Finite Element Methods in Overland Flow Modeling for an Integrated Multi-Scale Forecasting Scheme

Muhammad Akbar[1], Shahrouz Aliabadi [2]

Northrop Grumman Center for High Performance Computing of Ship Systems Engineering
Jackson State University, MS e-Center, Box 1400, 1230 Raymond Road, Jackson, MS 39204, U.S.A.

[1] *(Tel: 601-979-1839; e-mail: muhammad.k.akbar@jsums.edu)*
[2] *(Tel: 601-979-1821; e-mail: saliabadi@jsums.edu)*

SUMMARY

In this paper we present a finite element method for overland flow (flood) simulation in the coastal area. The research is part of an integrated forecasting tool development for multi-scale storm surge and overland flow due to hurricane. Three models are executed in sequence to get all the necessary results. Two of these are open source codes and the third one is our proposed overland model. The open source codes are extensively parallel to ensure real time forecast to deal with the emergency evacuation tasks days before the hurricane strikes the coast. Our overland code is relatively fast enough and did not require parallelization. The results from the models are fed into Geographical Information Systems (GIS) for visualization, analysis and decision-making. Although we present results for all three models, our primary focus of the present study is the overland flow modeling. We have taken hurricane Katrina (2005) and its water surge and flooding in the Mississippi coastal area as a case study.

KEY WORDS*:* multi-scale hurricane simulation, meteorological data, water surge, overland flow, finite element, parallel computation.

1. INTRODUCTION

Overland flow consists of a low depth water runoff over the ground surface. In general, overland flow represents flood water wave propagation, which is conceptually similar to open channel flow. Overland flow is of interest to a wide variety of users, including urban planners and emergency evacuation authorities. Such flow may occur in case of a flood caused by excessive rain, dam breakage, tsunami or hurricane, etc.

Tsunamis and storm surges exposes human occupation of low-lying coastal areas to severe flooding. Storm surges, which are generated by extreme wind stress acting on shallow, continental shelf seas can lead to severe coastal floods, particularly when they coincide with a high tide and result in overtopping and breaching of sea defenses [1]. It may result in substantial economic and social impacts, including loss of life, damage to property, and disruption of essential services [2-6]. Hurricane Katrina is a perfect example of such disastrous scenario.

An understanding of the nature and degree of exposure to coastal flooding is important for reducing its impacts on people and property. The understanding of the coastal flooding may be developed through field observations, modeling studies, or some combination of both. However, such observational data are too limited in both quantity and quality, which makes predictive extrapolation very difficult [7-8]. An extreme event typically alters floodplain conditions in many ways. Besides, the factors involved in those calamities are too many and may vary from occurrence to occurrence. Therefore, the reliability of flood models with historic observation is limited [9]. The observational data, however, should lead to an understanding of the underlying physics, which will help us to create physics-based computer models to explore and predict extreme flood hazards.

Many flood predictive models have been reported in the open literature [10-21]. These include applications of the two-dimensional (2-D) diffusion equation to flooding from storm drains [15], and applications of the full Saint-Venant equations to coastal flooding [16-17]. Most of these applications have focused on rural floodplains with limited number of structures [18]. The surface friction rendered by structures usually are either ignored or loosely approximated by parameterization [19-20]. It has been emphasized that studies of flooding within urban areas need more detail and careful simulation including appropriate blocking and frictional effects of buildings and structures [20-21]. Brown et al. [9] have employed a case study to demonstrate the application of a 2-D hydraulic model to flooding within an urban area. They have illustrated the importance of structural forcing inputs and boundary conditions, evaluated the propagation of uncertainties from model inputs to explore the uncertainties associated with model predictions.

Our integrated modeling scheme of a hurricane deals from its inception in the deep ocean to landfall and associated water surge and flooding in the coastal regions. Using the most updated meteorological data days before a hurricane strikes, the ground wind speed, pressure, rain, etc can be predicted using the open source parallel code Weather Research and Forecasting (WRF) [22]. We obtain wind speed and pressure data from WRF, which are used as input to another open source parallel code ADvanced CIRCulation (ADCIRC) [23] to predict water surge in the ocean caused by the hurricane. We use ADCIRC water elevation results to model the coastal area flooding phenomena using our finite element method based CaMEL Overland flow solver [24]. The graphical presentation in Fig. 1 shows the integration of the whole simulation and visualization process.

