ABSTRACT

Runoff modeling is critical to study hydrology, soil erosion and other earth surface processes. A general free surface flow model, CCHE2D, was modified for simulating the rain induced overland and subsequent channel flows. The model was verified and validated using analytical solutions and experimental cases. It was also applied to a real world agricultural watershed. The numerical simulations predicted the hydrologic process, the detailed temporal and spatial distribution of the water depth and flow velocity over the agriculture land surface which can be used for studying soil erosion, agro-pollutant transport and water quality.

KEY WORDS: Runoff; overland flow; numerical simulation; model validation; two dimensional model.

INTRODUCTION

Numerical simulation of overland flows with two-dimensional hydrodynamic models has become increasingly popular. Many researches involving models of different complexity have been proposed and tested (Liggett and Woolhiser, 1967; Cea et al., 2009; Kivva and Zheleznyak, 2005). Two of the simplified methods, the diffusion and kinematic wave methods, are commonly used (Morris and Woolhiser, 1980), depending on the terms of the momentum equations that are considered. The kinematic approximation is the simplest, in which the friction slope is set equal to the bed slope while the inertial terms are ignored (Book et al., 1981). When runoff and channel flows coexist, the simplified methods have limitations and the general hydrodynamic model is necessary. Shallow water equations are increasing used for simulating runoff processes. Costabile et al. (2012) solved the shallow water equations using the finite volume method. The model was applied to study a real event on a watershed of 40km². Finite element methods have also been applied to simulate runoff process. Venkata et al. (2009) developed a Galerkin diffusion wave finite element method and applied it to a small watershed. Singh et al. (2014) simulated runoff processes by solving the 2D shallow water equations with a shock capturing scheme and the finite volume method.

The major objective of this paper is to analyze the accuracy and the numerical effectiveness of a refined 2D model, CCHE2D to forecast fast flood events in different kinds of small catchments. The rainfall intensity is directly imposed in the hydrodynamic model as an input, and a rating curve is imposed as a boundary condition at the watershed (channel) outlet. Infiltration is not considered. Depth-averaged Reynold’s equations are solved in the model. Analytical and experimental studies are used to verify and validate numerical simulation results. In addition to overland runoff generated from the rainfall, this approach is capable of simulating both the overland runoff and channel flows. The CCHE2D model is finally used to simulate runoff in an agriculture watershed.

HYDRODYNAMICS MODEL

CCHE2D is a finite element based hydrodynamic model for unsteady turbulent free surface flows, sediment transport, pollutant transport, water quality, flooding, estuary and coastal process simulations (Jia, et al. 2002, 2013). This model is used for simulating the rainfall-runoff overland flow in this study. As the surface runoff due to precipitation is a shallow water flow, it can be well presented by the 2D shallow water equations. Depth integrated two dimensional Reynolds equations are solved for general hydrodynamic processes of the runoff and the channel flows.

Generally, a numerical model should be tested to insure its mathematical correctness, its capabilities of reproducing physics and applicability to real world problems. A series of tests was conducted in this study to achieve these goals.

VERIFICATION AND VALIDATION OF RUNOFF MODEL

To test the model’s capabilities of simulating runoff due to rainfall, CCHE2D was verified using analytical solutions of Singh and Regl (1981) and Singh (1983).

Fig. 1 Runoff hydrograph for analytical and numerical solutions of a 200 second rainfall event. Δx is the mesh spacing in runoff direction.

Fig. 1 shows the comparisons of the analytical and numerical solutions of runoff discharges for cases in which the rainfall stopped before a
steady runoff is formed over a slope. The peak discharge is the same for all locations because the flows at the lower locations are sustained by those from their upstream. As the period of the rain is relatively short, at the time the rain stops, the steady state condition has not yet been reached at all locations. The runoff recession is much earlier for the locations closer to upstream. The shape of the simulated hydrographs at all locations corresponded well with the analytic solutions.

