Journal of Hydrology 540 (2016) 331–339

Contents lists available at ScienceDirect

Journal of Hydrology

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

A hybrid method for flood simulation in small catchments combining hydrodynamic and hydrological techniques

Vasilis Bellos *, George Tsakiris

Laboratory of Reclamation Works and Water Resources Management & Centre for the Assessment of Natural Hazards and Proactive Planning, School of Rural and Surveying Engineering, National Technical University of Athens, Athens, Greece

ARTICLE INFO

Article history:
Received 6 April 2016
Received in revised form 20 May 2016
Accepted 18 June 2016
Available online 20 June 2016
This manuscript was handled by K. Georgakakos, Editor-in-Chief, with the assistance of Jennifer Guohong Duan, Associate Editor

Keywords:
2D flood modelling
Small catchments
FLOW-R2D model
Unit hydrograph
Kostiakov equation
Green-Ampt model

ABSTRACT

The study presents a new hybrid method for the simulation of flood events in small catchments. It combines a physically-based two-dimensional hydrodynamic model and the hydrological unit hydrograph theory. Unit hydrographs are derived using the FLOW-R2D model which is based on the full form of two-dimensional Shallow Water Equations, solved by a modified McCormack numerical scheme. The method is tested at a small catchment in a suburb of Athens-Greece for a storm event which occurred in February 2013. The catchment is divided into three friction zones and unit hydrographs of 15 and 30 min are produced. The infiltration process is simulated by the empirical Kostiakov equation and the Green-Ampt model. The results from the implementation of the proposed hybrid method are compared with recorded data at the hydrometric station at the outlet of the catchment and the results derived from the fully hydrodynamic model FLOW-R2D. It is concluded that for the case studied, the proposed hybrid method produces results close to those of the fully hydrodynamic simulation at substantially shorter computational time. This finding, if further verified in a variety of case studies, can be useful in devising effective hybrid tools for the two-dimensional flood simulations, which are lead to accurate and considerably faster results than those achieved by the fully hydrodynamic simulations.

© 2016 Elsevier B.V. All rights reserved.

1. Introduction

It is widely accepted that the physically-based models cannot simulate the total complexity of the hydrological cycle using the full set of equations for each phenomenon (e.g. interception, infiltration, overland flow, evaporation, etc.), due to the large number of parameters which should be estimated, the bulk of data needed, and the prohibitive computational cost. Therefore, for the majority of the physically-based models only one or two principal processes of the hydrological cycle are simulated comprehensively, whereas all the other processes are simulated by simplified methods (i.e. SWAT software (Neitsch et al., 2002)).

This study focuses on the hydrodynamic modelling for the simulation of the flood in a catchment created by a storm episode and especially on the two-dimensional (2D) modelling in which the full dynamic form of 2D Shallow Water Equations (2D-SWE) are used. It should be noted that in the majority of cases, the hydrodynamic simulation is applied only to the river channel or the floodplain (Abderrezzak et al., 2008; Bellos, 2012; Vacondio et al., 2016). In the following paragraphs, some of the efforts made for the 2D flood modelling at catchment scale, are briefly discussed.

The first studies for flood flow simulation employing 2D distributed models, used simplified forms of mass and momentum conservation equations instead of the full dynamic form of 2D-SWE, due to the computational cost of the latter. Indicatively, interesting applications in this category were published by Tayfur et al. (1993), Feng and Molz (1997), Liu et al. (2004), Kazezyilmaz-Alhan and Medina (2007) and Gottardi and Venutelli (2008).

However, the dynamics of the very shallow flows, such as the flow created by precipitation, (especially with low intensity rain) are quite complex and are characterised by mixed subcritical and supercritical conditions. According to some researchers, phenomena such as the backwater effect (Liang, 2010; Costabile et al., 2012b) or the river reach confluences, where momentum transfer is significant (Singh et al., 2014), was not able to be simulated satisfactorily by simplified approaches, such as the kinematic or diffusive wave methods. Therefore, the 2D Shallow Water Equations (2D-SWE) were used as an improvement of the simulation.

