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Risk and Vulnerability Studies for Water Infrastructures Using a GIS-Based Decision Support System with 2D Numerical Flood Modeling

RISK AND VULNERABILITY STUDIES FOR WATER INFRASTRUCTURES USING A GIS-BASED DECISION SUPPORT SYSTEM WITH 2D NUMERICAL FLOOD MODELING

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ABSTRACT

Failure of water control structures such as dams and levees generally lead to highly dynamic catastrophic floods that can cause loss-of-life and considerable damage to property and agriculture. Currently, dam/levee break/breaching flood studies are generally carried out with one-dimensional models. One-dimensional model results are then converted to two-dimensional results by means of digital elevation maps for flood impact analysis and flood risk mapping. This approach has several drawbacks, especially in flat areas where the spreading of flood can be two-dimensional.

The present article describes the development of a GIS-based decision support system for evaluating the impact of floods resulting from dam and levee break/breaching based on a two-dimensional shock capturing unsteady conservative finite-volume model that uses digital elevation model (DEM) directly as computational grid. The computational model allows the consideration of linear terrain features that cannot be represented at the resolution level of the DEM using an immersed boundary technique based on the ghost fluid method. The model also allows combined one- and two-dimensional flood simulation using the same technique. The GIS-based decision support system directly reads simulation results and allows the user to interface these results with spatial socio-economic data to determine probable loss-of-life and urban and agricultural flood damage.

Keywords: Dambreak, levee breach, 2D flood simulation, flood impact analysis

1. INTRODUCTION

Although dam and levee failures are considered to be rare events, due to significant development that may take place in the areas protected by these water infrastructures, the loss-of-life and vulnerabilities in case of their failure may be considerable (Figure 1). During the recent Midwest floods in the USA in June 2008, approximately 30 levees have failed leading to the inundation of large areas and the evacuation of tens of thousands of people. The total property damage amounts to billions of dollars and corn production has considerably suffered.

According to the public web pages of the US National Inventory of Dams (NID, 2008), there are currently more than 78,000 dams in the USA. Among these, about 11,000 dams are classified as *high-hazard* (or *Category I*, or *Class C*), meaning that their failure may cause loss-of-life, serious damage to homes, industrial or commercial buildings, important public utilities, main highways, or railroads. In fact, all dams constructed in residential, industrial, or commercial areas are considered to be *high hazard*, unless otherwise classified by a competent authority on a case-by-case basis. Although it is required by dam safety policy, about half of the 11,000 high-hazard dams do not yet have an emergency action plan (EAP) according to the standards set forth by Federal Emergency Management Agency (FEMA) (FEMA, 2004). The same document also confirms that 83% of the 22,000 *high-hazard* and *significant hazard* dams do not yet have an EAP. There is, therefore, an urgent need for the development of flood simulation models which can be linked with GIS-based decision support tools for evaluating the impact of various failure scenarios and preparing appropriate emergency management plans.

Figure 1 A high risk dam in Georgia, USA, due to significant urban development at the downstream (NRCS, 2008).

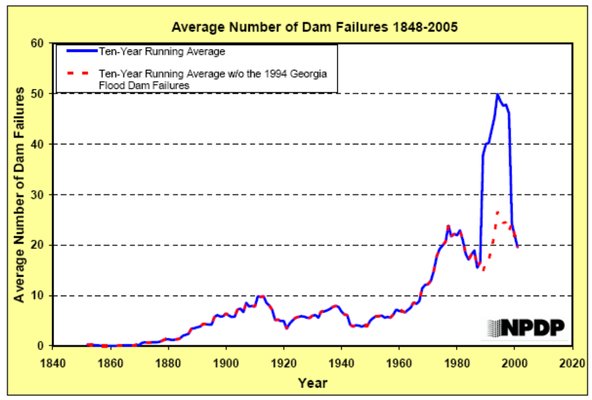

Figure 2 Ten year running average of dam failures in the USA according to the National Performance of Dams Program (NPDP, 2008)

In current engineering practice, dam and levee breach simulations are generally carried out using one-dimensional numerical models. These results need to be converted into two dimensions for use in GIS-based impact analysis. This conversion is carried out by interpolating the inundation area between the cross sections with the help of digital elevation maps. Although this approach may be applicable for slowly rising fluvial floods, it may lead to considerable errors in case of dam/levee break/breaching floods, which are highly dynamic. Moreover, one-dimensional modeling is not valid for floods spreading on a flat terrain.

The present paper describes an integrated system developed at the National Center for Computational Hydroscience and Engineering (NCCHE), The University of Mississippi, which couples a two-dimensional shock-capturing conservative model, called CCHE2D-FLOOD, with a series of decision support tools that allow interfacing of the two-dimensional numerical simulation results with spatial socio-economic data to evaluate probable-loss-of-life as well as urban and agricultural damage. The integrated system uses the Monte-Carlo method to evaluate various types of uncertainties. It also includes a pre-processing tool to prepare the DEM for flood simulation and to define linear terrain structures that are not adequately represented by the DEM due to insufficient resolution, but are likely to affect the propagation of the flood and the extent of the inundation area.

