [L/T] is rainfall intensity; z [L] is the depth from the surface; z_F [L] is the wetting front depth; L [L] the depth from the surface to the water table; $K = K(h)$ [L/T] is the soil water hydraulic conductivity as a function of the soil suction, h [L] (non-uniform with depth); K_s [L/T] is the saturated hydraulic conductivity; t_p [T] is the time to surface ponding from the beginning of the event; and t_w [T] and f_w [L/T] are the time and the vertical flow boundary condition when the wetting front reaches the water table (or its capillary fringe, h_b) at depth z_w (L) (Fig. 1). Two options for f_w are provided. A Vachaud and Thony (1971) condition is commonly used in experiments corresponding to vertical saturated flow, $f_w = K_s$ (Salvucci and Entekhabi (1995); Liu et al., 2011). This boundary condition can overestimate the final f in some field situations, particularly when the WT drains to the nearby stream. For this case, another option is available to simulate lateral drainage following Dupuit-Forchheimer assumptions (Van Hoorn and Van Der Molen, 1973), assuming a water table slope equal to the soil surface slope, S_o (Beven and Kirkby, 1979; Vertessy et al., 1993):

$$f_w \approx \frac{K_{sh} S_o z_w}{VL} \tag{2}$$

where K_{sh} [L/T] is the lateral (horizontal) soil saturated hydraulic conductivity, VL [L] is the filter length (VFS dimension in the flow direction), and z_w [L] is the effective saturation depth that depends