As a case study in the present research, we have chosen hurricane Katrina (2005) and its flooding impact on the Mississippi coastal region. The findings of our research will help to predict the immediate impact on the coastal structural establishments. Short and long term impact of flood on the geological system in the coastal region can also be derived from the behavior and pattern of the flooding. Understanding the overland flood wave routing theory and solving the governing equations accurately is an essential part of our ongoing research of modeling the integrated hydrological system in the coastal region.

2. INTEGRATED MODEL DETAILS

In an actual hurricane event WRF, ADCIRC, and CaMEL Overland codes must be executed in sequence two to three days before its landfall, most likely every 6 to 12 hrs. Repeated simulations of the codes are needed because the more recent meteorological data we use the better accuracy we obtain from WRF. The accuracy of WRF results propagate into ADCIRC and CaMEL Overland simulations through the wind and rain input. Parallel implementation of the codes is necessary to ensure real time hurricane and flood forecast.

WRF is a parallel model, which is designed to serve both operational forecasting and atmospheric research needs. It is suitable for a broad spectrum of applications across scales ranging from meters to thousands of kilometers. It allows researchers the ability to conduct simulations reflecting either real data or idealized configurations. We have studied the parallel implementation of WRF extensively in our parallel cluster, which has Intel Xeon processors and total of 80 cores. The speed up of WRF in our cluster is displayed in Fig. 2 (a).

Using the WRF wind speed and pressure data as input, ocean water surge is simulated using two-dimensional depth integrated (2DDI) model of ADCIRC. ADCIRC is a model for oceanic, coastal and estuarine waters. It is a highly developed computer program for solving the equations of motion for a moving fluid on a rotating earth. These equations have been formulated using the traditional hydrostatic pressure and Boussinesq approximations and have been discretized in space using the finite element method and in time using the finite difference method. The water elevation is obtained from the solution of the depth-integrated continuity equation in Generalized Wave-Continuity Equation (GWCE) form. The speed up of ADCIRC in our parallel cluster is displayed in Fig. 2 (b).

After the ADCIRC simulation, we model the coastal area water surge phenomena using our CaMEL Overland flow code. We have solved diffusive wave or Richard's equation by the Galerkin finite element method [24]. The time dependent water surge values simulated from ADCIRC along the shoreline is used as the Dirichlet boundary input in the model. The rain data predicted from WRF is used as the source term in the model. The detail of the Overland model is presented in the following few sections.

3. OVERLAND MODEL

The overland flow can essentially be represented by two dimensional shallow water equations. The shallow water equations are derived from the continuity and Navier-Stokes equations by integrating over the depth using kinematic boundary conditions [25-26]. Underlying assumptions are: pressure distribution is hydrostatic, and horizontal shear stresses are small [27-29].

Let us denote $\mathrm{x} \in \Omega$ and $t \in (0,T)$ the space and time domains, respectively. The boundary of Ω is defined by $\Gamma = \Gamma_g + \Gamma_h$, where Γ_g and Γ_h are portion of the boundary where Dirichlet and Neumman boundary conditions are imposed. The resulting fully dynamic unsteady flow equations are given by the conservation of mass and momentum equations written as:

$$\frac{\partial h}{\partial t} + \nabla \cdot (uH) = \dot{n} \quad (1)$$

$$\frac{\partial(\mathbf{u}H)}{\partial t} + \nabla \cdot (\mathbf{uu}H) = -gH\nabla h - gH\mathbf{S} \quad (2)$$

Here H, h, $\mathbf{u}$, $\mathbf{S}$ and $\dot{n}$, are water depth, water height measured from geoid reference point, velocity, friction slope, and source term due to rain, evaporation, and ground absorption, respectively. Note in this context, $h = H + Z$ where Z is the ground elevation. The notation of a typical water-land terrain system is shown in Fig. 3.