2. TWO-DIMENSIONAL FLOOD SIMULATION MODEL: CCHE2D-FLOOD

The numerical model CCHE2D-FLOOD solves the two-dimensional shallow water equations, i.e., Saint-Venant Equations, over arbitrary topography, defined by a regular

Cartesian mesh in *x-y* plane, using a conservative upwinding finite volume scheme:

$$\frac{\partial \mathbf{U}}{\partial t} + \frac{\partial \mathbf{F(U)}}{\partial x} + \frac{\partial \mathbf{G(U)}}{\partial y} = \mathbf{S(U)} \qquad (1)$$

where $\mathbf{U}$, $\mathbf{F(U)}$, $\mathbf{G(U)}$ and $\mathbf{S(U)}$ are the vectors of conserved variables, fluxes in the x and y direction, and sources, respectively. They are defined as:

$$\mathbf{U} = \begin{bmatrix} h \\ hu \\ hv \end{bmatrix} \quad \mathbf{F} = \begin{bmatrix} Q_x \\ Q_x^2 / h \\ Q_x Q_y / h \end{bmatrix} \quad \mathbf{G} = \begin{bmatrix} Q_y \\ Q_y Q_x / h \\ Q_y^2 / h \end{bmatrix} \quad \mathbf{S} = \begin{bmatrix} 0 \\ -gh(\partial Z / \partial x) - g\left(u\sqrt{u^2+v^2}/C^2\right) \\ -gh(\partial Z / \partial y) - g\left(v\sqrt{u^2+v^2}/C^2\right) \end{bmatrix} \qquad (2)$$

in which Z represents the water surface elevation and C the Chezy friction coefficient. Cell-centered finite-volume discretization of Eq. 1 over a rectangular control volume leads to the following explicit scheme:

$$U_{ij}^{n+1} = U_{ij}^{n} - \frac{\Delta t}{\Delta x_i}\left(F_{i+1/2,j} - F_{i-1/2,j}\right) - \frac{\Delta t}{\Delta y_j}\left(G_{i,j+1/2} - G_{i,j-1/2}\right) + \Delta t\, S_{ij} \qquad (3)$$

where Δx and Δy are the cell dimensions in x and y directions, and Δt is the time step. In CCHE2D-FLOOD the intercell fluxes are computed using the following first order upwinding suggested by Ying et al. (2004):

$$\mathbf{F}_{i+1/2j} = \begin{bmatrix} Q_x \\ Q_x^2 / h \\ Q_x Q_y / h \end{bmatrix}_{i+k} \quad k = \begin{cases} 0 & Q_x \geq 0 \\ 1 & Q_x \leq 0 \end{cases} \quad and \quad \mathbf{G}_{ij+1/2} = \begin{bmatrix} Q_y \\ Q_y Q_x / h \\ Q_y^2 / h \end{bmatrix}_{j+m} \quad m = \begin{cases} 0 & Q_y \geq 0 \\ 1 & Q_y \leq 0 \end{cases} \qquad (4)$$

The dry bed condition is handled by maintaining a small water depth. This numerical code has been fully tested and validated using the data from laboratory experiments and model tests, as well as limited field data available from past events (see Ying et al. 2003a and b, Ying and Wang, 2004, and Ying et al., 2004). It has been shown that the model is stable, oscillation-free, robust, and rigorously conserves mass.

CCHE2D-FLOOD can directly use a Digital Elevation Model (DEM) as a regular rectangular mesh. This simplifies data preparation and cuts down the model set-up time considerably. The results of the simulations, which are written as raster files, can also be readily exported into any commercial GIS software or further analysis and treatment.

The direct use of a DEM, however, also presents some important disadvantages. The typical cell sizes used in flood simulation studies vary from 10m to 100m. Even DEMs with a relatively high 10m resolution may not adequately capture linear terrain features, such as roads and railroads, which may considerably affect the propagation of the flood waters and the delineation of the inundated area. Although local mesh refinement and/or the use of unstructured triangular grid may be used to include these linear terrain features in the computational mesh, these techniques require the user to generate a mesh, which may be time consuming. Moreover, the direct link with GIS software, which uses a DEM, is lost.

In order to represent linear terrain features even in relatively coarse meshes a cut-cell technique was implemented in CCHE2D-FLOOD. The linear terrain feature to be represented in the model must be available as a three-dimensional polyline defined as a series of vertices, $P_i(x_i, y_i, z_i)$. The polyline is projected onto the DEM by imposing that a cell can only be cut by a single straight line. The cells that are cut into two irregular pieces by the projected line need to be handled in a special way. The method implemented in CCHE2D-FLOOD is a two-sided immersed boundary method (IBM) that uses the ghost-fluid method (GFM). A detailed discussion of the IBM and GFM can be found in Mittal and Iaccarino, 2005, and Ghias et al., 2007.

