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Effect of surface and subsurface heterogeneity on the hydrological response of a grassed buffer zone

Laura Gatel [a,b,*], Claire Lauvernet [a], Nadia Carluer [a], Claudio Paniconi [b]

[a] Irstea, UR MALY, centre de Lyon-Villeurbanne, F-69616 Villeurbanne, France
[b] INRS-ETE, Université du Québec, 490 rue de la Couronne, Quebec City G1K 9A9, Canada

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ABSTRACT

Grassed buffer zones are an effective method to reduce contaminant impacts on aquatic environments. The general objective of this study is to explore the impact of both surface and subsurface heterogeneity on the hydrological responses of a vegetative buffer strip. Heterogeneity is described by two variables, microtopography and saturated hydraulic conductivity. Numerous surface and subsurface heterogeneity scenarios were simulated with a physically-based numerical model of coupled surface/subsurface processes. The scenarios were evaluated relative to data from an experimental vegetative filter in a Beaujolais vineyard, France. The subsurface scenarios show that conductivity heterogeneity plays a key role on the buffer strip's capacity to infiltrate incoming surface runoff and on the ensuing runoff pathways. The conjunctive surface and subsurface scenarios indicate that microtopography variability is comparatively less influential on the hydrological interactions and pathways within the buffer strip, and that representing this heterogeneity via appropriate statistical distributions can be a good assumption in practice.

1. Introduction

Non-point source pollution due to contaminant transfer from agricultural fields to aquatic environments is still a major environmental problem. Amongst best management practices, landscape elements such as fences or buffer strips can help mitigate this transfer. In particular, vegetative buffer strips between crops and rivers are becoming mandatory in several countries (Poletika et al., 2009; Real et al., 2013). Such grassed zones create a fostering area for infiltration, sedimentation, adsorption and degradation (Dosskey, 2001; Fox et al., 2005). Within these zones, water, pesticide and sediment behaviours are complex, especially concerning runoff, surface lateral transfers and surface-subsurface interactions (Carter, 2000; Lacas, 2005). The sizing and placement of grassed buffer zones in a watershed requires a correct understanding and quantification of these complex processes. A first approach for doing this is via field experiments. For example, Lacas et al. (2012) showed on their experimental vegetative filter (Beaujolais vineyard, France) that buffer efficiency for a moderately soluble contaminant (Diuron) is related to two main mechanisms: water runoff infiltration and contaminant retention in the superficial soil horizons. These results are related to a specific context: the hillslope is steep (25% slope), with a highly permeable sandy clay topsoil overlying a granitic sand formation that induces lateral subsurface fluxes. This field study showed that permeability has a dominant influence on hydrological behaviour and buffer strip efficiency, but the results are not easily transferable to other sites characterized by different soil types, climate conditions and agricultural practices (Lacas et al., 2005; Poletika et al., 2009).

Physically-based models represent a second approach for the detailed investigation of the processes and dynamics associated with buffer strips. They allow us to describe the relevant physics with more detail and accuracy than conceptual models, which is necessary to study complex and interacting processes. For example the models GRASS (Lee et al., 1989), VFSMOD (Munoz-Carpena et al., 1999) and HYDRUS (Simunek et al., 1999; Yu and Zheng, 2010; Koehne et al., 2011) have all been used to simulate water behaviour in vegetative strips (Abu-Zreig, 2001; Lacas, 2005) and to assist in the design of these buffer zones (Dosskey, 2001). In modelling studies, saturated hydraulic conductivity (K_s) is generally found to be the most influential parameter on infiltration (Munoz-Carpena et al., 1999; Sovik and Aagaard, 2003; Herbst et al., 2006). This confirms the finding from other study sites and scales that K_s is dominant for relatively wet soils (Gribb, 1996; Yeh and Zhang, 1996; Boateng, 2001; Mertens et al., 2005), whereas saturated soil water content is the most influential

* Corresponding author at: Irstea, UR MALY, centre de Lyon-Villeurbanne, 5 rue de la Doua, BP 32108, 69616 Villeurbanne Cedex, France.
E-mail address: laura.gatel@irstea.fr (L. Gatel).

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parameter under dry soil conditions (Simunek et al., 1998; Abbasi et al., 2004; Dages et al., 2008).

Another parameter that can be highly influential in the context of vegetative buffer strips but that has been much less studied than K_s is microtopography, which is defined here as the soil surface variation from the 1 cm to 1 m scale (Liang and Xie, 2001; Polyakov et al., 2005; Moser et al., 2007). Measuring these two parameters that are representative of subsurface (K_s) and surface (microtopography) heterogeneity is costly, time-consuming and uncertain (Mohanty et al., 1994), since both are known to be highly variable horizontally and vertically (Beven et al., 1988; Ceddia et al., 2009; Mulla, 2010). Subsurface heterogeneity is highly influential on water movement, and thus solute transfer. On the surface, both K_s and microtopography play a key role in regulating surface runoff spatial distribution and intensity (Woolhiser et al., 1996; Sole-Benet et al., 1997). In their review of uncertainty in soil physical properties, Van Der Keur and Iversen (2006) summarize the assessment of horizontal saturated hydraulic conductivity autocorrelation from the literature: it can vary from 1 m (Sobieraj et al., 2004; Mulla, 2010) to 120 m (Cook et al., 1989) for field areas from 0.25 ha (Russo and Bresler, 1981) to 14 ha (Cook et al., 1989). The land surface heterogeneity effect has been much less studied, but according to Chen et al. (2013) and Frei et al. (2010), ignoring small scale dynamics by representing complex slopes as smooth landforms leads to an inaccurate representation of the hydrological response.