Depending on the further simplifications introduced to the shallow water equations, at least two different models can be distinguished. The first one is a fully dynamic model which solves the complete set of shallow water equations. In the second model acceleration terms in the momentum equations are neglected. It leads to a reduced momentum equation as following

$$\nabla h + \mathbf{S} = 0 \tag{3}$$

The above equation represents that the friction slope and the slope of the water surface are the same. By applying Manning-Strickler law, which relates water depth gradient to flow velocity, the velocity vector can be written as [30-31].

$$\mathbf{u} = -\frac{K}{H}\nabla h \tag{4}$$

where, K is defined as[27]

$$K = \frac{H^{5/3}}{n}\left\|\nabla h\right\|^{-1/2}, \quad n = \frac{H^{1/6}}{C} \tag{5}$$

Here, n and C are Manning and Chezy coefficients, respectively. Applying Eq. (4) and replacing h with $H+Z$ in the continuity equation, i.e., Eq. (1), leads to a non-linear diffusion equation in the following form. Note that ground elevation Z does not change with time.

$$\frac{\partial H}{\partial t} - \nabla \cdot \left(K \nabla H\right) = \dot{r} + \nabla \cdot \left(K \nabla Z\right) \tag{6}$$

In our model, we solve normalized form of Eq. (6). It is also called diffusive wave or Richard's equation. This diffusive wave equation describes the unconfined unsteady overland flow. Our system deals with slow flow dynamics in low gradient situation, and the primary driving force is the slope of the water surface. Therefore, the diffusive wave approach is appropriate. The fluid is assumed to be incompressible with constant and uniform density. The only degree of freedom in the model is the water depth. Non-linearity arises into the equation through the 'K' term, which is equivalent to the conductivity for water depth [25].

Equation (6) is completed by an appropriate set of boundary and initial conditions given by

$$\begin{aligned} &h = h_0 \quad \text{at } t = 0 \\ &h = h_{in} \quad \text{on } \Gamma_g \\ &K\,\nabla h \cdot \mathrm{n} = F \quad \text{on } \Gamma_h \end{aligned} \tag{7}$$

4. OVERLAND MODEL DETAIL

Finite Element Formulation

The Eq. (6) can be normalized with the following relationships:

$$H^* = L^{-1}H; Z^* = L^{-1}Z; \nabla^* = L\nabla; K^* = \left(L\sqrt{gL}\right)^{-1}K; \;\; \dot{r}^* = \left(\sqrt{gL}\right)^{-1}\dot{r}; \;\; C^* = g^{-1/2}C; t^* = \sqrt{g/L}\; t \tag{8}$$

Replacing the normalizing parameters given above and dropping the "*" signs, we get the normalized diffusion equation in the same form as Eq. (6). We have solved the normalized form of diffusion equation by the Galerkin finite element method. In the finite element formulations we first define appropriate sets of trail solution spaces, S_h and weighing function spaces, V_h. The stabilized finite element formulation of Eq. (6) can then be written as follows: for $\phi \in V_h$ find $H \in S_h$ such that

$$\int_{\Omega} \phi \frac{\alpha_1 H^{n+1} + \alpha_0 H^n + \alpha_{-1} H^{n-1}}{\Delta t} d\Omega + \int_{\Omega} \nabla\phi \cdot \left(K^{n+1} \nabla H^{n+1}\right) d\Omega$$
$$= \int_{\Omega} \phi \dot{r}\, d\Omega - \int_{\Omega} \nabla\phi \cdot \left(K^{n+1} \nabla Z\right) d\Omega - \int_{\Gamma_h} \phi\, H \mathbf{u} \cdot \hat{\mathbf{n}}\, d\Gamma \tag{9}$$

