Journal of Hydrology 519 (2014) 2215–2223

Contents lists available at ScienceDirect

Journal of Hydrology

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

A dry zone-wet zone based modeling of surface water and groundwater interaction for generalized ground profile

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ARTICLE INFO

Article history:
Received 5 June 2014
Received in revised form 25 September 2014
Accepted 30 September 2014
Available online 13 October 2014
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Aldo Fiori, Associate Editor

Keyword:
Groundwater–surface water interaction
Experimental investigation
Finite difference method

SUMMARY

An integrated groundwater–surface water interaction model is proposed for generalized ground surface profile. To simulate ground water flow, Boussinesq's equation and Darcy's law are applied. Surface water formulation utilizes depth averaged Navier–Stokes equation of continuity and momentum. The mathematical model uses finite difference method with upwinding scheme for discretization of the governing equations and Newton-Rhapson method for solving the equations. A novel dry zone-wet zone theory is proposed for modeling the system. It is assumed that the spatial domain is made up of dry and wet zones. Further, dry and wet zones are considered as clusters of dry and wet cells respectively. Verification of the model is performed for beach with vertical and inclined faces. Test results show that numerical simulation results are in good agreement with the analytical/experimental ones. Experimental verification of the model is performed using a sand-box set-up. Observation data obtained from pressure sensors show good match with the numerical solution. A plausible field situation is considered with arbitrary generalized ground surface profile. Obtained numerical solution for the generalized ground profile shows intuitively correct results. The coastal wetland with arbitrary ground profile demonstrates the potential applicability of the integrated groundwater–surface water interaction model for generalized ground surface conditions.

1. Introduction

Groundwater and surface water are two distinct components of hydrologic cycle. Traditionally, water resources flow models have focused on individual simulation of surface water or groundwater. In reality, all surface water bodies (e.g. streams, lakes, wetlands, coastal areas and estuaries) often hydraulically interact with groundwater aquifers. In the present work a coupled groundwater–surface water interaction model is proposed.

Interaction between surface and groundwater affects both their quantity and quality. Influent or effluent conditions occur due to the relative difference between surface water and groundwater levels. Monsoonal rains and dry-season irrigation pumping cause reversals in hydraulic gradients (water body source to ground water sink). Thus continuous withdrawal from surface water bodies can cause groundwater table depletion. Similarly, pumping of groundwater can deplete water in streams, lakes, or wetlands. Moreover, pumping in coastal areas can result increase in salinity over time. It is mainly due to saltwater intrusion from the ocean towards inland aquifer. Thus, effective land and water management requires a clear understanding of the linkages between groundwater and surface water under general hydrologic setting. Coupled modeling of surface and subsurface systems is a valuable tool for quantifying surface water-ground water interactions.

Considerable amount of research is available in the area of groundwater and surface water interaction. Erduran et al. (2005) have modeled ground and surface water interaction by introducing source-sink terms into the continuity equations. Vertical discharge is considered as the source/sink discharge for sub-surface flow equations. Li et al. (1997) developed a boundary element model for simulating tide induced fluctuations of a beach ground water table. In this model, the moving boundary i.e., the free water surface variation and the groundwater exit face are taken into account using a modified kinetic boundary condition. Yuan et al. (2008) also solved 2-D depth averaged Navier–stokes equations and extended Darcy's equation for modeling water interchange between coastal area and the ocean, with the hydrostatic pressure being assumed to apply for surface as well as groundwater flow. Similar kind of model is also developed by Yuan and Lin (2009), Kong et al. (2010) considering an integrated, vertically averaged Navier–Stokes equation for numerical simulations based on the

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http://dx.doi.org/10.1016/j.jhydrol.2014.09.088
0022-1694/

Nomenclature

ζ^s	surface–water height (m)
p^s	unit discharge in x direction of surface water ($m^2\,s^{-1}$)
q^s	unit discharge in y direction of surface water ($m^2\,s^{-1}$)
q^g	unit discharge of groundwater in y direction ($m^2\,s^{-1}$)
H	surface water Level (m)
β_m	momentum correction factor (–)
f	Coriolis Parameter
C	Chezy's coefficient ($m^{1/2}\,s$)
U	depth averaged stream wise velocity ($m\,s^{-1}$)
V	depth averaged lateral velocity ($m\,s^{-1}$)
W_x	wind velocity in stream wise directions (ms^{-1})
W_y	wind velocity in lateral directions ($m\,s^{-1}$)
v	depth mean Eddy Viscosity ($m^2\,s^{-1}$)
ρ	density of water ($kg\,m^{-3}$)
ρ_a	density of air ($kg\,m^{-3}$)
γ	air water resistance coefficient
q^s_m	source/sink surface water discharge ($m\,s^{-1}$)
q^g_m	source/sink groundwater discharge ($m\,s^{-1}$)
ζ^g	Groundwater Height (m)
n^ζ_e	effective porosity of the ground
p^g	unit groundwater discharge in x direction ($m^2\,s^{-1}$)
K	hydraulic conductivity of the soil ($m\,s^{-1}$)
A	Wave Amplitude of the reservoir (m)
ε	$Ak \cot \beta$
ω	angular frequency of the oscillation ($rad\,s^{-1}$)
k	$\sqrt{n^\zeta_e \omega / 2KD}$
D	mean sea level (m)
ζ	water surface level (m)
A	Wave Amplitude of the reservoir (m)
i	imaginary unit number
ω	angular frequency of the oscillation
k^*_0	complex conjugate of k_0