The details of the implementation of GFM in CCHE2D-FLOOD are presented in Miglio et al., 2008a and b, and will not be repeated here due to space limitation. Figure 3 shows a portion of a Cartesian grid cut by a projected polyline. In this figure the different types of cells are marked by assuming that the water is on the upper side of the cut-cell boundary. In fact the point of view changes depending on which cell is being calculated. This is shown in Fig. 4. For the case on the left, the center cell is being calculated. The cell below is on the other side of the cut-cell boundary, and thus is labeled as a ghost cell (GP). In order to be able to compute the intercell flux between these two cells, an appropriate values of conserved variables must be assigned at GP to simulate the presence of the cut line. First the cell center GP is reflected into the same side as the computed cell with respect to the cut-line, yielding the point RP. The values of conserved variables are interpolated from the known values at the four cell centers surrounding the RP. The values interpolated at RP are then extrapolated back to GP using the known boundary condition on the cut line.

Figure 3 Representation of a cut-cell boundary and different types of cells. Ghost cells are marked for the case the water is on the upper side of the barrier.

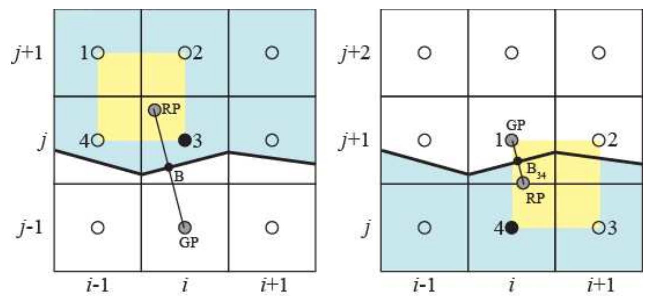

Figure 4 Schematic representation of two-sided ghost fluid method. Computed cell is marked by a solid circle at the center. The cell on the other side of the cut is treated as a ghost cell.

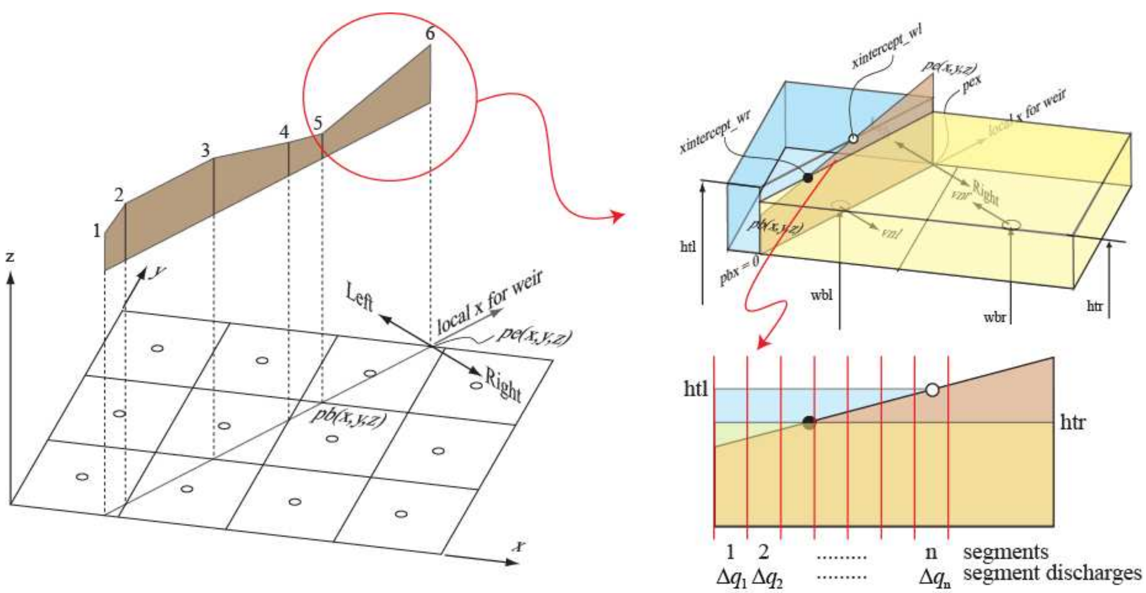

Figure 5 Schematic view of the cut-line boundary with overtopping and the method of computation of the overtopping discharge.

For an infinitely high cut-line, i.e., zero flux across the line, the following set of boundary conditions can be used:

$$Q_n = 0, \qquad dQ_t / dn = 0, \qquad dZ / dn = 0, \tag{5}$$

where Q_n and Q_t are the components of discharge normal and tangential to the boundary, respectively (Miglio et al., 2008).

Depending on the water depths and the height of the cut-line, in some cases there may be an overtopping discharge from one side to the other (see Figure 5). In such cases, CCHE2D-FLOOD calculates the overtopping discharge by dividing the length of the cut-line into n small segments, and using the ogee weir equation for each segment:

$$q = \sum_{1}^{n} \Delta q_j = \sum_{1}^{n} \left[\sqrt{2g}\ \mu\ L\ h_o^{3/2} \right]_j \qquad (6)$$

In the case of overtopping the boundary conditions in Eq. 5 need to be modified. One takes $Q_n = q$, and the third boundary condition is replaced by a momentum equation representing the weir flow. Figure 6 shows the results of a test case representing the passage of a dambreak wave over a constricted weir with infinitely high walls on both sides.

