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Coupled modelling of the effect of overpressure on water discharge in a tile drainage system

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SUMMARY

The effect of subsurface drainage on agricultural catchment outflow has been debated for quite some time. Concerning downstream peak flow, it is a complex task to predict the impact of agricultural drainage because different flow media are involved: the soil, pipe drainage networks and open channel networks. In France, drain pipes are designed to operate under a free-surface flow condition. Nevertheless, during intense rainfall events, some pipe sections may flow under pressurised conditions, so that a complex interaction between pipe networks and groundwater flows appears in the vicinity of these sections. In this paper, an integrated modelling strategy is considered in order to analyse these flow interactions. A 1D Saint–Venant network model is combined with a 2D Boussinesq shallow groundwater flow model by means of special internal boundary conditions which take into account the flow interactions. This study follows field experiments conducted in a small subsurface drained catchment, where drainage discharge and pressure heads were monitored in a buried pipe collector and water table profiles were monitored in the field. The simulation results of the coupled model are in good agreement with experimental observations. Moreover, it satisfactorily simulates the behaviour of the drainage system during the pressurisation stages. The model is also applied to a scenario addressing the effect of pressurisation, as compared to non-pressurisation, at the outlet. The coupled model reveals the relation existing between pipe pressurisation and hydrograph timing. Pipe pressurisation results in temporary storage of discharging water, which is released later when pressurisation stops.

1. Introduction

Subsurface drainage of cultivated fields may influence a catchment's hydrological response (e.g. Robinson and Rycroft, 1999; Rycroft, 1990; Skaggs et al., 1994). Indeed, subsurface drainage networks draw shallow water tables down and consequently increase the soil's storage capacity and may significantly decrease surface runoff (e.g. Augeard et al., 2005; Kao et al., 1998). Agricultural drainage has also been known to discharge many agricultural pollutants into watercourses (Skaggs et al., 1994). After heavy rainfall events, precise evaluation of the actual impacts of subsurface drainage on water quantity and quality turns out to be quite difficult because many processes are involved. Furthermore, these processes interact increasingly when the system's behaviour moves from free-surface flow (normal condition) to pressurised flow (Henine et al., 2010).

In France, agricultural drainage systems are designed so as to operate under a free-surface flow condition on the basis of rainfall with a 1-year return period lasting 3 days (Lesaffre, 1989). Consequently, for typical models, computing groundwater discharge considers a free-surface flow in drain pipes and ignores the interaction between the groundwater and pipe flow during pipe pressurisation (e.g. Bouarfa and Zimmer, 2000; Stillman et al., 2006).

If the intensity of a rainfall event rises considerably, a pressurised flow may be initiated in parts of the drainage system, either at a submerged downstream outlet of the pipe network or locally within a pipe if the flow rate exceeds the design value. The flow rate that can be collected by each pipe in the network strongly depends on its overall drained area, drain design criteria (depth and spacing) and soil hydrodynamic parameters (drainable porosity and permeability). The coexistence of free-surface flow and pressurised flow within the drainage network, also called mixed flow, may lead to very sudden changes. Pressurisation may also rise in the drainage network up to the field drains and influence groundwater flow. When the pressure head rises sufficiently in the drains, it may cause backflow in the system (Henine et al., 2010).

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The main goal of this study was to examine how pressurisation periods alter the behaviour of agricultural drainage systems. Konyha and Skaggs (1992) as well as Khan and Rushton (1996) presented two different studies of model results according to which a pressurisation flow (or limitation of flow capacity) of the drainage system modified its efficiency as well as the overall discharge. However, these studies addressed a single soil profile, assuming the pipe pressurisation to be general and homogenous at the field scale.

This question has also been studied by several authors in other contexts such as sewage and hydro-electric power generation systems showing similar processes (Bourdarias and Gerbi, 2007; Djordjević et al., 2005). In hydrological modelling, different approaches of interactions between flow media (stream-water, groundwater and surface-water flows) have been examined (Sophocleous, 2002). Different models and analyses considering these interactions have been developed, such as the interaction between the water table and the stream-water level or surface runoff (e.g. Kao et al., 2001; Panday and Huyakorn, 2004; Weill et al., 2009). Indeed, the water level in a stream influences groundwater recharge or discharge, and the probability of surface runoff occurrence increases when the groundwater table rises to the soil surface. These interaction processes are similar to those observed in drainage systems (Henine et al., 2010).

The method presented in this work combines approaches designed for flow descriptions in both media – soil and pipes – by means of coupled numerical models, respectively, a 2D Boussinesq shallow groundwater model and a 1D Saint–Venant network model. The numerical solution is compared to experimental data collected from a subsurface drained field, in the vicinity of which flow rates and hydraulic heads were monitored in the buried pipe collector. Groundwater flow during pipe pressurisation was investigated through the simultaneous monitoring of a water table profile in the drained field.