Cea et al. (2008) conducted three runoff experiments of complex topography and simulated these cases using a 2D numerical model. The watershed of the lab experiments was formed by three planes with different slopes. The experiments were a two-dimensional artificial rectangular watershed (2m x 2.5m) made by three planes of stainless steel, each of them with a slope of 0.05. Two dikes were placed in the watershed to vary the topography and the pattern of the runoff hydrograph. The length of the two dikes were 1.86m and 1.01m. Dikes were set in the watershed to adjust the runoff direction and distribution (Fig. 2). The runoff accumulated and became channel flows along intercepting lines of slopes and dikes. These are the cases that can only be handled by hydrodynamic models solving full governing equations. The simulated flow velocity pattern indicated how the runoff flows along the slope, redirected by dikes and accumulated in the downstream channel. The channel part of the flow has a much larger water depth and recirculations (Fig. 2). All three experiments were simulated numerically. The discharge hydrograph corresponding to a rainfall with two peaks is shown in Fig. 3. The simulated hydrograph agreed well with the observed.

CURVATURE EFFECT CORRECTION FOR WATER SURFACE INTERPOLATION

In CCHE2D water surface elevation is solved at the cell centers of the mesh. The elevation is then interpolated to the colocation nodes where the momentum equations are solved. The bi-linear interpolation has no problems for general channel flows because the water depth is large. When runoff is simulated, however, the water depth is very little: often significantly less than the elevation variation of bed topography from one point to another. In this case, the interpolated water surface elevation may be lower than the bed if it is concave downward; or the interpolated surface is too high if the bed is concave upward. In the first case, dry nodes are created artificially to block the runoff flow; in the second case, artificial masses are created for extra runoff flows. Fig. 4 illustrates the described problem. In the figure, the water depth is very small, the water surface and bed surface overlaps. The circular points are collocation points and the triangles are cell centers. These interpolation induced problems are clearly shown.

A correction has been made for this interpolation error. Fig. 5 shows a concept of the correction for the bed curvature. For simplicity, bed elevation is interpolated for the discussion. It is seen an error $\Delta b$ is produced if the values at the cell centers are interpolated to the middle collocation point. The bed elevation profile is represented by three points: $b_1$, $b_2$, $b_3$. The interpolated value (bed elevation, for instance) from the cell centers to a node is denoted as $b'_2$. It can be seen that bed elevation is decreased by the interpolation. The difference is obviously due to bed curvature and is expressed as (assuming constant mesh spacing):

$$\Delta b = \frac{1}{4} \left( b_1 - 2b_2 + b_3 \right)$$

If the water surface elevation at the cell centers is interpolated, the same error would occur. Water surface elevation needs to be corrected using this equation. Practically, the correction should be computed considering irregular mesh spacing.

APPLICATION TO A REAL WATERSHED

This section presents the application of CCHE2D to an agricultural watershed (Fig. 6). The watershed has an area of approximately 973,000m², indicated by a dark, closed curve. This watershed is identified to contribute the flow to the monitoring gage station. In this region of low relief, watersheds are of intensively cultivated fields drained by ditches and streams or bayous intermittently. Because the area is very flat, the runoff simulations were conducted over a much larger area, some part of the watershed outline was identified using the
simulated flow directions. No infiltration is considered because the soil
in the watershed is clayish and only heavy rainfall events were selected.

Fig. 6 Identified watershed of this study.

Runoff simulations were calibrated by adjusting Manning’s roughness
coefficient and the results were fitted with a rating curve. The gage
station set in the channel across the watershed (Fig. 6) recorded the
water surface elevation at regular time intervals. The flow discharge
was not measured directly, therefore, to compare the measured and
simulated flow discharge hydrograph trial and error method was used
to obtain the parameters of the rating curve:

\[ Q = r(L - L_0)^z \]  \hspace{1cm} (2)

where \( Q \) is the runoff discharge, \( L \) is the measured water surface
elevation, \( r \) and \( z \) are parameters identified by trial and error, and \( L_0 \)
is the water surface elevation near the gage station at which the runoff
starts before a rain. The channel across the watershed (Fig. 6) is used
by farmers for water storage, the water surface elevation in the channel
is often changed by human activities rather than hydrology. Because
the channel of the gage is irregular and \( L_0 \) varied for different rain
events, it was found difficult for the studied rain events to have the
same rating curve parameters. Table 1 shows the identified hydrograph
parameters for the simulated heavy rainfall events.