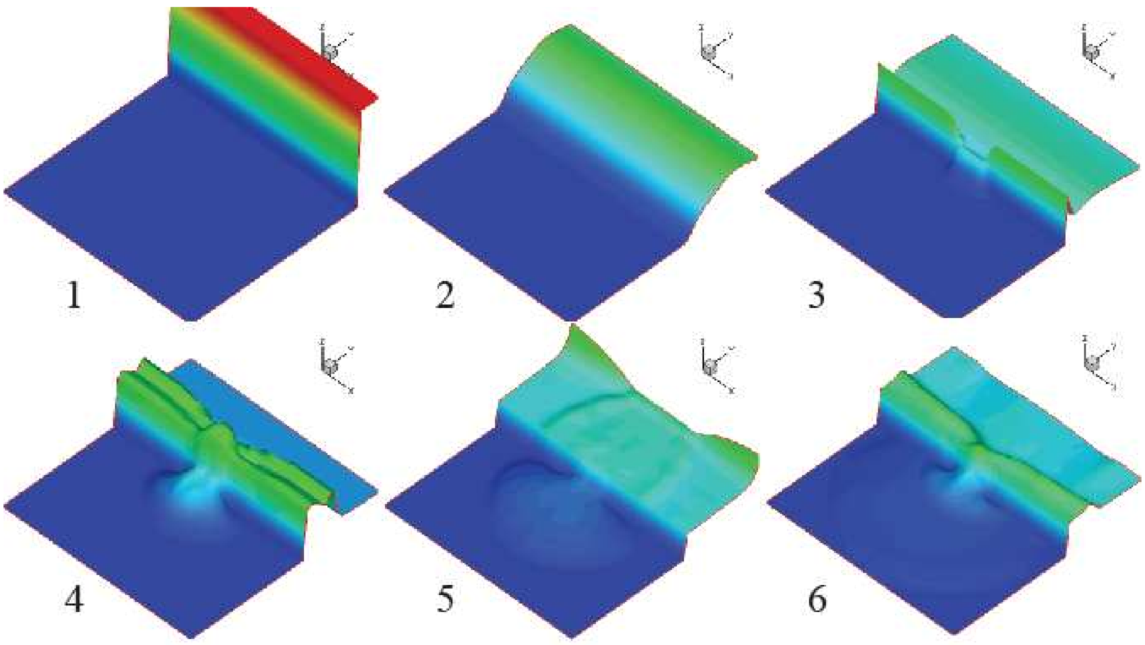

Figure 6 Screen shots from a test case showing the passage of a dambreak flood over a constricted weir represented using the cut-cell boundary technique. The computational domain is 50×50m and the cell size is 10m. The initial height of the dam is 8m and the weir height is 0.5m. On both sides of the weir, the cut-line is infinitely high.

A special version of the cut-cell boundary method is also used to couple a one-dimensional shock capturing unsteady channel model with the two-dimensional CCHE2D-FLOOD model (Altinakar et al., 2008b) to carry out levee-breach flood simulations in a single run (see Figure 7). In this special case, the cut-cell boundary represents the planview of a river. The river is represented by a series of user-defined cross-sections as in a normal one-dimensional model. Several boundary condition types are available for the one dimensional model. The inlet boundary condition is generally a specified hydrograph. At the outlet boundary condition, one can specify the stage discharge curve, or define the depth as a function of time, etc. The user also specifies the initial conditions. One- and two-dimensional models have their own time steps which are automatically defined by the program. The cross sections do not have to be aligned with any grid feature. The program takes care of bookkeeping of the correspondence between the two-dimensional model cells and the river reaches, and computes the exchange discharges in left and right sides of the river. The river is allowed to begin and end outside of the two-dimensional domain.

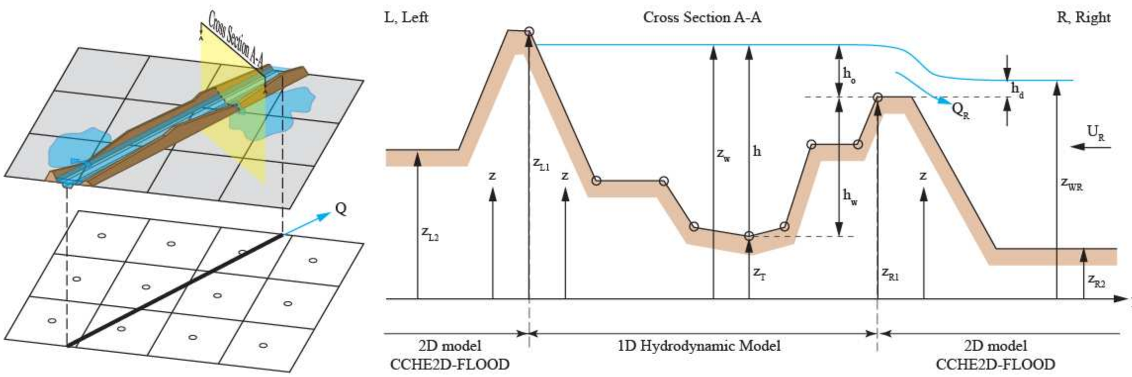

Figure 7 A special version of cut-cell boundary is used to couple a one-dimensional shock capturing unsteady model with CCHE1D-FLOOD. The cut-line projected onto the two-dimensional grid represents a river with user-defined cross sections. The exchanges from river to two-dimensional model and vice-versa are allowed and computed using the weir equation.

