Springer Water

Philippe Gourbesville
Guy Caignaert *Editors*

Advances in Hydroinformatics—SimHydro 2023 Volume 1

New Modelling Paradigms for Water Issues

Springer

Springer Water

The book series Springer Water comprises a broad portfolio of multi- and interdisciplinary scientific books, aiming at researchers, students, and everyone interested in water-related science. The series includes peer-reviewed monographs, edited volumes, textbooks, and conference proceedings. Its volumes combine all kinds of water-related research areas, such as: the movement, distribution and quality of freshwater; water resources; the quality and pollution of water and its influence on health; the water industry including drinking water, wastewater, and desalination services and technologies; water history; as well as water management and the governmental, political, developmental, and ethical aspects of water.

Philippe Gourbesville · Guy Caignaert
Editors

Advances in Hydroinformatics—SimHydro 2023 Volume 1

New Modelling Paradigms for Water Issues

Springer

Editors
Philippe Gourbesville
Polytech Lab
Université Côte d'Azur
Sophia Antipolis, France

Institute of Water Resources
and Hydropower Research (IWHR)
Beijing, China

Guy Caignaert
Ecole Nationale des Arts et Métiers
Hydrotechnique Society of France
Paris, France

ISSN 2364-6934 ISSN 2364-8198 (electronic)
Springer Water
ISBN 978-981-97-4071-0 ISBN 978-981-97-4072-7 (eBook)
https://doi.org/10.1007/978-981-97-4072-7

This Springer imprint is published by the registered company Springer Nature Singapore Pte Ltd.
The registered company address is: 152 Beach Road, #21-01/04 Gateway East, Singapore 189721, Singapore

Preface

With the current digital environment in modern societies and its development, hydroinformatics defined as management of information related to the water sector using ICT tools is becoming over the last decade a broader domain of engineering technology and sciences. Modelling and simulation are historically the points of departure for hydroinformatics and are one of the most important parts of it. Neither the SimHydro cycle of international conferences since 2010 nor the present book has the purpose or ambition to cover thematically the whole extent of the subjects. The main purpose is to concentrate on a limited number of specific areas and subjects that are not usually considered as such during most global international conferences or publications.

Modelling in fluid mechanics, hydraulics and hydrology, whether using digital tools or scale models, has reached sufficient maturity to be in daily use by engineers for analysis, design, and for communication. Increasingly, complex cases can be handled thanks to ever-more sophisticated tools and increasingly abundant computing power and data resources. The emerging environment populated with new generation of sensors, using cloud-computing resources, producing big data, is challenging the current practices of modelling and requests innovation in methodology and concepts for a real integration into the decision-making processes that are more and more requested for crisis management. The computing resources supported by AI technics allow today to enter the real-time application and open the door to decision support systems that could be mobilized at different stages including during major water related crisis. At the same time, the request to integrate vulnerability and resilience dimension in the various engineering approaches is becoming more and more frequent especially for environments directly exposed to major natural hazards like floods and inundations.

With respect to these issues, however, several questions still remain open and concentrate development efforts: coupling of models, data acquisition and management, uncertainties (both epistemic and random) of results supplied by models, use of 3D CFD models for complex phenomena and for large-scale problems, added value of AI processes combined to deterministic approaches, … All these points are continuously explored and investigated by researchers, scientists and engineers. Like in all scientific domains, most recent and advanced developments must be discussed and shared regularly in a growing community that has to face every day more challenging and complex situations. The SimHydro 2023 conference, following the six previous editions, has contributed to this objective by providing a platform for exchanges and discussion for the different actors involved in the water domain. The face-to-face format of the conference, coming after the hybrid experience of 2021, has underlined, if needed, all the added value of physical attendance and demonstrated the liveliness of the synergies during the coffee and the lunch breaks. In addition, as the conference was hosted by EDF lab in Chatou, participants had the opportunity to increase exchanges over the technical visits of the experiment hall and the dam lock of Chatou managed by Voies Navigables de France (VNF). All have particularly enjoyed the possibility to directly interact with EDF research teams and operators of VNF.