Even when heterogeneity is recognized, one challenge is to define it properly for modelling. The study scale is an important factor to consider before trying to take into account the heterogeneity. For example, Seyfried (1998) shows that a spatial variability that is significant at the 12 m^2 scale can be described as random in larger scale models. Other studies have dealt with heterogeneity by upscaling soil property variability from fine scale to larger areas (e.g., Samouelian et al., 2011).

When K_s heterogeneity is represented in studies, it is via a log-normal distribution per layer (Dagan and Bresler, 1983) or even for the whole soil (Abdou and Flury, 2004; Craig et al., 2010; Govindaraju et al., 2012; Pasetto et al., 2015), with the challenge being to define the relevant correlation scale, which is also dependent on the study scale (Van Der Keur and Iversen, 2006). For microtopography, most hillslope scale studies describe it with a Gaussian distribution (Zinn and Harvey, 2003; Antoine et al., 2011; Appels et al., 2011; Yang and Chu, 2015), despite recognition that the degree and structure of this heterogeneity are scale and time dependent (Atkinson and Tate, 2000; Thompson et al., 2010). The influence of both K_s and microtopographic heterogeneity in modelling has never been studied simultaneously despite being recognized as an important factor for improving models (Anderton et al., 2002). Today, with more attention given to integrated water resources management and with the emergence of detailed process-based models for simulating surface-subsurface interactions (Paniconi and Putti, 2015), the roles of surface and subsurface heterogeneity need to be jointly examined.

The general objective of this study is to assess the impact of both surface and subsurface heterogeneity, characterized by microtopography and saturated hydraulic conductivity, on the hydrological responses and interactions that occur in a vegetative buffer strip. The insights gained should help improve model parameterization schemes. We use the physically-based coupled hydrological model CATHY (Camporese et al., 2010) applied to the experimental buffer strip from Lacas (2005). The hydrological responses considered include surface runoff pathways and outputs, infiltration to the subsurface, and water volume partitioning between surface and subsurface (both saturated and unsaturated) domains. The intent was not to precisely model this specific vegetative buffer strip, but rather to rely on the experimental data to ensure that the simulated results are realistic. In a first step, we assess the effect of K_s heterogeneity on surface and subsurface hydrological fluxes by applying the CATHY model with several K_s distribution scenarios to an artificial runoff event and a natural rain and runoff event. In the second step of the study, the effects of microtopography coupled to K_s heterogeneity on the hydrological responses of the buffer strip are examined.

2. Material and methods

2.1. CATHY model

The CATHY (CATchment HYdrology) model (Paniconi and Putti, 1994; Camporese et al., 2010) is a physically-based model that simulates surface and subsurface water flows and their interactions in three dimensions. It integrates the 3D Richards equation for variably saturated porous media and a 1D diffusive wave equation, which is a simplification of Navier-Stokes equations, to describe surface flow through overland and stream channel networks:

$$S_w S_s \frac{\partial \psi}{\partial t} + \phi \frac{\partial S_w}{\partial t} = \nabla[K_s K_r(\nabla \psi + \eta_z)] + q_{ss} \quad (1)$$

$$\frac{\partial Q}{\partial t} + c_k \frac{\partial Q}{\partial s} = D_h \frac{\partial^2 Q}{\partial s^2} + c_k q_s(h, \psi) \quad (2)$$

where S_w [−] is the water saturation $\left(S_w = \frac{\theta}{\phi}\right)$, θ [−] is the volumetric moisture content, ϕ [−] is the saturated moisture content or the porosity, S_s [L^{-1}] is the aquifer specific storage, ψ [L] is the pressure head, t [T] is time, ∇ [L^{-1}] is the gradient operator, K_s [$L\,T^{-1}$] is the saturated hydraulic conductivity, K_r [−] is the relative conductivity, $\eta_z = (0, 0, 1)$, z [L] is the vertical coordinate directed upward, q_{ss} [$L^3\,L^{-3}\,T$] is a source (positive) or sink (negative) term that includes the exchange fluxes from the surface to the subsurface, Q [$L^3\,T^{-1}$] is the discharge (volumetric flow) along the overland and channel network, s [L] is the coordinate direction for each segment of the overland and channel network, c_k [$L\,T^{-1}$] is the speed of the kinematic wave, D_h [$L^2\,T^{-1}$] is the hydraulic diffusivity, h [L] is the height of the surface water (ponding head at the surface, representing state variable continuity with subsurface head) and q_s [$L^3\,L^{-1}\,T$] is the inflow or outflow rate from the subsurface to the surface.

Eqs. (1) and (2) are solved on a regular mesh at the surface that is replicated vertically to form a 3D tetrahedral mesh. The vertical layers can be of varying thickness, and different soil hydraulic properties can be assigned to each node of the mesh. Boundary conditions and atmospheric forcing can be dynamically prescribed. The surface mesh for the routing Eq. (2) is generated in a preprocessing step that establishes the flow paths (s directions) from topographic analysis of a digital terrain model and partitions the catchment into overland (hillslope) and channel (stream) cells (Orlandini et al., 2003). The coupling between surface and subsurface processes in CATHY involves boundary condition switching according to the balance between atmospheric forcing (rainfall and potential evaporation) and the infiltration or exfiltration soil capacity. More details on the CATHY model can be found in Camporese et al. (2010).

2.2. Experimental buffer strip

The CATHY model is applied in the frame of several numerical experiments on a steeply sloping (25%) buffer strip monitored by