1D-2D coupling capability was tested for simulating the case of a dambreak flood entering a one-dimensional river represented as a cut-cell boundary. The computational domain is 200×300m and the cell size is 10m. The initial height of the dam located on the left side of the river is 8m. The cross sections of the river are shown in Fig. 8. Near the downstream end the left bank has a low point. There is also a low point on the right bank near the upstream end.

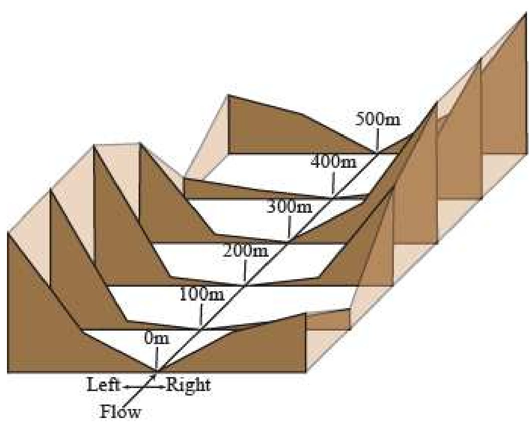

Figure 8 Oblique view of the cross sections of the one-dimensional river used for testing 1D-2D model coupling. A constant discharge of 0.1m3/s enters the river at the upstream end. The downstream depth is fixed at 0.5m throughout the simulation to reflect the wave back. The initial water depth in the river is 0.5m.

The screen shots of the simulation showing both the two-dimensional domain and the water surface in the one-dimensional river are plotted in Figure 9. Water from the 2D model enters the river at the downstream end from the lower left bank. A positive surge forms in the 1D model and travels upstream. When the higher water level reaches the low point on the right bank near the upstream end of the channel, the water spills into the 2D model.