Fiedler and Ramirez (2000) developed their algorithm solving the 2D-SWE, using the Finite Difference Method (FDM) and the McCormack numerical scheme. Infiltration is simulated through

* Corresponding author.
E-mail addresses: vmpellos@mail.ntua.gr (V. Bellos), gtsakir@central.ntua.gr (G. Tsakiris).

http://dx.doi.org/10.1016/j.jhydrol.2016.06.040
0022-1694/© 2016 Elsevier B.V. All rights reserved.

the Green-Ampt method. In their study, numerical experiments were performed in a micro-scale simulating the rainfall-runoff process. Esteves et al. (2000) have also developed a numerical model solving the 2D-SWE with the same procedures (FDM and the McCormack numerical scheme and Green-Ampt method for the infiltration losses), which was validated using the experimental data derived from an experimental basin at a micro-scale, constructed in the Niger river (West Africa). Liang et al. (2007) combined 2D-SWE for overland flow with the Boussinesq equations for groundwater flow. Costabile et al. (2012a, 2013) have tested their model for various benchmark scenaria. They have also applied their model in a sub-basin of the Reno river (Italy), simulating an extreme rainfall episode. Kim et al. (2012) applied their 2D model, which incorporates precipitation, ice melting, infiltration and groundwater dynamics, in a real world episode which occurred in Peacheater Creek watershed of the Oklahoma state, USA. Singh et al. (2014) simulated a rainfall-runoff episode in Goodwin Creek watershed (Mississippi, USA). For the infiltration simulation the Green-Ampt method was used. Finally, the authors of this paper have proposed an in-house 2D fully hydrodynamic model, called FLOW-R2D, which is based on the solution of the Shallow Water Equations using a modified form of McCormack numerical scheme incorporating artificial viscosity (Tsakiris and Bellos, 2014). The model was tested recently in complex built-up areas (Bellos and Tsakiris, 2015a). A short description of this model is presented in the next section of this paper.

Most of the recent applications of hydrodynamic models showed an increased accuracy in 2D flood simulations. However, although the speed of calculations has been considerably increased due to the technological innovations in computing facilities, the computational time for a fully hydrodynamic simulation (particularly in large watersheds) is still high and in many cases still unmanageable. This led researchers to redirect their efforts towards hybrid methods which exploit the merits of the hydrodynamic modelling but at the same time use also some simpler hydrological approaches aiming at reducing the computational time. A recent example in this direction is the hydrological-hydraulic model proposed by Nguyen et al. (2015), called HiRes Flood-UCI. This model combines the hydrological model HL-RDHM as a rainfall-runoff model, but instead of the classical hydrological routing scheme, it uses the 2D hydrodynamic BreZo model. The model has been successfully tested in a catchment of the Illinois river in USA using a decameter resolution.

In the present study a novel hybrid method which combines both the hydrodynamic and the hydrological approaches is used, in order to simulate flood events in small catchments. The implementation of the method is performed in three steps: (a) the Unit Hydrographs of the catchment are derived using a 2D hydrodynamic model, (b) the effective rainfall depth of the storm episode is calculated using an appropriate infiltration model, (c) the final flood hydrograph of the event is generated based on the principle of hydrograph superposition.

The performance of the proposed method is tested in a flash flood event which occurred in a small catchment of the Halandri stream, in a suburb of Athens-Greece, in February 2013. For the derivation of the Unit Hydrographs, the in-house 2D hydrodynamic model FLOW-R2D is used and for the infiltration process, both the Kostiakov equation and the Green-Ampt model, are used. The results from the proposed hybrid method in the above event are compared directly with the available recorded data and the results derived from the fully hydrodynamic simulation of the entire flood episode.

