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Development, testing and application of *DrainFlow*: A fully distributed integrated surface-subsurface flow model for drainage study

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ABSTRACT

Hydrological and hydrogeological investigation of drained land is a complex and integrated procedure. The scale of drainage studies may vary from a high-resolution small scale project through to comprehensive catchment or regional scale investigations. This wide range of scales and integrated system behaviour poses a significant challenge for the development of suitable drainage models. Toward meeting these requirements, a fully distributed coupled surface-subsurface flow model titled *DrainFlow* has been developed and is described. *DrainFlow* includes both the diffusive wave equation for surface flow components (overland flow, open drain, tile drain) and Richard's equation for saturated/unsaturated zones. To overcome the non-linearity problem created from switching between wet and dry boundaries, a smooth transitioning technique is introduced to buffer the model at tile drains and at interfaces between surface and subsurface flow boundaries. This gives a continuous transition between Dirichlet and Neumann boundary conditions. *DrainFlow* is tested against five well-known integrated surface-subsurface flow benchmarks. *DrainFlow* as applied to some synthetic drainage study examples is quite flexible for changing all or part of the model dimensions as required by problem complexity, problem scale, and data availability. This flexibility enables *DrainFlow* to be modified to allow for changes in both scale and boundary conditions, as often encountered in real-world drainage studies. Compared to existing drainage models, *DrainFlow* has the advantage of estimating actual infiltration directly from the partial differential form of Richard's equation rather than through analytical or empirical infiltration approaches like the Green and Ampt equation.

1. Introduction

In artificially drained land, several physical processes of water transfer from land surface into tile-drained ground are involved during a rain event. Rainwater infiltrates from ground surface through the soil profile to the saturated zone, raising the water table. Water moves into the drains if the water table rises above drain level.

It may happen during the rain event that rainfall rate exceeds infiltration capacity. This will be evident initially as ground surface ponding in micro-depressions. Once depression storage capacity is exceeded, any subsequent excess rainfall moves downslope as either overland sheet flow or micro-channel flow. The presence of any surface water means that infiltration will continue after rainfall cessation until the water has evaporated, infiltrated, or drained downslope.

Taking these multiple surface and subsurface processes into account means that developing a comprehensive model for an artificially drained land area is a challenge because subsurface drainage is strongly connected to surface flow (Skaggs, 1980). In addition, the modelled spatial scale may vary from high-resolution small scale investigations through to comprehensive catchment-scale or regional studies.

Many empirical/analytical expressions (Hooghoudt, 1940, Moody, 1966, Sakkas and Antonopoulos, 1981, Mishra and Singh, 2007, Mishra and Singh, 2008, Çimen, 2008, Kirkham, 1958, Van der Molen and Wesseling, 1991, Dagan, 1964, Hammad, 1962, Ernst, 1962, Youngs, 1975, Youngs, 1965, List, 1964, Childs, 1969, Collis-George and Youngs, 1958, Miles and Kitmitto, 1989, Tiwari, 1996, Tiwari, 1996, Lovell and Youngs, 1984, Kirkham, 1966, Youngs, 2012, Youngs, 2013) and numerical solutions (Gureghian and Youngs, 1975, Zaradny and Feddes, 1979, Smedema et al., 1985, Khan and Rushton, 1996c, Khan and Rushton, 1996b, Khan and Rushton, 1996a, Zaradny, 2001, Zavala et al., 2007, Castanheira and Santos, 2009, Pandey et al., 1992, Chavez et al., 2011a, Chavez et al., 2011b, Jiang et al., 2010, Shokri and Bardsley, 2014, Henine et al., 2014) have been developed to relate tile drain discharge to

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soil hydrodynamic properties, tile drain depth, and drain spacing. In addition, a number of special-purpose computer codes have been developed for estimating optimal drain spacing, including *DRAINMOD* (Skaggs, 1980), *DRENAFEM* (Castanheira and Santos, 2009) and *MHYDAS-DRAIN* (Tiemeyer et al., 2007).

Existing analytical and numerical drainage models rarely link surface and subsurface flow explicitly with overland flow and groundwater transfer (Weill et al., 2009). In fact, neither subsurface nor surface flow models in themselves have capacity to reflect the complete surface-subsurface flow behaviour in an artificially drained catchment.

Coupled surface-subsurface physical flow processes have been extensively investigated over the last decade (Weill et al., 2009, Sophocleous, 2002, Panday and Huyakorn, 2004, Furman, 2008, Weill et al., 2011). The literature describes a range of environmental process applications including irrigation and drainage (Schoups et al., 2005, Zerihun et al., 2005, Zerihun et al., 2005, Rozemeijer et al., 2010, Shokri, 2011, Banti and Zissis, 2011, Dong et al., 2013, Morrison, 2014), solute transport and particle-tracking (Weill et al., 2011, Sudicky et al., 2008), sediment transport (Li and Duffy, 2011, Ran et al., 2007), flood control (Liang et al., 2007), residence time and hydrograph separation (Liggett et al., 2014, Partington et al., 2013, Partington et al., 2011, Meyerhoff and Maxwell, 2011, Kollet and Maxwell, 2008, Bayani Cardenas, 2008), land surface recharge (Guay et al., 2013, Smerdon et al., 2008, Lemieux et al., 2008), and runoff generation (Meyerhoff and Maxwell, 2011, Delfs et al., 2013, Sulis et al., 2011, Gauthier et al., 2009, Camporese et al., 2009, Mirus et al., 2009, Maxwell and Kollet, 2008, Li et al., 2008, Jones et al., 2008, Qu and Duffy, 2007, Heppner et al., 2007, Ebel et al., 2007).