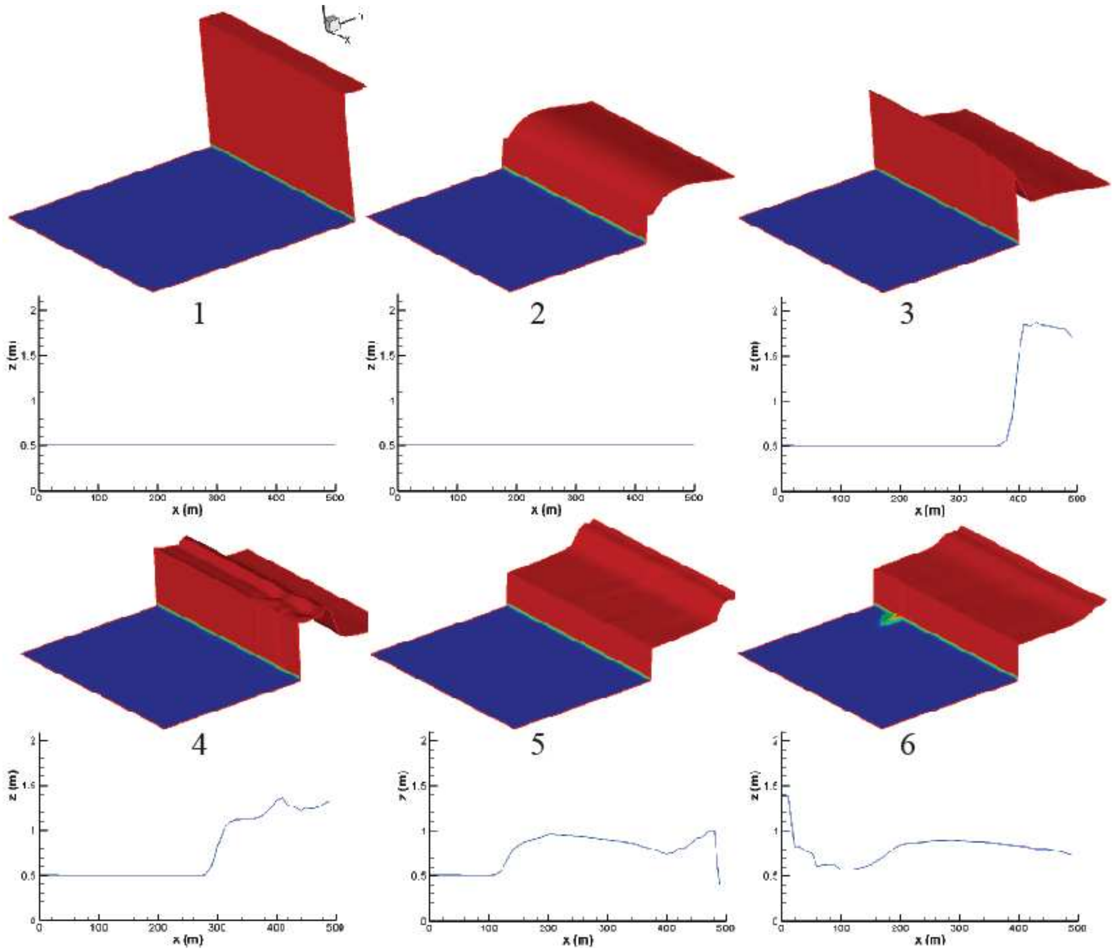

Figure 9 Screen shots for the 1D-2D coupling test case.

3. GIS-BASED DECISION SUPPORT SYSTEM

Flood simulation with the numerical model CCHE2D-FLOOD provides the information on the extent of the flooded area and spatial distribution of flood depth at various times, spatial distribution of flood velocities (in two horizontal directions) at different times, arrival time of the flood at each point of the computational domain, and duration of the flood at each point of the computational domain. In addition, results files representing the envelope maps of maximum depth and maximum velocity are also provided. These files can readily be imported into a GIS software, ArcGIS in the present case, for mapping as well as for further treatment to analyze the impact of the flood.

A collection of GIS-based decision support tools have been prepared to interface the numerical results provided by CCHE2D-FLOOD with spatial socio-economic data, such as classified remote sensing data, census block data, as well as GIS shape layers for infrastructures including roads and railroads, urban data (buildings, critical structures, etc.), agricultural data (crop fields, farm buildings, livestock, fishponds, etc.) in order to evaluate the potential flood losses and damages, evacuation needs, shelter needs, to test and compare the efficiency various mitigation measures (structural and non structural), and to plan emergency operations. A detailed description of the available decision support tools can be found in Altinakar and Qi (2006). Some selected tools are are briefly described below.

Estimation of probable loss-of-life

The estimation of the probable loss of life follows the methodology developed by Graham (1999) and Dise, (2002), which assumes that the loss-of-life due to a flood is influenced by the following factors: 1) The number of people occupying the floodplain, also called people at risk (PAR); 2) The warning time available to the PAR; 3) The severity level of the flooding; and 4) The emergency preparedness and/or awareness level of the population. Figure 10 shows the flowchart of the computations for estimation probable loss-of-life.

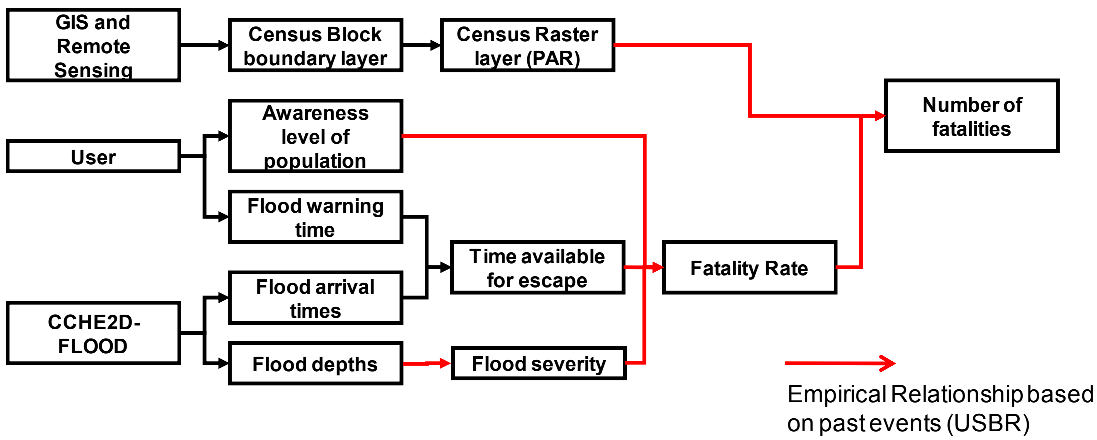

Figure 10 Flowchart showing the procedure to estimate probable loss-of-life due to a flood.

The PAR values are obtained from the census block data, which is usually a GIS vector polygon layer (for example, in TIGER format) showing spatial variation of population. After importing census block layer into ArcGIS, the population densities are calculated based on the total population and area of each census block, and converted to a raster layer. In fact the PAR distribution depends heavily on the population dynamics based on the time of the day and day of the year. If available, the PAR data may be extracted directly from a population dynamics model. The warning time is computed for each cell as the time interval between the first public warning (a user defined parameter) and the arrival of the flood wave, which is given by the simulation. The local flood severity in each cell is classified as low, medium, and high directly based on the flood depth. The level of awareness of the population (high, low, etc.) is specified by the user based on the existence of the public education programs and the sociological impact of past flood events.

Estimation of urban and agricultural damage.

