NUMERICAL FLOOD SIMULATION BY DEPTH AVERAGED FREE SURFACE FLOW MODELS

A. I. Delis
Department of Sciences, Technical University of Crete, Chania, Crete, Hellas. Institute of Applied and Computational Mathematics, Foundation for Research and Technology, Heraklion, Crete, Hellas.

N. A. Kampanis
Institute of Applied and Computational Mathematics, Foundation for Research and Technology, Heraklion, Crete, Hellas.

Keywords: Floods, Numerical Simulation, Depth averaged models, Shallow water equations, Finite Volume Schemes, Source terms, Wetting and Drying, Benchmarking.

Contents

Summary

Numerical flood simulation has matured significantly over the last decades and has come to the point where a quite realistic picture of potential flood threats can be produced at reasonable cost. The quality of a flood simulation model fully depends on its descriptive capabilities of the physical system in terms of topographic and roughness data, the representativeness of the equations, and the numerical method applied. This contribution reviews and explains the current practice and state of the art of numerical flood simulation models. In particular, the most important and widely used depth averaged model is reviewed and discussed along with its numerical treatment. Proceeding with the two-dimensional flow description and its numerical discretization principles, numerical discretization of depth averaged two-dimensional shallow water equations are presented with special attention given to the correct and robust modeling within the finite volume framework. Some popular finite volume models for solving the depth averaged two-dimensional shallow water equations are described, with special attention to the modeling of shock (bore) waves, the treat of natural topographies, and the appearance of wet/dry fronts.

1. Introduction

The risk and impact of floods in rural as well as in urban areas has been increased in the last few decades as population and urbanization processes rapidly increase and subsequently more and more people and properties are being concentrated in flood-prone coastal zones and river flood-plains. In addition, there is an increasing awareness about climate changes and extreme weather conditions that can lead to the emergence of natural disasters such as, flash floods and failures of flood defense structures, including dams, weirs and flood dykes. Moreover, floods in urban areas can be much more devastating than any other areas and they can pose a significant threat to human life. Worldwide, coastal, riverine and flash floods are responsible for more than 50% of the fatalities and for about 30% of the economic losses caused by all natural disasters. The state of the art of numerical flood simulation has progressed significantly over the last decades and has come to the point where a quite realistic picture of potential flood threats can be produced at reasonable costs. New data collection techniques have emerged which alleviate the traditional problem of lack of data for topographic and terrain modeling. In addition, numerical techniques have matured, providing robustness and efficiency in model simulation.

Modeling and simulation of flood events are necessary to understand the mechanisms of the process and therefore to better protect urban areas and increase public safety; for example, they can be important for developing emergency plans. The information provided from simulations about potential floods must include such data as (i) time of the flood wave arrival at some points in a valley or a city, (ii) extreme water levels in the flooded area, (iii) duration and range of flooding and (iv) water depths and velocities in the flooded zones. As such, flood inundation and propagation modeling can be defined as the art of quantitatively describing the evolution and characteristics of the flow that is set up when a large amount of water moves along the earth surface in an uncontrolled way (Mandych, 2004). The progress of flood propagation models is linked directly to (a) the understanding the flow processes relative to the problem, (b) the formulation of appropriate mathematical laws, (c) the development of effective numerical techniques to solve them and (d) the validation of the model output against benchmark, experimental and real life data. The underlying mathematical models describing the flood process are basically variations of models for free surface water flow. These models are mainly governed by unsteady non-linear Partial Differential Equations (PDE's) in general three dimensional (3D) domains, with a free surface boundary condition.

An important feature of free surface flows is that they are unbounded in space, the limits of the spatial domain being an unknown of the problem to be solved. Problems in which the limits of the fluid are unknown and unsteady include among others, dam-break induced flows, tidal flow in estuaries and flood propagation in rivers. In these situations it is necessary to compute a non-stationary wet/dry front, which is part of the solution we are looking for. The full flow field can be described by the Navier-Stokes equations. However, qualitative and/or quantitative approximations of the actual solution are given by approaches based on simplified equations. This is done in a systematic effort to overcome the need, usually, of excessively demanding numerical techniques to resolve the Navier-Stokes equations (supplied possibly with appropriate turbulence closure models). A widely used approach is that of the 2D depth averaged models. The 2D character of the free surface flow is usually enforced by a horizontal length scale which is much larger than the vertical one, and by a velocity field quasi-homogeneous over the water depth. This small ratio between the vertical and horizontal length scales characterizes flood situations as well as many engineering applications, mainly in river and coastal engineering. Despite their shortcomings, depth averaged models are effectively used in engineering practice in order to model environmental flows in rivers and coastal regions, as well as shallow flows in hydraulic structures. Concerning topographies of flooded territories and the complexity of city structures, flow simulations in 2D in the horizontal plane are indispensable. As such many geophysical flows can be modeled by the shallow water (SW) or Saint-Venant (SV) system of equations or their variations. Extensions of these equations are useful to model sedimentary flows, tsunamis, avalanches, river mouths and junctions, marine flows. The choice of methods and algorithms for computing solutions to these equations is very wide. Among them the Finite Volume formulation, is nowadays the most applied modeling strategy for such computations.