Table 1: Parameters of selected runoff events for numerical simulations

<table>
<thead>
<tr>
<th>Event</th>
<th>Rainfall (mm)</th>
<th>Volume*(km$^3$)</th>
<th>( z )</th>
<th>( r )</th>
<th>( L_0 ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/27-4/28/2011</td>
<td>88.39</td>
<td>85817</td>
<td>2.4</td>
<td>1.223</td>
<td>0.45</td>
</tr>
<tr>
<td>10/30-11/4/2013</td>
<td>53.59</td>
<td>52182</td>
<td>1.9</td>
<td>4.24</td>
<td>0.78</td>
</tr>
<tr>
<td>11/21-25/2011</td>
<td>62.99</td>
<td>61333</td>
<td>1.4</td>
<td>1.613</td>
<td>0.45</td>
</tr>
<tr>
<td>5/20-24/2013</td>
<td>48.77</td>
<td>47483</td>
<td>1.0</td>
<td>1.436</td>
<td>0.59</td>
</tr>
<tr>
<td>9/25-27/2011</td>
<td>52.32</td>
<td>50946</td>
<td>1.8</td>
<td>5.211</td>
<td>0.48</td>
</tr>
</tbody>
</table>

*Computed from the main bulk of the rain event.

Fig. 7 shows the comparisons of the simulated runoff discharge
hydrographs and the rating curves identified using the gage data.

All simulations applied the same calibrated Manning’s coefficient.
Events 9/2011 and 10/2013 have one major peak, while those of
11/2011 and 5/2013 have two major peaks. The simulated hydrographs
fit well with those computed from Eq. 2. The two rain peaks of the
5/2013 event were separated by 2 hours approximately, but those of the
11/2011 event were separated by 15 hours. The runoff discharge of the
5/2013 event showed only one peak because the two rain peaks were
very close, and the runoff response had a delay and smoothed out the
double peak feature. However, the time interval of the two peaks of the
11/2011 event was much longer, so the hydrologic response also
displayed two peaks. These watershed responses are reproduced by the
numerical simulations.

Fig. 8a) Velocity direction distribution near the end of the simulation.
8b) Bed elevation contours of this area.

Fig. 8a shows a simulated vector direction field and Fig. 8b shows the
contours of the land topography of a small simulation area in the
watershed (Fig. 6) for the April 2011 rainfall event (Table 1). The bed
elevation of this area ranges from 47.4m to 46.8m approximately. Fig.
8a shows the vector directions near the end of the simulation when the
runoff is weak. Although the variation of the bed surface topography is
very small the simulation shows how the runoff is controlled by micro-
topography (Fig. 8b): converging into rills and diverging from ridges.

Figs. 9a and 9b show the vector direction field and water depth at the
peak time of the rainfall. The overall water depth is much deeper at this
time because of the rainfall intensity and there is a berm on the left side
of the area causing some water depth accumulation. In this situation,
the flow directions are less affected by the local micro-topographic
features. The flow on the right side of the domain is still runoff while
there is a free surface flow on the left with the water depth more than
0.2 m. The advantage of this model for runoff prediction is that it
provides not only the hydrograph, but also the temporal and spatial
distribution of the water depth and flow velocity, which can be used for
studying soil erosion, agro-pollutant transport and water quality.

CONCLUSIONS

Numerical model CCHE2D was enhanced and used to model runoff
from watersheds large and complex enough to include both overland
and channel flow processes. The model was verified and validated
using analytical solutions and experimental data, and applied to a real
word watershed. Good agreements between the analytical solutions,
experimental data, and numerical simulations were obtained. For the
experimental cases with a complex shaped watershed, the numerical
model has the ability to model runoff over the slope surfaces and the
channel flows. The model is able to simulate the runoff, free surface
flow and their transitions seamlessly. The capability would be useful
for studies related to top soil erosion and agro-pollutant transport.
Additional work is needed to further extend the research toward these
areas.

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