Note that the last term on the right hand side in the above equation is due to the Neumann boundary condition. The time integration can be done using backward difference scheme. The finite element formulation in Eq. (9) is nonlinear. In Newton-Raphson nonlinear iteration algorithm, we perturb H such that $H^{n+1} = H + H'$ to obtain the linearized finite element formulation as follows

$$\frac{\alpha_1}{\Delta t} \int_{\Omega} \phi H' d\Omega + \int_{\Omega} \nabla\phi \cdot \left(K \nabla H'\right) d\Omega + \int_{\Omega} \left(\nabla\phi \cdot \nabla h\right) \frac{\partial K}{\partial H} H' d\Omega =$$
$$- \int_{\Omega} \phi \frac{\alpha_1 H + \alpha_0 H^n + \alpha_{-1} H^{n-1}}{\Delta t} d\Omega - \int_{\Omega} \nabla\phi \cdot \left(K \nabla h\right) d\Omega + \int_{\Omega} \phi \dot{r}\, d\Omega - \int_{\Gamma_h} \phi\, H \mathbf{u} \cdot \hat{\mathbf{n}}\, d\Gamma \tag{10}$$

Here H^n and H^{n-1} are the solution at previous time steps n and $n-1$, respectively. For first order time accurate scheme (BDF1), $\alpha_1 = 1.0$, $\alpha_0 = -1.0$, and $\alpha_{-1} = 0.0$ and for second order time accurate scheme (BDF2), $\alpha_1 = 1.5$, $\alpha_0 = -2.0$, and $\alpha_{-1} = 0.5$.

To discretize the finite element formulation in Eq. (10), we use linear interpolation functions. As a result, at a given time step and a nonlinear iteration, we solve the bilinear form of the following equation:

$$\mathbf{B}\left(\sum_i N_i \phi, \sum_j N_j H'_j\right) = -\mathbf{A}\left(\sum_i N_i \phi, \sum_j N_j H_j\right) \tag{11}$$

where the subscript *i* and *j* are the indices referring to nodal values. Here both *i* and *j* stand for all nodes excluding the ones with prescribed values (i.e., Dirichlet boundaries). The resulting discretization leads to a linear equation system with the stiffness matrix as the coefficient matrix. The system is solved by matrix-free implicit GMRES solver [32]. The underlying matrix-free finite element method has been discussed in details in the solution of Poisson equation in Tu and Aliabadi [32]. To save memory, we are not forming the global stiffness matrix. Instead, we follow a matrix-free implementation [33-34]. Source term due to rain, evaporation, or ground water absorption is considered to be zero.

Wet and Dry Phenomena

Our computational domain is two-dimensional, with Dirichlet condition applied in one boundary and zero-flux conditions in the other three boundaries. Initially zero water height, *i.e.*, *h=0*, condition is applied in the domain. Water propagates from the Dirichlet boundary side into the domain. A node is assumed to be wet if its water depth (*H*) is higher than a threshold value, typically *1e-12*. An element is assumed to be wet if its all nodes are wet. Similarly, an element is dry if all nodes are dry, while an element with one or two wet nodes is considered to be mixed. The graphical representation of the wet and dry condition is displayed in Fig. 4. In our solution technique, we solve only for the wet and mixed elements in the domain, which makes the solution significantly faster.

5. OVERLAND MODEL VALIDATION

In this section we compare our results with three benchmark cases to validate the code.

Case 1: A case with two Dirichlet boundary conditions

A two dimensional computational domain, $(x, y) = [-5, 5] \times [0, 0.03]$ is defined. To ensure symmetric one dimensional results, (1000×3) structured square elements are used in the domain. The upstream and downstream ends of the domain have Dirichlet boundary conditions of $h_{x=-5} = 1\text{m}$ and $h_{x=5} = 2\,\text{m}$, respectively. The other two boundaries have zero flux boundary conditions, resulting in symmetric solutions in the y-direction. Considering steady state, an analytical solution can be derived for this case, as

$$h^4 = \left(h_L^4 - h_0^4\right)\frac{x}{L} + h_0^4 \quad (12)$$

Figure 5 shows the hydraulic head variation in the computational domain, and the comparison of the results with the analytical solution given in Eq. (12). Note that for this case the ground elevation, *Z,* coincides with geoid, and hence *h* and *H* have the same value.

Case 2: A case with a semi-circular bump in the center and one Dirichlet boundary condition

This case has one Dirichlet condition in the inlet boundary, and the domain has a semicircular bump or obstacle in the center. The rest of the boundaries have zero-flux conditions. The domain dimensions are same as in the Case 1. The bump radius is 1m, and the Dirichlet boundary value is 1.5m. The water should go over the bump to fill in the other side of the domain as simulation time progresses. The steady state solution should be 1.5m water height everywhere. This case demonstrates the wet and dry phenomena very well. The transient pattern of the flow is displayed in Fig. 6.