Depending on their objective, flood simulation models may differ in their requirements. Criteria for the selection of the appropriate tools are often based on the required speed of computation, completion time for a simulation, level of accuracy in the results, data requirements, numerical robustness, user-friendliness of the software, and possible others, depending of the model. These objectives may be related to flood risk analysis, flood forecasting and control and may be based upon a variety of causes, such as, storms, dam or dike breaks, hurricanes and geologically induced tsunamis. The development of suitable numerical techniques and that of powerful computer equipment has enable to produce reliable simulations for practical applications. In the area of numerical flood simulation some frequently used tools, that are currently available commercially or as freeware and utilize 2D depth averaged models, are the Mike 11 (1D) and Mike 21 (2D) modeling systems of the Danish Hydraulics Institute, the SOBEK modeling system of Delft Hydraulics, the ISIS tool and InfoWorks of Walling-ford Software, the TUFLOW software of BMT WMB Consultants, the HEC-RAS system of the US Army Corps of Engineers, the LISFLOOD-FP flood inundation system of the University of Bristol, the TELEMAC2D modeling system of Electricité de France (EDF), the BASEMENT software of the Swiss Federal Institute of Technology (ETH), the ANUGA Hydrodynamic Modeling of Geosciences Australia, and the CARPA modeling system of the Flumen research group. In addition, several research projects and consortiums have been initiated (e.g. the CADAM, IMPACT and FLOODsite European research projects and the Floodrisk British consortium) in order to establish cutting edge research to enhance flood risk management practice and to deliver tools and techniques to support improvements in flood modeling and simulation.

This presentation is focused on the mathematical and numerical modeling of 2D free surface flows under the influence of gravity. It reviews and summarizes some previous theoretical, numerical and experimental studies about the simulation of flood propagation using depth averaged models. The derivation of the 2D SW equations is summarized and discussed, in order to understand the limitation of these equations and asses the numerical results obtained from them. In addition, state of the art finite volume numerical schemes and discretization techniques implemented in flood flow simulations and solve the 2D SW equations are described and discussed in more detail.

2. Mathematical Modeling of Flood Propagation

2.1. Navier-Stokes (NS) and Related Models

Flood propagation over the earth's surface is a 3D time dependent, incompressible, fluid dynamics problem with a free surface. By not considering the erosion and deposition effects, which are a subject of a separate branch of study, the flow can be considered as a single phase flow. The well known Navier-Stokes (NS) equations (Bardos, 2005), in 3D, perfectly describe the dynamics of a portion of fluid. However, the main drawback to a fully 3D approach is its computational cost, especially in environmental problems, where the size of the spatial domain can be very large and there are flow patterns of different length scales involved in the flow. The flow is turbulent and of geographical size, and the cascade of length and time scales present is huge what impairs any attempt to solve the 3D NS equations by any means; only in very simple geometry configurations it is possible to solve directly the NS equations using appropriate numerical methods such as Direct Numerical Simulations (DNS) (Wagner, 2006). In a DNS it is necessary to resolve all the scales of motion appearing in the flow, since they interact with each other; in order to do that, the computational mesh size must be smaller than the smallest significant scale motion, and the simulation time step must be small enough to resolve the highest frequency oscillations appearing in the flow. This constitutes a significant reservation for using DNS.

In order to circumvent the problem of turbulence the NS equations can be averaged in time in order to obtain the so-called Reynolds-Averaged Navier-Stokes equations (RANS) that describe the mean flow. The effects of the turbulent fluctuations on the mean flow are taken care of by means of turbulence models, i.e. formulations whereby the stress due to turbulence are related to the mean flow variables. Currently there are dozens of turbulence models in use, each adapted to a particular fluid dynamics situation. The RANS equations are of wide use in industrial fluid mechanics and aerodynamics (Chabard and Laurence, 2004) but are still too complex to be applied in order to describe flood propagation, mainly due to the resolution that would be needed to make such a procedure meaningful. Furthermore, since turbulence models are developed to be well suited to specific situations, those currently available may not even make sense in a flood propagation scenario.