The coupled model was first applied to verify its ability to handle pressurised conditions in both buried pipes and the water table above the drain. It was then applied to study the effects of field topography and the network set-up on network pressurisation and outlet discharge.

2. Overall model set-up

Two numerical models were used for this study. The first one, referred to as D2D, simulates the field drainage discharge of a two-dimensional groundwater flow from a shallow water table. Flow rates computed by D2D as entering buried and parallel drain pipes are routed down to the drainage network outlet by the second model, referred to as Elixir. The two models are coupled in a global scheme which satisfies the local mass balance together with the geometry of the field and drainage system.

2.1. Field drainage model (D2D)

Model D2D (Drainage model in 2 Dimensions) simulates flow in a shallow water table and computes the discharge rate into a network of parallel and regularly spaced buried drains. Based on the extended Dupuit–Forchheimer assumption (i.e. streamlines nearly parallel to the sloping bed), the mathematical model solves the Boussinesq Eq. (1) (Chapman, 1980):

$$\mu_d \frac{\partial Z_s}{\partial t} + R = \frac{\partial}{\partial x}\left[K_x H cos^2(\alpha_x)\frac{\partial Z_s}{\partial x}\right] + \frac{\partial}{\partial y}\left[K_y H cos^2(\alpha_y)\frac{\partial Z_s}{\partial y}\right] \quad (1)$$

where x, y are the coordinates along two perpendicular axes defined in the horizontal plane, Δx and Δy (Fig. 1) are the spatial discretisation (L) along both axes (x and y), respectively, t is the elapsed time, $Z_s(x, y, t)$ is the water table elevation (L), $H(x, y, t)$ is the height of the water table above the impervious layer (L), $K_x(x, y)$ and $K_y(x, y)$ are the hydraulic conductivities in the x and y directions, respectively (LT^{-1}), $R(x, y, t)$ is the net vertical recharge (LT^{-1}), μ_d is the drainable porosity ($-$), and α_x and α_y are the angles of the impervious layer with the horizontal in the x and y directions, respectively.

Eq. (1) is solved using a backward finite difference scheme on a rectangular grid (Fig. 1), in which errors introduced at any time diminish progressively during the following time steps. In general, errors can be reduced by decreasing the time step and grid spacing (e.g. Anderson and Woessner, 1992; Batu, 2006).

The finite-difference grid is spatially oriented and spaced so that some of its nodes (drain nodes) are precisely located along the drain axes and some of the others (collector nodes) along the collector axes (Fig. 1). The lines of the drain and collector nodes, located inside the domain, are used to define the internal boundary conditions to simulate subsurface drainage flow. Internal boundary nodes can also represent open channels, to simulate river–aquifer exchange (e.g. Anderson and Woessner, 1992).

The initial condition is defined as a set of prescribed values for water table elevation on the entire simulation domain. These values result from a method, described below, applied to the overall scheme including the pipes.

Two types of boundary conditions are set up. A no-flow boundary condition (Neumann type) is applied at the nodes bounding the field, and an internal specified head boundary condition (Dirichlet type) is applied at the drain nodes. The drain head condition ($Z_{s(drain)}$) is calculated as (Fig. 2):

$$Z_{s(drain)} = (drain\ elevation) + h_{drain}(t) \quad (2)$$

where the hydraulic head inside the drain pipe is converted into a water column height (h_{drain}). The model assumes that the hydraulic head in the drain pipes can be instantaneously transmitted to the groundwater flow model so that its equivalent water column equals the water level above the drain. The model also assumes that the water level above the drain results only from the pressurised flow in the drain. The additional water table elevation due to head losses attributable to flow resistance near the drain (e.g. Cavelaars et al., 1994; Dierickx, 1999; Kohler et al., 2001) is ignored.

Fig. 2 shows the three exchange modes between the drain and the water table as considered in the coupled model. Free surface flow in the drain (Fig. 2a) has no backward influence on the groundwater flow. In this case, the water table connects to the drain pipe. If the hydraulic head in the drain is positive but lower than the water

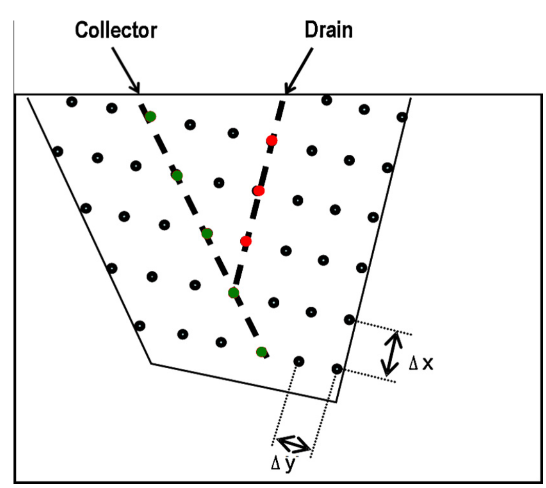

Fig. 1. The finite difference grid based on drain and collector direction: drain nodes (red), collector nodes (green) and other nodes (black). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)