Journal of Hydrology 542 (2016) 172–184

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

A fully coupled depth-integrated model for surface water and groundwater flows

Yuanyi Li [a], Dekui Yuan [a,*], Binliang Lin [b,c], Fang-Yenn Teo [d]

[a] Department of Mechanics, School of Mechanical Engineering, Tianjin University, Tianjin 300072, PR China
[b] State Key Laboratory of Hydroscience and Engineering, Department of Hydraulic Engineering, Tsinghua University, Beijing 100084, PR China
[c] School of Engineering, Cardiff University, Cardiff CF24 3AA, UK
[d] Department of Irrigation and Drainage, Kuching, Sarawak 93660, Malaysia

A R T I C L E I N F O

Article history:
Received 13 June 2016
Received in revised form 10 August 2016
Accepted 31 August 2016
Available online 12 September 2016
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Rao S. Govindaraju, Associate Editor

Keywords:
Surface water
Groundwater
Coupled model
Coarse media
Quadratic friction

A B S T R A C T

This paper presents the development of a fully coupled surface water and groundwater flow model. The governing equations of the model are derived based on a control volume approach, with the velocity profiles of the two types of flows being both taken into consideration. The surface water and groundwater flows are both modelled based on the unified equations and the water exchange and interaction between the two types of flows can be taken into account. The model can be used to simulate the surface water and groundwater flows simultaneously with the same numerical scheme without other effort being needed to link them. The model is not only suitable for the porous medium consisting of fine sediments, but also for coarse sediments and crushed rocks by adding a quadratic friction term. Benchmark tests are conducted to validate the model. The model predictions agree well with the data.

1. Introduction

Interactions between surface water and groundwater exist in almost all natural water body, such as lakes, wetlands, rivers, ocean, coast and estuaries. Surface water and groundwater are the two important components in the hydrological cycle. To model both components simultaneously and take into account of the interactions between them, we developed a fully coupled model based on the governing equations for both components.

In the hydrological cycle on the earth, surface water and the groundwater are the two closely-linked components. Santos et al. (2012) reviewed the mechanisms of interactions between the surface water and the groundwater. The difference in the pressures between the surface water and groundwater are the dominant driving force of influent and effluent between them. The tide, wave and water usage can change the hydraulic gradient and modify the pressure at the interface of the two components. Therefore, changes in either of the two components shall affect the other component. For example, the groundwater table in the beach oscillates due to the tides and waves movement. Also, the pumping of groundwater will result in a decrease in the level of groundwater and hence, it may even cause seawater intrusion. In some coastal areas, such as the north of China, the depletion of groundwater has caused the salinity level rising in the groundwater due to seawater intrusion. The fluctuations in the beach-water table also have an impact on the transport of beach sediments and the exchange of solute and water mass between coastal aquifer and seawater (Horn, 2006; Hsu and Raubenheimer, 2006; Li et al., 2000). The beach is filled more easily than it is drained under gravity, which leads to a steeper rising than decline in the level of groundwater (Horn, 2006), for which the seepage face often occurs on the gently slope bank and beach. Baird et al. (1998) pointed out that the seepage face is significant to the exchange of solute between the surface water and groundwater via infiltration and exfiltration. Gardner (2005) suggested that most groundwater discharge and recharge occur through the bank. When the groundwater table is higher than the mean sea level, it tends to enhance offshore sediment transport and beach erosion. Conversely, when the water table is lower than the mean sea level, onshore sediment transport and beach accretion is promoted (Grant, 1948).

* Corresponding author.
E-mail addresses: liyuanyi@tju.edu.cn (Y. Li), dkyuan@tju.edu.cn (D. Yuan), linbl@mail.tsinghua.edu.cn (B. Lin), teofy@water.gov.my (F.-Y. Teo).

http://dx.doi.org/10.1016/j.jhydrol.2016.08.060
0022-1694/

In order to investigate the interaction between surface water and groundwater flows in coastal regions, both physical experiments and mathematical methods were conducted. In the early studies, surface water and groundwater flows were regarded as two separate ingredients of a water system and they were analysed independently. This was partly due to the significant difference in the transport time scales between these two types of flows. In addition, the difficulty in measuring and modelling the interaction was another reason (Winter et al., 1998). Parlange et al. (1984) studied the water table fluctuation in the porous media driven by the change of surface water level. Liu and Wen (1997) derived a periodic analytic solution of this problem. Based on a perturbation method, Nielsen (1990) derived an analytical solution to represent the beach water table distribution. Li et al. (2000) refined the solution derived by Nielsen (1990) and extended it to moving boundary problems. Teo et al. (2003) derived a higher-order solution to the nonlinear moving boundary problems, with the solution being valid for a wider range of beach slopes. Attenuation of wave-induced pressure variation of groundwater in porous media was experimentally studied by Massel et al. (2004) and then a solution for the pore water pressure and velocity induced by surface waves was proposed by them. Based on two widely used software packages, namely MIKE 11 and MIKE SHE, Thompson et al. (2004) developed a coupled model and applied it to the Elmley Marshes, a lowland wet grassland in the southeast of England. Ebrahimi et al. (2007) set up a physical model to observe the processes of tidal, groundwater and shallow wetland flows and the transport of tracers over an idealised coastal wetland. In their research, a coupled numerical model based on DIVAST (Depth Integrated Velocities and Solute Transport) was applied to predict the phenomena observed in the experiment. Based on the Finite Volume Method (FVM), Erduran et al. (2005) and Das et al. (2002) developed hydrodynamic models for predicting combined free and porous flows in two sub-surface regions. In their models, the two types of flows were linked through matching conditions at the interface. Also, based on DIVAST and a shock-capturing TVD-MacCormack scheme, Liang et al. (2007) set up a 2D model, in which the surface water and groundwater flows are connected, and the height of free surface decides which equation is solved at each grid point. Yuan et al. (2008) developed a coupled model that computes the surface water and groundwater flows simultaneously. Pahar and Dhar (2014) further developed the method by Yuan et al. (2008) and rewrote the continue equation of shallow water flows. Recently, a 3-D coupled model (Spanoudaki et al., 2009) was developed based on Reynolds-Averaged Navier-Stokes (RANS) equations. In this model different methods were used to solve the two types of flows. To realize the incorporation of the flow in the two sub-regions, an interface-matching method similar to Das et al. (2002) was used.