Further to the problem of turbulence, the NS and RANS based models have the added difficulty of the air-water interface movement. The free surface moves with the velocity of the fluid particles located at the boundary and therefore its position is one of the unknowns that must be solved for during a computational procedure. The problem lies in that, the equations of motion only apply to the space occupied by the fluid which is not known *a priori*. Several methods have been developed to circumvent these difficulties, mostly relying on iterative procedures. A rather general classification distinguishes between mesh methods and meshless methods. Meshless methods use a Lagrangian formulation in order to compute the movement of fluid particles applying Newton's Second law. The most popular meshless method is the Smoothed Particle Hydrodynamics (SPH) method. It has the advantage of being able to treat complicated free surface deformations, but it has problems with the correct modeling of boundaries.

Mesh methods can be classified in moving grid methods and fixed grid methods. Moving grid methods use a Lagrangian formulation in order to move the grid nodes and boundaries with the fluid. The free boundary is computed with a front tracking technique. The main disadvantage is the computational cost, since the nodes of the mesh move at each time iteration, and thus, the geometric properties of the mesh need to be recomputed. Lagrangian methods are mainly used when the movement of the free surface is small, because otherwise it is necessary to add or remove some nodes from the mesh in order to avoid a large distortion of the elements.

Fixed grid methods are more commonly used. They can use a fully Eulerian formulation (interface capturing) or a combined Eulerian-Lagrangian formulation (interface tracking). Among the Eulerian methods the Volume of Fluid (VOF) method and Marker in Cell (MAC) methods have gained a reputation of accuracy and robustness, but their application to flooding problems has not yet been possible due to the extraordinary computational power needed for their application. Simulations of propagating and breaking waves as well as dam beak flows with these methods have been obtained however, these simulations are limited to idealized, two dimensional (in the vertical plain) cases with no practical interest or to limited size industrial applications. Furthermore, in order to simplify the problem either only laminar flows are considered or the diffusive re-dropped from the NS equations thus solving the inviscid (Euler) equations. Fully 3D simulations are usually limited to steady or slow flows which in not the case in flooding scenarios, or applied only to solve local flow effects.

As it was mention earlier, the main drawback of a fully 3D approach is its computational cost, specially in environmental problems, where the spatial domain is very large and there are flow patterns of very different length scales involved in the flow. For that reason, it is not yet efficient to use the fully 3D approach in most environmental hydraulic flows. In shallow water flows it is possible to simplify the 3D RANS equations assuming a hydrostatic pressure distribution. In such a case the vertical momentum equation is simplified to the hydrostatic pressure equation, and therefore, only the two horizontal momentum equations need to be solved in a 3D computational mesh. The continuity equation is used in order to compute the free surface level, which in turn, defines the hydrostatic pressure distribution. A computational mesh in this case is often built as a 2D horizontal mesh with several layers in the vertical direction and with in this way well oriented simplified mesh generation can be archived for some common environmental flow problems such as stratified flows. This approach is usually called a 3D SW equations computation and it has been used for simple or simplified geometries. Some work has been done using this 3D approach to model free surface flows in complex geometries using a singled value height-function formulation in order to track the free surface.

Given their increased computational demand, it seems that NS or even Euler (inviscid) based models can be outflanked, regarding their practical effectiveness, by reduced simulation models for use in realistic flood propagation modeling.

-
-
-

Bibliography

A. Bermudez and M.E (1994). Von.azquez-Cendon Upwind methods for hyperbolic conservation laws with source terms. *Computers and Fluids*, 23:1049. [Research article that introduces the upwind treatment of the topography source term for the shallow water equations in one dimension].

A. Colagrossi and M. Landrinni (2003). Numerical simulation if interfacial flows by Smooth Particle Hydrodynamics. *J. Comp. Phys.*, 191:448. [Research article where an implementation of the smoothed particle hydrodynamics (SPH) method is presented to treat two-dimensional interfacial flows, that is, flow fields with different fluids separated by sharp interfaces].

A. Harten (1983). High resolution schemes for hyperbolic conservation laws. *J. Comp. Phys.*, 49:357. [A classic advanced research article where the notion of the Total Variational Diminishing (TVD) stability was introduced].