2. Theoretical background

For the hydrodynamic part of the hybrid method, the numerical model FLOW-R2D is used, based on the solution of the two-dimensional Shallow Water Equations (2D-SWE) by the Finite Difference Method, in a cell-centred, non-staggered computational grid (Tsakiris and Bellos, 2014):

$$\frac{\partial W}{\partial t}+\frac{\partial F}{\partial x}+\frac{\partial G}{\partial y}=D \tag{1}$$

where

$$W=\begin{vmatrix} h \\ uh \\ vh \end{vmatrix},\quad F=\begin{vmatrix} uh \\ u^2h+0.5gh^2 \\ uvh \end{vmatrix},\quad G=\begin{vmatrix} vh \\ uvh \\ v^2h+0.5gh^2 \end{vmatrix},$$
$$D=\begin{vmatrix} r-f \\ ghS_{0,x}-\tau_{b,x}/\rho \\ ghS_{0,y}-\tau_{b,y}/\rho \end{vmatrix} \tag{2}$$

and h is the water depth, u is the horizontal component of flow velocity at x-direction, v is the horizontal component of flow velocity at y-direction, $S_{0,x}$, $S_{0,y}$ are the bottom slopes for the x and y-directions, respectively, and ρ is the fluid density. Shear stresses $\tau_{b,x}$ and $\tau_{b,y}$ can be modelled by various methods such as the Manning equation which is used in the present study, as follows:

$$\frac{\tau_{b,x}}{\rho}=\frac{gn^2u(\sqrt{u^2+v^2})}{R^{1/3}},\quad \frac{\tau_{b,y}}{\rho}=\frac{gn^2v(\sqrt{u^2+v^2})}{R^{1/3}} \tag{3}$$

where n is the Manning coefficient and R is the hydraulic radius.

The two terms, r and f in the Continuity Equation, represent the precipitation rate (source term) and the rate of losses, such as infiltration or drainage (sink term), respectively. It should be noted that infiltration and rainfall are not incorporated into the Momentum Equations of the model because their magnitude is very small in comparison with the other components.

A modification of the explicit McCormack numerical scheme (McCormack, 1969) is used to solve the 2D-SWE. It is noted that this scheme has been also used by several researchers (i.e. Kalita, 2016). With this modification, artificial viscosity is added through a diffusion factor. The oscillatory errors are smoothed out while the shock capturing capability of the scheme is retained (the solution has still second order accuracy) and therefore discontinuities of the flow can be simulated. Wet/dry modelling is achieved through a water depth threshold which distinguishes the wet and the dry cells. In the dry cells the water depth and flow velocity are taken as zeros. In the following equations, the discretisation of 2D-SWE using the McCormack numerical scheme is obtained in two steps (predictor strep in Eq. (4) and corrector step in Eq. (5)):

$$W^{*}_{i,j}=W^{k}_{i,j}-\frac{\Delta t}{\Delta x}\left(F^{k}_{i+1,j}-F^{k}_{i,j}\right)-\frac{\Delta t}{\Delta y}\left(G^{k}_{i,j+1}-G^{k}_{i,j}\right)+\Delta t D^{k}_{i,j} \tag{4}$$

$$W^{k+1}_{i,j}=\frac{1}{2}\left[\omega W^{k}_{i,j}+\frac{1}{4}(1-\omega)\left(W^{k}_{i+1,j}+W^{k}_{i-1,j}+W^{k}_{i,j+1}+W^{k}_{i,j-1}\right)+W^{*}_{i,j}-\frac{\Delta t}{\Delta x}\left(F^{*}_{i,j}-F^{*}_{i-1,j}\right)-\frac{\Delta t}{\Delta y}(G^{*}_{i,j}-G^{*}_{i,j-1})+\Delta t D^{*}_{i,j}\right] \tag{5}$$

where Δt, Δx, Δy are the time step, the space step in x- and the space step in y-direction, respectively, and ω is the diffusion factor.

Finally, the non-rectangular computational domains are represented by a pseudo-computational rectangular domain which encloses the real domain. A detailed description of the FLOW-R2D can be found in Tsakiris and Bellos (2014). An extensive grid convergence study of the model has been also performed for steady and dynamic evolution state applications and can be found elsewhere (Bellos and Tsakiris, 2016). Further, interesting applications of the model in urban environments can be found in Bellos and Tsakiris (2015a, 2015b).

In order to calculate the effective rainfall depth which is transformed into direct runoff, the infiltration losses should be determined. Various empirical equations have been proposed and

Download English Version:

https://daneshyari.com/en/article/6409537

Download Persian Version:

https://daneshyari.com/article/6409537

Daneshyari.com