unstructured finite difference/finite volume in a coastal hydrologic system. The Courant–Friedrichs–Lewy (CFL) stability conditions are loosely satisfied by the model. A coupled model of surface and groundwater is also developed using the finite difference based modeling software like the MIKE SHE and MIKE 11 by Thompson et al. (2004), where between the surface water and groundwater bodies, seepage exists and the water table exit point is allowed to be considered isolated from the driving head. Yuan et al. (2012) used approximate Riemann solver to solve the extended shallow water equations applicable for shallow surface as well as the groundwater equations in finite volume formulation. The flux gradient and the source/sink terms are balanced by the surface gradient method.

Cartwright et al. (2004) observed horizontal and vertical variations in water surface level in a homogeneous porous media in a lab-scale for simple harmonic oscillation in the clear water reservoir acting across a sloping boundary. The observed water level can be simulated by existing small-amplitude perturbation theory with significant capillary effect. Parlange et al. (1984) obtained experimental as well as numerical solution of waves through rectangular block of sand. Liu and Wen (1997) gave an analytical expression for the waves traveling through porous media. Nielson (1990) also performed similar kind of experiment with steep sloping beach and obtained an analytical expression for waves with relatively smaller amplitude.

Ebrahimi et al. (2007) performed an experiment of surface and groundwater flow and transport of contaminants over a prototype of coastal wetland. The numerical verification is performed by DIVAST [Depth Integrated Velocities and Solute Transport] model and GWK [Ground Water Key].

For surface water simulation normally the two dimensional shallow water Navier–stokes equations or the Saint–Venant equations are used commonly, while Darcy's Law or Richard's equation is often used for groundwater flow. Some models have proposed that surface water and groundwater can be simulated in same or different time level. But considering the interaction to be a simultaneous process, both the flow should be calculated within same time step. Existing interaction models consider that the interaction can be obtained by introducing source/sink terms in the continuity equation. This criterion holds good only for the situation, when flow in the vertical plane is predominant. However, for stream/coastal aquifer interactions flow in horizontal direction is the main constituent. In the present work a coupled groundwater–surface water interaction model considering the flow equations is proposed. Existing models mostly take water level as interaction criteria. The present model considers discharge as well as water level for interaction criteria. Both periodic and transient boundary conditions are considered during analysis. In presence of transient boundary condition continuity equation becomes dictating factor for the physical problem.

2. Methodology

Coupled modeling of surface water and groundwater is a challenging task. Interaction models will differ depending upon the region on which the model is being applied. For coastal aquifer or stream aquifer interaction, flow in vertical directions will be very less. Thus, depth variation of velocity (in case of surface water) and specific discharge (in case of groundwater) are neglected during numerical modeling. Dupuit's assumptions can be taken into account for groundwater modeling. The mathematical results are validated against existing analytical solutions.

2.1. Governing equations and their discretization

2.1.1. Navier–Stokes equation of free surface flow

In case of surface water, Navier–Stokes continuity and momentum equations are taken. Depth averaged two dimensional Navier–Stokes equation can be written as (Lin and Falconer, 2005):

$$\frac{\partial \zeta^s}{\partial t} + \frac{\partial p^s}{\partial x} + \frac{\partial q^s}{\partial y} = q^s_m \tag{1}$$

$$\frac{\partial p^S}{\partial t} + \frac{\partial}{\partial x}(\beta_m \mathrm{U} \mathrm{p}^s) + \frac{\partial}{\partial y}(\beta_m \mathrm{V} \mathrm{p}^s) = \mathrm{f} \mathrm{q}^s - \mathrm{g} \mathrm{H} \frac{\partial \zeta^s}{\partial x} + \frac{\gamma \rho_a W_x W_y}{\rho} - \frac{\mathrm{g} \mathrm{p}^s \sqrt{(p^s)^2 + (q^s)^2}}{H^2 C^2} + v\left(\frac{\partial^2 p^s}{\partial x^2} + \frac{\partial^2 p^s}{\partial y^2}\right) \tag{2}$$

$$\frac{\partial q^S}{\partial t} + \frac{\partial}{\partial x}(\beta_m \mathrm{U} \mathrm{q}^s) + \frac{\partial}{\partial y}(\beta_m \mathrm{V} \mathrm{q}^s) = \mathrm{f} \mathrm{p}^s - \mathrm{g} \mathrm{H} \frac{\partial \zeta^s}{\partial y} + \frac{\gamma \rho_a W_x W_y}{\rho} - \frac{\mathrm{g} \mathrm{q}^s \sqrt{(p^s)^2 + (q^s)^2}}{H^2 C^2} + v\left(\frac{\partial^2 q^s}{\partial x^2} + \frac{\partial^2 q^s}{\partial y^2}\right) \tag{3}$$