A. Harten, P.D. Lax, and B. van Leer (1983). On upstream differencing and Godunov-type schemes for hyperbolic conservation laws. *SIAM Rev.*, 25:35. [Research article where the HLL-type Riemann solver was introduced].

A. Kurganov and Petrova G (2007). A second-order well-balanced positivity preserving central-upwind scheme for the Saint-Venant system. *Comm. in the Mathematical Sciences*, 5:133. [Research article where an improved second-order central-upwind scheme is developed, capable to both preserve stationary steady states (lake at rest) and to guarantee the positivity of the computed fluid depth].

A. Valiani, V. Caleffi, and A. Zanni (2002). Case study: Malpasset dam-break simulation using a two-dimensional finite volume method. *J. Hydraulic Engrg-ASCE*, 128:460. [Research article about the application and performance of a HLLE-type finite volume scheme on quadrilateral meshes].

A.A. Akanbi and N.D. Katopodes (1987). Model for flood propagation on initially dry land. *J. Hydraul. Engrg.-ASCE*, 114:689. [Research article where a summary of problems encountered in the numerical simulation of flood waved propagating over dry bed was presented].

A.F. Mandych (1979). Classification of floods. In V.M. Kotlyakov, Editor, *Natural Disasters* in *Encyclopedia of Life Support Systems (EOLSS)*. Developed under the Auspices of the UNESCO, Eolls Publishers, Oxford, U.K., 2004.

A.I. Delis and Th. Katsaounis (2005). Numerical solution of the two-dimensional shallow water equations by the ap-plication of relaxation methods. *Applied Mathematical Modelling*, 29:754. [Research article for the application of relaxation finite volume schemes, where neither Riemann solvers nor characteristic decomposition is needed, for the solution of the SW equations with source terms].

A.I. Delis, M. Kazolea, and N.A. Kampanis (2008). A robust high resolution finite volume scheme for the simulation of long waves over complex domain. *Int. J. Numer. Meth. Fluids*, 56:419. [Research article for the construction and application of a well-balanced high resolution finite volume scheme utilizing the Roe Riemann solver for the SW equations].

B. Cockburn, G. Karniadakis, and S.W. Shu (2000). *Discontinuous Galerkin methods-Theory, Computations and Applications*. Vol. 11 of Lecture Notes in Computer Sciences and Engineering, Springer-Verlag. [Advanced text book for the analysis and application of Discontinuous Galerkin finite element methods].

B. Einfeldt (1988). On Godunov-type methods for gas dynamics. *SIAM J. Numer. Analysis*, 25:294. [Research article where the HLLE Riemann solver was introduced].

B. van Leer (1979). Towards the ultimate conservative difference scheme V. A second order sequel to Godunov's method. *J. Comp. Phys.*, 32:101. [A classic reference research article for schemes to hyperbolic equations. The classic (to day) scheme called MUSCL is presented].

B. van Leer (2006). Upwind and high-resolution methods for incompressible flow: From donor cell to residual-distribution schemes. *Comm. in Computational Physics*, 1:192–206. [A review article focused on the historical development of upwind difference schemes for CFD applications].

B.F. Sanders (2007). Evaluation of on-line DEMs for flood inindation modeling. *Adv. Water Resour.*, 30:1831. [Research article where the utility of several on-line digital elevation models (DEMs) is examined with a set of steady and unsteady test problems. This study highlights utility in SRTM as a global source of terrain data for flood modeling].

C. Bardos (2005). A basic example of nonlinear equations: The Navier-Stokes equations. In H. Araki, Editor, *Mathematics: Concepts, and Foundations* in *Encyclopedia of Life Support Systems (EOLSS).* Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford, U.K.

C. Hirsch (1990). *Numerical Computation of Internal and External Flows*. J. Wiley and Sons Ltd., Chichester, England. [This two volume book covers the fundamentals of numerical discretization techniques and describes all the steps in the definition and development of a numerical simulation with application to the problems of fluid dynamics].

C. Wagner (2006). Mathematical models in hydrodynamics. In J.A. Filar and J.B Krawczyk, Editors, *Mathematical Models*, in *Encyclopedia of Life Support Systems (EOLSS)*. Developed under the Auspices of the UNESCO, Eolls Publishers, Oxford, U.K.

C.B. Vreugdenhil (1994). *Numerical Methods for Shallow-Water Flow*. Kluwer, Dordrecht, The Netherlands. [In this book the theory of shallow water flow and its numerical simulation is presented mainly in two spatial dimensions].