The flowchart of the procedure to compute urban and rural flood damage is presented in Figure 11. The information regarding the building and infrastructure stock and the agricultural exploitation data is normally extracted from field surveys. If field surveys are not available, the tool also accepts classified remote sensing data. The damage to a given property, whether urban or rural, is calculated based on the maximum water depth and maximum velocity information provided by the numerical model. A knowledge base provides the depth (and/or velocity) versus percent damage relationship for various building types (residential, public utility, industrial, etc.), infrastructures (roads, bridges, railroads, electric lines, etc.), crop fields, farm houses, fish ponds, agricultural installations, etc. The knowledge base also provides the property values and their contents. Details of the computational method and the percent damage curves can be found in Qi et al. (2005, 2006).

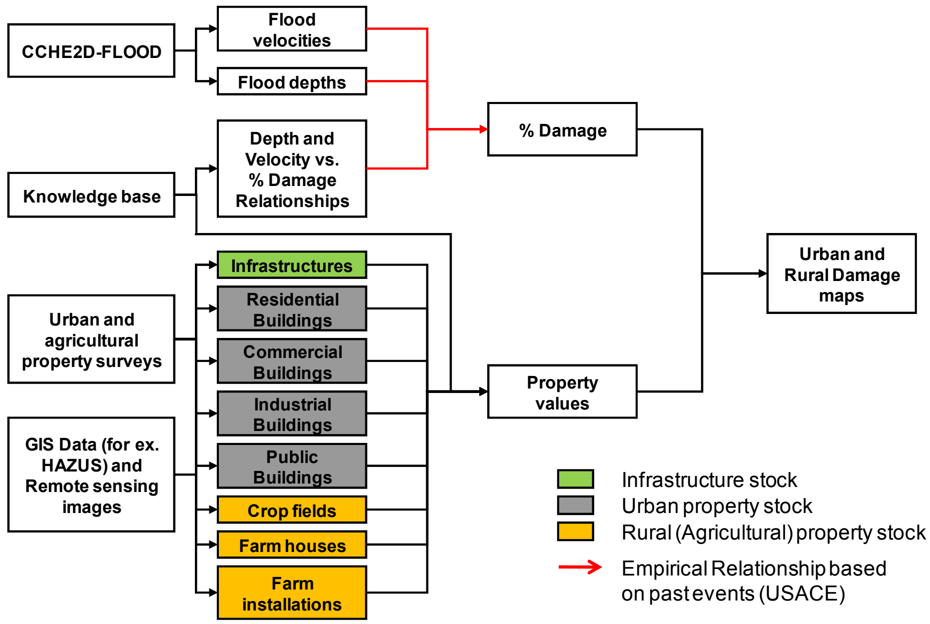

Figure 11 Procedure for the estimation of urban and rural (including agricultural) damage.

4. CONCLUSIONS

The paper described an integrated system which combines a two-dimensional numerical model with a series of GIS-based decision support tools to estimate probable loss-of-life as well as urban and rural flood damage by interfacing numerical results with spatial socio-economic data obtained from field surveys and /or classified remote sensing maps. The decision support tools use the Monte-Carlo method to simulate uncertainties associated with different variables. The numerical model includes a cut-cell boundary capability to represent linear terrain features that cannot be captured in the DEM. A special version of the cut-cell boundary method couples 1D and 2D simulations for carrying out levee breach simulations in a single run. The integrated system can be used to establish Emergency Action Plans (EAP) for high-hazard and significant hazard dams, as well as emergency management planning. Figure 12 shows an example different types of flood impact maps that can be prepared.

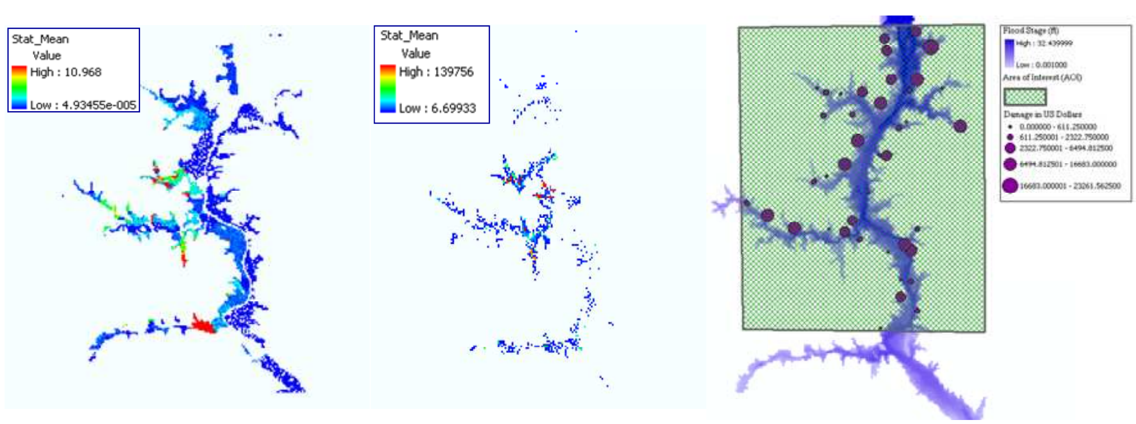

Figure 12 Maps showing expected values of number of casualties (left), expected values of urban property damage in USD (middle), and expected values of rural property damage in USD (right) for a hypothetical breaking of Sinclair Dam on Oconee River in Georgia.