Case 3: A case with semi-circular water break in the center with zero-flux boundaries

This case has the same domain as in the Case 1, except all boundaries have zero-flux condition. There is a semi-circular water break in the center of the domain. The initial radius of the water dome is 1m. As simulation time progresses water should spread in both sides of the domain to reach a steady state. If mass is conserved, area under the curve should remain same all the time. Figure 7 shows the transient pattern of the water spread. The steady state solution matches with the exact solution. Similar to the Case 1, for this case the ground elevation, *Z,* coincides with geoid, and hence *h* and *H* have the same value.

6. RESULTS AND DISCUSSION

The simulation of hurricane Katrina in the Gulf of Mexico is chosen as a case of study in the paper. This is primarily because we have good amount of data available for Katrina. It facilitates more accurate simulation and comparison with observed data recorded during or after Katrina.

6.1 WRF Results

WRF uses structured mesh with the option of multiple nested domains. We used a single domain with 300 grid points in east-west, and 220 grid points in south-north. Each segment was 8 km. The computational grid for WRF is displayed in Fig. 8

Figure 9 shows the comparison of Katrina simulation and actual track path. Figure 9(a), (b), (c), and (d) show the WRF simulated track paths starting from Aug 26 - 00 A.M., Aug 27 - 00

A.M., Aug 27 – 12 P.M., and Aug 29 - 00 A.M., respectively. Figure 9 (e) shows the actual track path obtained by using the Planetary Boundary Layer (PBL). Note that the PBL method interpolates the wind information from the published meteorological data for already past events. The published track path of Katrina is shown in Fig. 9 (f). From the comparison with both Fig. 9 (e) and (f), Fig. 9(a) and (b) show that these WRF simulation were started too early. These landfall locations are somewhat east of the actual one. Figure 9(c) appears to have the best result. Although Fig. 9(d) had the latest meteorological data, the hurricane was already too close to the land and it appears to subside.

WRF seems to work best with latest meteorological data, while the hurricane is still at least 24 hr far away from the land. Hurricane may take unexpected turns, which only the latest meteorological data may reflect. Hurricane landfall location has a huge impact on ocean water surge. Experience suggests that water rises rapidly if the hurricane hits Louisiana coast due to the converging funnel effect of complicated land structure. On the contrary, hurricane hitting the Alabama coast is most likely to cause much lesser water surge. The computer modeling done by other researchers suggests that the funnel effect in Louisiana area may increase the surge by 20 to 40 percent [35].

6.1 ADCIRC Results

The ADCIRC grid used in our simulation is the same as Mukai et al. [36], which consists of 254,565 nodes and 492,179 elements. The computational grid for ADCIRC is displayed in Fig. 10. Atmospheric wind and pressure fields for Katrina are generated with a Planetary Boundary Layer (PBL) code for the duration of Aug 23, 6 P.M. to Aug 27, noon. It prepares a wind data file from the hurricane track information, which is available for a past event. Katrina track information is downloaded from the National Hurricane Center [37] website. Although the track information is available for the whole Katrina period, we used WRF predictive results for the duration of Aug 27, noon to Aug 31, 0 A.M. to generate wind data. Therefore, a combined PBL and WRF wind data from Aug 23, 6 P.M. to Aug 31, 0 A.M. is used for our simulation.

Zero-flux boundary conditions are used on the land boundary, and tidal conditions are used in the ocean boundary. ADCIRC Tidal Database [38], Version ec2001_v2d, is used to extract tide data during Katrina period. The total model period is 7.25 days with the time step of 1s. The 2DDI ADCIRC simulation starts from scratch, i.e., Cold Start parameter is on. The weighting factor in generalized wave continuity equation and the time weighting factor are default values. Wetting/drying function is turned off. The hybrid nonlinear bottom friction formulation is used to represent the increase of the drag coefficient as the water depth decreases in shallow water, and the default values are used for the drag coefficients. The ADCICR data is recorded every 10 minutes of the simulation.