C.D. Lloyd (2004). Landform and earth surface. In P.M. Atkinson, Editor, *Geoinformatics* in *Encyclopedia of Life Support Systems (EOLSS),*. Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford, U.K.

C.W. Hirt and B.D. Nichols (1981). Volume of fluid (VOF) method for the dynamics of free boundaries.*J. Comput. Phys.*, 39:201–225. [Research article. The initial article where the VOF method was presented].

C.W. Shu and S. Osher (1989). Efficient implementation of essentially non-oscillatory shock capturing schemes II. *J. Comp. Phys.*, 83:32. [Research article. High level article about high order accurate and non-oscillatory (ENO) schemes for hyperbolic systems].

D. Liang, L. Binliang, and R.A. Falconer (2007). Simulation of rapidly varying flow using an efficient TVD-MacCormack scheme. *Int. J. Num. Meth. Fluids*, 53:811. [Research paper about the application of the two step TVD-MacCormack finite volume scheme on structured meshes. It includes results for the Toce River benchmark case].

D.C. Mason, D.M. Cobby, M.S. Horritt, and P.D. Bates (2003). Floodplain friction parameterization in 2D river flood models using vegetation heights derived from airborne scanning laser altimetry. *Hydrolog. Process*, 17: 1711. [Research paper that investigates how vegetation height data can be used to realize the currently unexploited potential of 2D flood models to specify a friction factor at each node of a finite element model mesh].

D.C. Mason, M.S. Horritt, D.M. Cobby, and P.D. Bates (2007). Use of fused airborne scanning laser altimetry and digital map data for urban flood modelling. *Hydrolog. Process*, 21:1436. [This research paper describes the development of a LiDAR post-processor for urban flood modeling based on the fusion of LiDAR and digital map data].

E. Mignot, A. Paquier, and S. Haider (2006). Modeling floods in a dense urban area using 2D shallow water equations. *J. Hydrol.*, 327:186. [Research article where an explicit second-order scheme is used to simulate the severe October 1988 flood in the Richelieu urban locality of the French city of Nimes].

E. Pranzini and L. Wetzel (2008). *Beach Erosion Monitoring: Results from BEACHMEDe/ OpTIMAL Project*. Nuova Grafica Fiorentina, Florence. [Reference work where the application of LiDAR for obtaining topographic and bathymetric data is surveyed].

E.F. Toro (1997). *Riemann Solvers and Numerical Methods for Fluid Dynamics*. Springer-Verlag, Berlin, Germany. [This textbook gives a comprehensive, coherent and practical presentation of upwind and central computational techniques for Computational Fluid Dynamics].

E.F. Toro (2001). *Shock-Capturing Methods for Free Surface Shallow Flows*. Wiley and Sons, Chichester. [The first of its kind in the field, this book examines the use of modern, shock-capturing finite volume numerical methods, in the solution of partial differential equations associated with free-surface flows, which satisfy the shallow-water type assumption].

E.F. Toro and P. Garcia-Navarro (2007). Godunov-type methods for free-surface shallow flows: A review. *J. of Hydraulic Res.*, 45:736. [An excellent review article for the application of numerical methods of the Godonov type to the computation of the approximate solutions to free-surface flows modeled under the shallow water type assumption].

F. Dubois (2003). An introduction to finite volume methods. In V.V. Shaidurov and O Pironneau, Editors, *Computational Methods and Algorithms* in *Encyclopedia of Life Support Systems (EOLSS)*. Developed under the Auspices of the UNESCO, Eolls Publishers, Oxford, U.K.

F.H. Harlow and J.E. Welsh (1965). Numerical simulation of time-dependent viscous incompressible flow of fluid with free surface. *Phys. Fluids*, 8:2182–2189. [Research article where the MAC method was initially presented].

FloodRisk. *http://www.floodrisk.org.uk*.

FLOODsite. Integrated flood risk analysis and management methodologies. *http://www.floodsite.net*.

G. Aronica, B. Hankin, and K. Beven (1998). Uncertainty and equifinality in calibrating disturbed roughness coefficients in a flood propagation model with limited data. *Advances in Water Resources*, 22:349. [This research paper compares two frameworks for the calibration and interpretation of the predictions of a flood model of a real event, in an extremely complex system, on the basis of highly limited measurements].

G.S. Stelling and A. Verwey (2006). Numerical flood simulation. In M.G Anderson, editor, *Encyclopedia of Hydrological Sciences. Part2. Hydroinformatics*, page 257. John Wiley and Sons, Ltd,. [This review article describes and discusses the state of the art of numerical flood simulation with models based upon hydraulics laws].