REFERENCES

Altinakar, M.S., Miglio, E. and Wu, W. (2008b), Coupling 1D-2D Shallow Water Models for Simulating Floods due to Overtopping and Breaching of Levees, The proceedings of 8th World Congress on Comp. Mech. (WCCM8) and 5th European Congress on Comp. Meth. in Appl. Sciences and Engrg (ECCOMAS 2008), Venice, Italy, June 30-July 4, 2008.

Altinakar, M.S. and Qi, H (2006), Numerical Simulation-Based Decision Support System for Catastrophic Flood Management and Water Infrastructural Security; Keynote Lecture, Proc. of Int. Seminar on Urban Flood Mgmt: Design Techniques for Urban Flood Mitigation organized by Korea Institute of Constr. Techn. (KICT), Seoul, Dec. 12, 2006.

Dise, K.M. (2002), Estimating Potential for Life Loss Caused by Uncontrolled Release of Reservoir Water. Risk Analysis Methodology Appendix O, U.S. Bureau of Reclamation, Technical Service Center, Denver, CO, USA.

FEMA (2004), Federal Guidelines for Dam Safety: Emergency Action Planning for Dam Owners, prepared by the Interagency Committee on Dam Safety, Published in Oct 1998 and reprinted in Apr 2004 (http://www.fema.gov/plan/prevent/damfailure/fema64.shtm).

Ghias, R., Mittal, R. and Dong, H. (2007), A sharp interface immersed boundary method for compressible viscous flows, J. Comput. Phys., 225, pp.528-553.

Graham, W.J. (1999), A Procedure for Estimating Loss of Life Caused by Dam Failure. Report No. DSO-99-06, Dam Safety Office, US Bureau of Reclamation, Denver, CO.

Miglio, E., Altinakar, M.S. and Fijołek, E.K. (2008a), Representation of Linear Terrain Features in 2D Free Surface Models using Ghost-Fluid Method, Proceedings of 8th World Congress on Comp. Mech. (WCCM8) and 5th European Congress on Comp. Meth. in Appl. Sciences and Engrg (ECCOMAS 2008), Venice, Italy, June 30-July 4, 2008.

Miglio E., Altinakar, M.S. and Tayfur, G. (2008b), Representation of Linear Terrain Features in 2D Free Surface Models using Cut-Cell Boundary Method, Proceedings of River Flow 2008, Int. Conference on Fluvial Hydraulics, Cesme, Izmir, Turkey, Sep. 3-5, 2008.

Mittal, R. and Iaccarino, L. (2005), Immersed Boundary Methods, Annual Review of Fluid Mechanics, Vol. 37: 239-261.

NID (2008), http://crunch.tec.army.mil/nidpublic/webpages/nid.cfm, last visited 6/18/2008.

NPDP (2008), http://npdp.stanford.edu/npdphome/index.htm, last visited 6/18/2008.

NRCS (2008), http://www.ga.nrcs.usda.gov/programs/watrehab.html, last visited 6/18/2008.

Qi, H., Altinakar, M.S. and Jeon, Y. (2006), A Decision Support Tool for Flood Management under Uncertainty Using GIS and Remote Sensing, Proceedings of 7th International Conference on Hydroscience and Engineering (ICHE 2006), Philadelphia, PA, Sept 2006.

Qi, H, Altinakar, M.S., Ying, X. and Wang, S.S.Y. (2005), Risk and Uncertainty Analysis in Flood Hazard Management Using GIS and Remote Sensing Technology, Proc. of the American Water Resources Association (AWRA) Annual Conference, Seattle, Nov 2005.

Ying, X., Khan, A.A. and Wang, S.S.Y. (2003a), An Upwind Method for One-Dimensional Dam Break Flows, Proc. of 30th IAHR Congress, pp. 245-252, Thessaloniki, Greece, August, 2003.

Ying, X., Khan, A. A. and Wang, S.S.Y. (2004), An Upwind Conservative Scheme for Saint Venant Equations, Journal of Hydraulic Engineering. Vol.130, No.10, pp. 977-987, 2004.

Ying, X. and Wang, S.S.Y. (2004) Two-Dimensional Numerical Simulations of Malpasset Dam-Break Wave Propagation, Proc. of 6th Int. Conf. on Hydroscience and Engrg, Brisbane, Australia, Book of Abstracts, pp.137-138, Manuscript on CDROM,, May, 2004.

Ying, X., Wang, S.Y. and Khan, A.A. (2003b), Numerical Simulation of Flood Inundation Due to Dam and Levee Breach, Proceedings of ASCE World Water & Environmental Resources Congress 2003 (CD-ROM), Philadelphia, USA, June 2003.