Katrina ocean water elevation plots from ADCIRC with different wind speed and pressure input from WRF and/or Planetary Boundary Layer (PBL) are displayed in Fig. 11. Figure 11 (a)-(c) use WRF wind input with different starting date and time. Note that PBL wind data is used at beginning part of the simulation until WRF results kick in on Aug 27, noon for Fig. 11 (a) –(c). Figure 11(d) uses actual Katrina wind data provided by PBL for the whole simulation duration. From the comparison of Fig. 11(a) – (c) with Fig. 11(d), it is evident that the starting date of WRF simulation has huge impact on the results. It is because of the fact that the latest meteorological data in WRF generates more accurate wind speed, pressure, and landfall location of hurricane. The impact subsequently is carried to ADCIRC and overland codes. In addition to that, ADCIRC simulation has to be done for several days around the hurricane period, typically for 5-7 days, to get reasonably good results. Longer simulation period captures both short and long ocean waves.

6.3 CaMEL Overland Results

The overland computation domain covers from 88.35 W to 89.69 W and from 30.147 N to 30.45 N, with 505358 nodes and 1005369 elements. The domain has the matching shoreline boundary with the ADCIRC mesh. However, to get refined mesh in the overland shoreline area, additional nodes are inserted along the boundary. Water height values for those inserted nodes are interpolated from two neighboring boundary nodes, which are overlapping with ADCIRC boundary nodes. The overland domain and mesh is displayed in Fig. 12. Please note that the figure reflects exaggerated ground elevation pattern. The water elevation data in the shoreline boundary are taken from ADCIRC every 10 minutes interval. The time step of the overland simulation is 1 seconds. When the simulation times of overland and ADCIRC models are not matching, linear interpolation between two ADCIRC output files is done for the boundary water elevation.

The inland water elevation contours are plotted in Fig. 13. The plots show flood development in the Mississippi coastal region after every 100 minutes - beginning from Aug 29, 9:20 A.M. The scale was kept same for all the plots for better comparison. Different parts of the coast get higher water elevations at different times, which depends on the hurricane landfall and the incoming water surge. The transient water surge is similar to a sinusoidal curve. From the plots it is evident that the code can simulate water diffusion from the shore to the inland very well, at least from the qualitative point of view. This model, however, does not account for the building structures and ground resistances.

The inland water velocity contours are plotted in Fig. 14 after hurricane Katrina made landfall. The plots show water velocity in the coastal region after every 100 minutes - beginning from Aug 29, 9:20 A.M. The water velocity is reasonably small enough to justify our diffusive approach in the simulation.

Maximum water elevation that happens in the overland domain anytime during the entire simulation period is displayed in Fig. 15. This figure predicts whether any building or structure in the domain will be flooded, damaged, or unaffected because of the flooding. This is one of the most important information that will help setting up the evacuation plan for the coastal regions.

Figure 16 displays the observatory data collected after hurricane Katrina using the High Water Mark (HWM) remained on the structures by the flood water. Figure 16a shows the observation stations on the domain (zoomed). Figure 16b shows the comparison of simulated results with the HWM. The comparison, in general, is satisfactory. At some locations simulated results are somewhat lower than the HWM, while at some other locations simulated results are somewhat higher. There may have multiple reasons for this kind of mismatch. Since the scheme is integrated, any error in WRF and/or ADCIRC propagates into overland. That error may be significant depending on the predicted hurricane landfall location. The HWM may also have some inaccuracy, since it was collected mostly by observation after the Katrina flood water receded from the coastal zone. Definite comments cannot be made without knowing exactly how the HWM was collected, which is unavailable at this point. In addition to that, the presence of structures and buildings and surface friction may have some influence on the overland flow, which we have ignored in the present study. Nevertheless, some kind of margin in the overland results must be assumed since this model will be used primarily as a predictive tool at a time when the exact wind and pressure information of the hurricane will not be available.