H.S. Spurk (1997). *Fluid Mechanics*. Springer Verlag, Berlin. [This textbook emphasizes the unified nature of all the disciplines of Fluid Mechanics as they emerge from the general principles of continuum mechanics].

IMPACT. Investigation of extreme flood processes and unsertainty. *http://www.samui.co.uk/impact-project*.

J. Burguete and P. Garcia-Navarro (2004). Implicit schemes with large time step for non-linear equations: Application to river flow hydraulics. *Int. J. Numer. Meth. Fluids*, 46:607. [In this research article first-order upwind implicit schemes are considered].

J. Murillo, P. Brufau, and P. Garcia-Navarro (2006). Extension of an explicit finite volume method to large time steps (CFL >1): application to shallow water flows. *Int. J. for Numer. Methods in Fluids*, 50:63–102. [Research article where an explicit first order upwind scheme is presented under a formalism that enables the extension of the methodology to large time steps].

J. Murillo, P. Garcia-Navarro, J. Burguete, and P. Brufau (2007). The influence of source terms on stability, accuracy and conservation in two-dimensional shallow flow simulation using triangular finite volumes. *Int. J. for Numer. Methods in Fluids*, 54:543. [Advanced research article where explicit first and second order in space upwind finite volume schemes are analyzed to provide an understanding of the stability constraints, making emphasis in the numerical conservation and in the preservation of the positivity property of the solution when necessary in the presence of source terms].

J.A. Gunge, F.M. Holly, and A. Verwey (1980).*Practical Aspects of Computational River Hydraulics*. Pitman, London, U.K. [This classic book describes the use of mathematical modeling techniques for the solution of complex engineering problems concerning unsteady flow in rivers and canals. The book is meant to give guidance in using model results; constructing and exploiting models; and developing individual mathematical modeling capability].

J.G. Zhou, D.M Causon, D.M. Ingram, and C.J. Mingham (2002). Numerical solutions of the shallow water equations with discontinuous bed topography. *Int. J. Numer. Meth. Fluids*, 38:769. [Research article where the MSGM was introduced for the treatment of the topography source terms in the SW equations].

J.H.W. Lee and J.J. Sharp (2004). Fluid mechanics. In J.M. Jordaan and A. Alexander Bell, Editors, *Hydraulic Structures, Equipment and Water Data Acquisition Systems* in *Encyclopedia of Life Support Systems (EOLSS)*. Developed under the Auspices of the UNESCO, Eolls Publishers, Oxford, U.K.

J.J. Stoker (1986). *Water Waves*. Interscience Publishers, Inc., New York. [This, now classic, book contains the general theory of water wave, different approximations of this theory for solution hydraulic problems and their applications to river and sea engineering].

J.M. Hervouet and A. Petitjean (1999). Malpasset dam-break revisited with 2-dimensional computations.*J. of Hydraulic Res.*, 37:777. [This paper presents two-dimensional computations of Malpasset dam-break performed with TELEMAC-2D].

J.P. Chabard and D. Laurence (2004). Turbulent flow modeling. In J.M. Jordaan and A. Alexander Bell, Editors, *Hydraulic Structures, Equipment and Water Data Acquisition Systems* in *Encyclopedia of Life Support Systems (EOLSS)*. Developed under the Auspices of the UNESCO, Eolls Publishers, Oxford, U.K.

J-H. Saiac (2004). Finite element method. In V.V Vladimir V. Shaidurov and O Pironneau, Editors, *Computational Models and Algorithms* in *Encyclopedia of Life Support Systems (EOLSS)*. Developed under the Auspices of the UNESCO, Eolls Publishers, Oxford, U.K.

K. Mahmood and V. Yevjevich (1975). *Unsteady Flow in Open Channels*. Water Research Publications, Fort Collins, Colorado. [This three volume book provides a comprehensive coverage of unsteady flow in open channels].

L. Cea, J. Puertas, and M.E. Vazquez-Cendon (2007). Depth averaged modeling of turbulent shallow water flow with wet-dry fronts. *Arch. Comput. Methods Eng.*, 14:303. [Advanced research paper that presents the most important and widely used depth averaged turbulence models and their numerical solution within the finite volume framework].