Different types of governing equations were used to represent the groundwater flows. According to Darcy's law, the flux in pore water is proportional to the pressure gradient. Many early studies on the flows in porous media used an extended version of Darcy's law and took the convection and linear viscosity into consideration (Nield, 1994). Joseph et al. (1982) introduced a quadratic drag term into Darcy's equation and showed that it would generate a better result than Darcy's law when the Reynolds Number (Re_p) non-dimensionalized with the dimension of pore was larger than 10. Based on Brinkman-Forchheimer equation, Hsu and Cheng (1990) derived a set of equations similar to the Navier-Stokes (N-S) equations and use them to study thermal conduction in flows with a high Re_p.

The water exchange process between the surface water and groundwater flows is complex. In early studies, the flow variables at the interface of free water (surface water) and pore water (groundwater) were considered continuous. However, Ishizawa and Hori (1966) proved that the no-slip assumption is invalid in some cases and there is a tangential velocity component, which is known as Darcy slip phenomenon, near the interface. Beavers and Joseph (1967) and Beavers et al. (1970) experimentally demonstrated the existence of a shear mechanism inside a porous medium adjacent to a free flow in a channel and proposed a relationship between the velocities at the two sides of the interface. Jones (1973) modified the relationship proposed by Beavers and Joseph and extended it to 3-D flows. Applying the relationship, Das et al. (2002), Hanspal et al. (2006) and Hanspal et al. (2013) developed 3-D models to simulate the combined flows occurring in industrial processes and in natural environment.

In this paper, the development of a fully coupled model for simulating the combined surface water and groundwater flows is reported. Unlike the existing models (Liang et al., 2007; Pahar and Dhar, 2014; Yuan et al., 2008), we derived a set of equations that can be applied to both surface water and groundwater flows and developed the coupled model based on these equations. In this model, the surface water flow is represented by the widely used shallow water equations, which is the same as that used in Yuan et al. (2008). However, instead of Darcy's law used in the existing models (Liang et al., 2007; Pahar and Dhar, 2014; Yuan et al., 2008), the groundwater flow is represented by equations similar to Brinkman-Forchheimer (B-F) equations, in which the convection term of the pore water flow is retained. The quadratic resistance component included in B-F equations is used. It is a higher order term when Re_p is smaller than 10, but the same order if Re_p is larger than 10. In this way, surface water and groundwater flows can be described and simulated using the same equations and the two flows are fully coupled. In the model, the surface water and groundwater couple through not only the mass conservation, but also the momentum exchange between the two types of flows. In this way, the tangential velocity slip at the interface between the two regions can be taken into consideration. Additionally, the coupled equations are written in the same form as that of the shallow water equations, thus the numerical techniques used to solve the shallow water equations can be applied to this model without any additional difficulty.

This paper is organized as follows. In Section 2, the governing equations for coupled surface water and groundwater flows are derived using a control volume approach. In Section 3, the discrete scheme of the governing equations is presented. In Section 4, the performance of the new model is evaluated through several benchmark tests. Section 5 summaries the conclusions from this research.

2. Governing equations

In this section, the governing equations of the coupled model are derived following the principle of mass and momentum of conservation. Consider surface water and groundwater system shown in Fig. 1, it can be seen that there are three kinds of control volumes: (1) with both surface water and groundwater, i.e. Control Volume I, (2) only with surface water, i.e. Control Volume II, and (3) only with groundwater, i.e. Control Volume III. Since Control Volumes II and III are special cases of Control Volume I, it is reasonable to take the Control Volume I as the universal one to derive the governing equations of the model. The dimensions of the control volume along the x and y directions are Δx and Δy, respectively (Fig. 2). The free surface, the surface water and groundwater interface and the impermeable bottom of the groundwater are marked as S_S, S_I, S_B, respectively; and the elevations at S_S, S_I, S_B are denoted as $z_S(\eta)$, z_I and z_B, respectively. Labels S_1-S_4 are used to denote the four vertical surfaces of the control volume containing surface water and groundwater.