7. CONCLUSIONS

We have primarily presented finite element method based overland flow modeling. This model is an essential part of the integrated modeling scheme of a hurricane from its approach to landfall and associated water surge and flooding in the coastal regions. For that purpose, overland code is to be used in sequence after WRF and ADCIRC models. We have solved diffusion wave or Richard's equation for the overland model. The simulations results are compared with the available observed Katrina data. In general, the comparison is good. It is imperative that some kind of error margin is used for the hurricane prediction schemes because of the integrated nature of it. We have demonstrated that repeated simulations of the codes are needed because the more recent meteorological data we use, in general, the better accuracy we obtain from WRF. The accuracy of WRF results propagate into ADCIRC and overland simulations through the wind and rain input. The diffusion velocity in the overland flow is reasonably small, which justifies the diffusion type modeling approach we have taken.

ACKNOWLEDGMENTS

This work is sponsored by US Department of Homeland Security (DHS) through SERRI project. Authors would like to thank DHS for their support.

REFERENCES

[1] Pugh DT. *Tides, Surges and Mean Sea Level*. John Wiley, Chichester, U. K., 1987.

[2] Knabb RD, Rhome JR, Brown DP. Tropical cyclone report hurricane Katrina 23-30 August 2005. National Hurricane Center, 20 December 2005.

[3] Wilkinson C. Crawling from the wreckage. *Observer*, 13 Aug, 2006.

[4] Gram-Jensen I. *Sea Floods*. Dan. Meteorol. Inst., Copenhagen, 1991.

[5] Tsuchiya YY, Shuto N. *Tsunami: Progress in Prediction, Disaster Prevention and Warning*. Kluwer Acad., Dordrecht, Netherlands, 1995.

[6] Danard M, Munro A, Murty T. *Storm surge hazards in Canada*. Nat. Hazards, 28, 2003, pp. 407–431.

[7] Giarrusso CC, Dodd N. Numerical modelling of coastal flooding. *Third International Symposium: Waves 97*, HR Wallingford, Virginia Beach, Va., 3–7 Nov., 1997.

[8] Haider S, Paquier A, Morel R, Champagne J-Y. Urban flood modelling using CFD. *Proc. Inst. Civ. Eng. Water Mar. Eng.,* 155(WM2), 2003, pp. 129–135.

[9] Brown JD, Spencer T, Moeller I. Modeling storm surge flooding of an urban area with particular reference to modeling uncertainties: A case study of Canvey Island, United Kingdom. *Water Resources Research*, v 43, n 6, 2007, pp. W06402

[10] Bates PD, Anderson MG. A two-dimensional finite element model for river flow inundation. *Proc. R. Soc. London A*, 440, 1993, pp. 481–491.

[11] Stelling GS, Kernkamp HWJ, Laguzzi MM. Delft flooding system: A powerful tool for inundation assessment based upon a positive flow simulation. *Hydroinformatics*, 1998, pp. 449– 456, A. A. Balkema, Rotterdam, Netherlands.

[12] Bates PD, Hervouet JM. A new method for moving-boundary hydrodynamic problems in shallow water. *Proc. R. Soc. London A*, 455, 1999, pp. 3107–3128.