L.S. Kuchment (2007). Unsteady flow on river basin slope and in river channels. In L.S. Kuchment and V.P. Singh, Editors, *Hydrological Systems Modeling* in *Encyclopedia of Life Support Systems (EOLSS)*. Developed under the Auspices of the UNESCO, Eolls Publishers, Oxford, U.K.

M. Morris (2000). CADAM: Concentrated action on dambreak modeling–Final report, HR Wallingford. *Rep. No SR 571*, http://www.hrwallingford.co.uk/projects/CADAM. [The final technical report from the CADAM project where the paractice and experience from this working project is summarized].

M.B. Abbott (1979). *Computational Hydraulics; Elements of the Theory of Free Surface Flows*. Pitman Publishing Ltd., London. [This classic textbook provides the principles of the theory of surface flow and survey modeling in hydraulic, coastal and offshore engineering].

M.E. Hubbard and P. Garcia-Navarro (2000). Flux difference splitting and the balancing of source terms and flux gradients. *J. Comp. Phys.*, 165:2. [Reasearch article about the construction of high resolution well-balanced flux and slope limiting numerical schemes for hyperbolic systems].

M.S. Horritt, P.D. Bates Bates, and M.J. Mattinson (2006). Effects of mesh resolution and topographic representation in 2D finite volume models of shallow water fluvial flow. *J. of Hydrology*, 329:306. [Research paper about showing that flow simulations can be more sensitive to mesh resolution than topography data sampling].

N. Cranjaric, S. Vucovic, and L. Sopta (2004). Balanced finite volume WENO and central WENO schemes for the shallow water and the open channel flow equations. *J. Comp. Phys.*, 200:512. [Research article for introducing the well balanced property in the application of WENO schemes for treating the topography source term for the SW and SV equations].

N. Goutal (1999). The Malpasset dam failure -An overview and test case definition. *Proceeding of the 4rd CADAM workshop*, Zaragoza. [Technical report from the CACAM project with the detailed description of the Malpasset test case].

N.M. Hunter, P.D. Bates, M.S. Horritt, and M.D Wilson (2007). Simple spatially-distributed models for predicting flood inundation: A Review. *Geomorphology*, 90:208. [This paper reviews recent progress in the use of reduced complexity models for predicting floodplain inundation].

N.M. Hunter, P.D. Bates, S. Neelz, G. Pender, I. Villanueva, N.G. Wright, D. Liang, R.A. Falconer, B. Lin, S. Waller, A.J. Crossley, and D.C. Mason (2008). Benchmarking 2D hydraulic models for urban flood simulations. *Proc. Inst. Civ. Eng.-Wat. Mgmt.*, 161:13. [This paper describes benchmark testing of six 2D hydraulic models in terms of their ability to simulate surface flows in a densely urbanized area].

P. Brufau and P. Garcia-Navarro (2000). Two-dimensional dam break flow simulation. *Int. J. Num. Meth. Fluids*, 33: 35. [Research article where a first-and second-order accurate cell centered finite volume method based on Roe’s approximate Riemann solver is applied].

P. Brufau, M.E. Vazquez-Cendon, and P. Gracia-Navarro (2002). A numerical model for the flooding and drying of irregular domain. *Int. J. Numer. Meth. Fluids*, 39:247. [Advanced research article presenting a treatment for wet/dry calculations within the finite volume framework].

P. Brufau, P. Garcia-Navarro, and M.E. Vazquez-Cendon (2004). Zero mass error using unsteady wetting-drying conditions in shallow flows over dry irregular topography. *Int. J. Numer. Meth. Fluids*, 45:1047. [Advanced research article where a wetting-drying condition for unsteady shallow water flow in two dimensions leading to zero numerical error in mass conservation is presented].

P. Venkatachalam (2009). GIS as a tool for development. In A. Jhunjhunwala, Editor, *Information Technology and Communications Resources for Sustainable Development* in *Encyclopedia of Life Support Systems (EOLSS)*, Developed under the Auspices of the UNESCO, Eolls Publishers, Oxford, U.K..

P.K. Sweby (1984). High resolution schemes using flux limiters for hyperbolic conservation laws. *SIAM J. Numer. Anal.*, 21:995. [Advanced research article where different nonlinear limiter functions that satisfy the TVD property are presented].

P.L. Roe (1981). Approximate Riemann solvers, parameter vectors, and difference schemes. *J. Comp. Phys.*, 43:357. [The seminal paper where the Roe Approximate Riemann solver was originated].