At the same time, there has been progress in coupled surface/subsurface flow modelling. This includes, for example, *ParFlow* (Kollet and Maxwell, 2008, Kollet and Maxwell, 2006, Maxwell and Miller, 2005) *PAWS* (Shen and Phanikumar, 2010), *CATHY* (Camporese et al., 2010), *HydroGeoSphere* (HGS) (Brunner and Simmons, 2012, Aquanty Inc., 2013), *InHM* (Qu and Duffy, 2007, Kumar et al., 2009), *tRIBS + VEGGIE* (Kim et al., 2013, Ivanov et al., 2010, Ivanov et al., 2008), and *OpenGeoSys (OGS)* (Delfs et al., 2009, Delfs et al., 2012). However, the available codes may not be sufficiently flexible to apply specifically to drainage studies in their present form, without some further adaption to enable application over a variety of spatial and time scales.

As a contribution to this subject area, a new fully distributed coupled surface-subsurface model named hereafter as *DrainFlow* model has been developed and is presented here. It has particular advantage in handling the scale issue through optional dimensioning of surface and subsurface flow domains relative to complexity of the physical situation, scale of application, and data availability. The model utilizes the fact that even though higher dimensions enable a wider range of application, it often happens that useful solutions can be obtained from lower-dimension specification.

DrainFlow is constructed as linked modules of code which are specific to various surface and subsurface flow processes in the COMSOL Multiphysics environment, which is a finite element code for various physics and engineering applications (COMSOL, 2012). All *DrainFlow* modules interact during model operation, giving model output as soil moisture, overland flow rates, drain outflow rates, and water level in the subsurface domain. In contrast to traditional analytical and numerical drainage models, *DrainFlow* uses aspects of COMSOL to enable actual infiltration estimation directly from the partial differential Richards equation (Richards, 1931) rather than using analytical/empirical methods like Green and Ampt (Green and Ampt, 1911).

One specific feature of *DrainFlow* is incorporation of a function allowing smooth switching between dry and wet boundaries. The serves to buffer the model against potentially numerically unstable situations such as tile drain boundary conditions or the interfaces of surface and subsurface flow domains.

With reference to the structure of this paper, Sections 2, 3, and 4 introduce the surface and subsurface flow modules, relevant equations, and the methodology for coupling the relevant equations and modules. Section 5 gives results from testing *DrainFlow* against five well-known integrated surface-subsurface flow benchmarks introduced by Maxwell et al., (2014). Section 6 illustrates application of *DrainFlow* to two hypothetical examples.

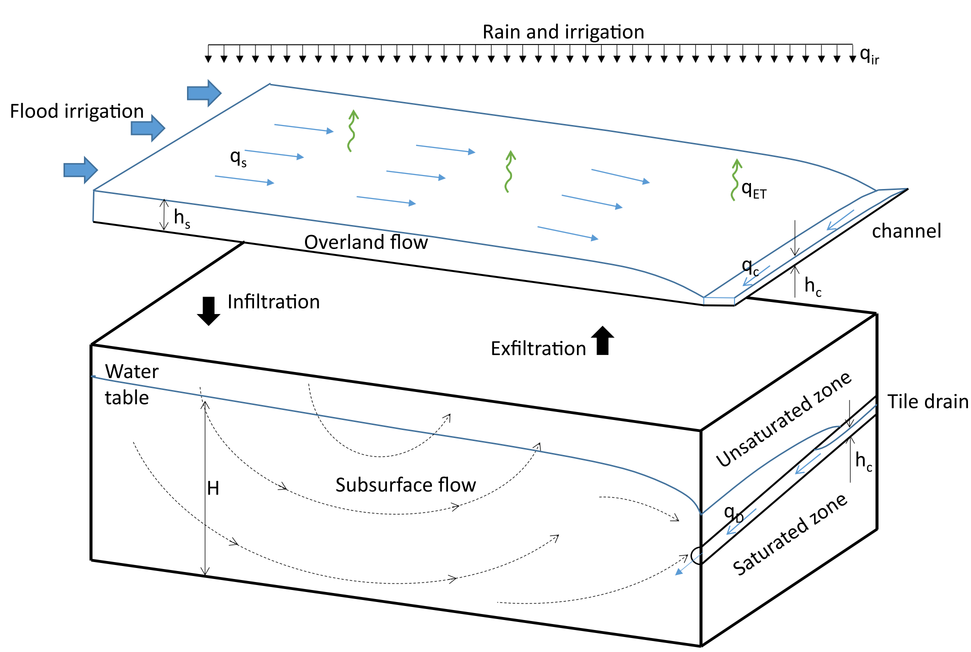

Fig. 1. Schematic overview of the *DrainFlow* structure and components.