[13] Makhanov SS, Vannakrairojn S, Vanderperre EJ. 2D numerical model of flooding in east Bangkok. *J. Hydraul. Eng.*, 125, 1999, pp. 407–414.
[14] Beffa C, Connell RJ. Two-dimensional flood plain flow: 1. Model description. *J. Hydrol. Eng.*, 6, 2001, pp. 397–405.
[15] Hsu MH, Chen CH, Chang TJ. Inundation simulation for urban drainage basin with storm sewer system. *J. Hydrol.*, 234, 2000, pp. 21–37.
[16] Brown JD. Uncertainty propagation through a numerical model of storm surge flooding. Ph.D. thesis, 2004, 530 pp., Univ. of Cambridge, Cambridge, U. K.
[17] Mignot E, Paquier A, Haider S. Modeling floods in a dense urban area using 2D shallow water equations. *J. Hydrol.*, 327(1 – 2), 2006, pp. 186– 199.
[18] Tayefi V, Lane SN, Yu D, Hardy RJ. Comparison of 1D and 2D methods for predicting flood inundation over complex rural floodplains. *Hydrol. Processes*, v 21, n 23, 2007, pp. 3190-3202
[19] Yu D, Lane SN. Urban fluvial flood modelling using a two dimensional diffusion-wave treatment: 1. Mesh resolution effects. *Hydrol. Processes*, 20, 2006a, pp. 1541–1565.
[20] Yu D, Lane SN. Urban fluvial flood modelling using a twodimensional diffusion-wave treatment: 2. Development of a sub-grid scale treatment. *Hydrol. Processes*, 20, 2006b, pp. 1567–1583.
[21] Braschi G, Gallatti M. Simulation of a level-breaking submersion of planes and urban areas. *Proceedings of the International Conference on Computational Modeling and Experimental Methods in Hydraulics: Hydrocomp*, 1989, Elsevier, New York.
[22] Michalakes J, Dudhia J, Gill D, Klemp J, Skamarock W. Design of a next-generation regional weather research and forecast model : Towards Teracomputing. *World Scientific*, River Edge, New Jersey, 1998, pp. 117-124.
[23] Westerink JJ, Luettich RA, Blain CA, Scheffner NW. ADCIRC: An advanced three-dimensional circulation model for shelves, coasts and estuaries. Report 2: Users' Manual for ADCIRC-2DDI. *Technical Report DRP-94*, U.S. Army Corps of Engineers.
[24] Akbar MK, Aliabadi S, Wan T, Patel R. Overland Flow Modeling of Mississippi Coastal Region Using Finite Element Method. Accepted, *19th AIAA Computational Fluid Dynamics Conference*, June 22-25, 2009, San Antonio, TX.
[25] Beinhorn M, Kolditz O. *Overland flow theory and implementation*. GeoSys - Preprint. Tubingen March 2005. Version 2005.1.1. ZAG Publisher.
[26] Kolditz O. *Computational methods in environmental fluid mechanics*. Graduate Text Book, Springer Science Publisher, Berlin, 2002.
[27] Rijn LCV. *Principles of Fluid Flow and Surface Waves in Rivers, Estuaries, Seas and Oceans*, Aqua Publications, The Netherlands, 1986.
[28] Vreugdenhil CB. *Numerical Methods for Shallow-water flow*, Kluwer Academic Publishers, Dordrecht, 1994.
[29] Jain SC. *Open-Channel Flow*, John Wiley and Sons, New York, 2001.
[30] Giammarco D, Todini PE, Lamberti P. A conservative finite elements approach to overland flow: the control volume finite element formulation. *J. Hydrol.* 175, 1996, pp. 267-291.
[31] Hromadka TV, Lai C. Solving the two-dimensional diffusion flow model. *Proc. of the Specialty Conf. sponsored by the Hydraulics Div. of ASCE*, Lake Buena Vista, FL, Aug 12-17, 1985.
[32] Tu S, Aliabadi S. Development of a hybrid finite volume/element solver for incompressible flows. *International Journal for Numerical Methods in Fluids*. 55, 2007, pp. 177-203.

[33] Aliabadi S. Parallel finite element computations in aerospace applications. Ph.D. Thesis, University of Minnesota, 1994.
[34] Tu S, Watts M, Fuller A, Patel R, Aliabadi S. Development and performance of CaMEL Aero, a truly matrix-free, parallel and vectorized unstructured finite volume solver for compressible flows. *Proceedings of the 25th Army Science Conference*, Orlando, FL, November 2006.
[35] Day, J., Ford, M, Kemp, P., Lopez, J. Mister Go Must Go - A Guide for the Army Corps Congressionally-Directed Closure of the Mississippi River Gulf Outlet. December 4, 2006. (http://www.edf.org/documents/5665_Report%20-%20Mister%20Must%20Go.pdf)
[36] Mukai AY, Westerink JJ, Luettic Jr. RA, Mark D. Eastcoast 2001, A tidal constituent database for western north Atlantic, Gulf of Mexico, and Caribbean Sea. *U.S. Army Corps of Engineers, ERDC/CHL TR-02-24*.
[37] National Hurricane Center (NHC) 2008. http://maps.csc.noaa.gov/hurricanes/download.jsp
[38] ADCIRC Tidal Database 2008. http://www.unc.edu/ims/ccats/tides/tides.htm.