P.L. Roe (1986). Upwind differenced schemes for hyperbolic conservation laws with source terms. In Carasso, Raviart, and Serre, editors, *Proc. Conf. Hyperbolic Problems*, page 41. Springer Verlag, St. Etienne. [Research article on the application of Upwind discritizations For Hyperbolic Conservation Laws With Source Terms].

R. Abgrall (2003). Computational methods for compressible flow problems. In V.V. Shaidurov and O. Pironneau, Editors, *Computational Methods and Algorithms* in *Encyclopedia of Life Support Systems (EOLSS)*,Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford, U.K.

R.J. LeVeque (2002). *Finite Volume Methods for Hyperbolic Problems*. Cambridge University Press. [A complete book about numerical schemes for solving hyperbolic systems write in conservative form in the finite volume framework].

S. Noelle, N. Pankratz, G. Puppo, and J.R. Natvig (2006). Well-balanced finite volume schemes of arbitrary order of accuracy for shallow water flows. *J. Comp. Phys.*, 213:474. [Research paper where a

WENO class of schemes of any desired order of accuracy which preserve the lake at rest perfectly are constructed].

S. Soares Frazao and G. Testa (1999). The Toce River test case: Numerical results analysis.*Proceeding of the 3rd CADAM workshop*, Milan. [Technical report from the CACAM project with the detailed description of the Toce river test case].

S.K. Godunov (1959). Finite difference method for numerical computation of discontinuous solutions of the equations of fluid dynamics. *Mathematicheskii Sbornik*, 47:271. [The seminal article where the Codunov conservative scheme was suggested by considering the conservative variables as piecewise constant over the mesh cells at each time step and the time evolution is determined by the exact solution of the Riemann problem at the inter-cell boundaries].

S.R. Idelsohn, M.A. Storti, and E. Onate (2001). Lagrangian formulation to solve free surface incompressible inviscid fluid flows. *Comput. Methods Appl. Mech. Eng.*, 191:583–593. [Research article where a particle method is presented for the solution of the incompressible invisid fluid flow equation using a Lagrangian formulation].

V. Caleffi, A. Valiani, and A. Zanni (2003). Finite volume method for simulating extreme flood events in natural channels. *J. of Hydraulic Res.*, 41:167. [Research article about the application and performance of a finite volume scheme utilizing the HLLE Riemann solver and proper source terms discretization].

W. Rodi (2003). *Turbulence Models and Their Application in Hydraulics-a State of the Art Review*. Third Edition, IAHR Monograph Series, Delft. [A concise and informative textbook containing many examples of civil engineering and hydraulics applications of turbulent flows].

X. D. Liu, S. Osher, and T. Chan (1994). Weighted essentially non-oscillatory schemes. *J. Comp. Phys.*, 115:200. [Advanced research article about high order accurate and non-oscillatory schemes for hyperbolic systems].

X. Ying, S. S. Y. Wang, and A. A. Khan (2003). Numerical simulation of flood inundation due to dam and levee breach. In P. Bizier and P. DeBarry, editors, *World Water and Environmental Resources Congress 2003*, page 366. ASCE, (2003). [Research paper about the application of a Roe-type finite volume scheme on structured meshes. Results are presented for the Toce River and Malpasset benchmark cases].

Y. Zech and S. Soares-Frazao (2007). Dam-break flow experiments and real-case data. A database from the European IMPACT research. *J. Hydraul. Res.*, 45:5. [This special issue article summarizes the various types of available data and how to use the database from the IMPACT project].

Biographical Sketches

Anargiros I. Delis is an Assistant Professor in the Department of Sciences at the Technical University of Crete (TUC), Greece and a collaborative member at FORTH-IACM. He holds a Mathematics degree form the University of Crete, Greece, an MSc degree in Numerical Analysis and Computing from Manchester University and UMIST, U.K., and received his PhD in Computational and Applied Mathematics from the University of West of England, Bristol in 1998. His research interests are focused on the numerical solution of PDE's, Computational Fluid Dynamics and Scientific Computing with emphasis to environmental and geophysical flows.

Nikolaos A. Kampanis is a Senior Researcher at FORTH-IACM. He received his PhD in Numerical Analysis (1992), from University of Crete. His research focuses on computational fluid dynamics (environmental, physiological and technological incompressible flows) and on computational wave propagation (underwater and atmospheric sound propagation). He participates to the ERCIM Environmental Modelling Group, organized Workshops of the group and other scientific associations. He participates in EU and national research and development projects. He has 25 journal papers, 1 special issue as editor, 2 book chapters, 1 book as editor, and several papers in conferences proceedings.