SimHydro is a permanent cycle of conferences held every 2 years, hosted by EDF lab Chatou in 2023 after Université Côte d'Azur/Polytech Nice Sophia for the previous editions, and organised by the Société Hydrotechnique de France (SHF) and its partners. It aims, as the subject, at recent advances in modelling and hydroinformatics and at the participation and exchanges at European scale (it is open to all other researchers and participants, but the purpose is to maintain a specific platform for the region that was a birthplace of both domains).

The latest SimHydro conference was held over 3 days in EDF Lab Chatou, France, from 8th to 10th of November 2023. The conference was jointly organized by the Société Hydrotechnique de France (SHF), Université Côte d'Azur/Polytech Nice Sophia and with the active support of the International Association for Hydro-Environment Engineering and Research (IAHR). As for previous editions, several sponsors also supported the conference: Electricité de France (EDF) and Compagnie Nationale du Rhône (CNR). The conference attracted 180 delegates from 38 countries who participated in 22 sessions where 105 papers were presented. The programme was organised around seventeen main themes:

1. Models for droughts, floods and water sharing strategies
2. AI for water issues
3. Digital twins
4. Hydro-environmental issues and extreme situations
5. Uncertainties and data assimilation
6. AI solutions for water
7. Intensive computing for hydraulic simulations
8. Extreme in hydraulics: how to deal with?
9. Decision Support System and models: concepts, design, challenges, implementation and operation
10. Real time management and models
11. Hydraulic structures and networks: real time operation
12. Scale models in hydraulics and their place and complementarity in simulation concepts
13. Modelling methods and tools for floods management

14. 3D multi-phase flows (experiments and modelling)
15. Hydraulic machinery
16. Diphasic flows and cavitation
17. Modelling in ecohydraulics and morphology

The general theme of the conference was focused on “New modelling paradigms for water issues?”. The objective was to address some of the key challenges faced by the water modelling community regarding processes to simulate such as water services, extreme events (floods, droughts, etc.), hydrological cycle at catchment scale and to assess the added value of emerging concepts and methods such as Artificial Intelligence (AI) and Digital Twins that are gaining interests. In addition to the recurrent topics of the conference, SimHydro 2023 was focused around 3 major themes:

- Models for droughts, floods and water sharing strategies: Since 2021, many regions of the world have faced one of the most exceptional drought events of the past 50 years. In a similar way, extreme flooding took place in numerous locations in Europe and worldwide with a significant increase of the damages and affected population such as in Pakistan. Under those exceptional circumstances, once again the need for modelling tools able to address and to anticipate this type of situation has been underlined for the development of sustainable water sharing strategies. Obviously, the innovative approaches regarding wastewater treatment for water reuse and recycle have gained interest and appear on the list of operational solutions. A holistic approach is called and requests efficient modelling tools. In this context, the current modelling approach needs to be updated and to integrate a wider spectrum of processes to be able to formulate proper management strategies encompassing water uses, natural environment preservation and water related hazards mitigation.
- Artificial Intelligence (AI) for water issues: With the availability of computational resources and real-time communication protocols, the Artificial Intelligence (AI) methods and tools are flowing within all scientific and technical sectors including the water domain. The massive deployment of those tools is obviously attracting interest of the water community as they offer the possibility to address complex problems and can potentially support real-time operations that represent a major step for many professionals engaged within operations. However, if the perspectives look promising, the practical development and implementation requests to go through a critical and validation process that is not yet fully formalized. Based on the latest AI developments and the most recent implementations in the water domain, the plenary session will address the added value of the AI approaches and the associated challenges that should be understood by the water community.
- Digital twins: The concept digital twin is gaining interest in the water community and especially for water services. The virtual representation of devices and water systems is the logic “next step” following the SCADA deployment that has been already used for decades. The digital twins have demonstrated their efficiency in mechanical sector and obviously for the energy production related domain. The ambition to address water networks to improve their efficiency and performance

requests to integrate an increased complexity that is not formalized within the current scope of digital twins. Within this perspective, the deployment of the digital twin concept to catchments represents even a greater challenge. The sessions addressed the latest developments for digital twins in hydropower production, water services and water resources management.

The water field is continuously mobilizing models for addressing complex issues and new challenges. Within the context of the climate change, the water issues are exacerbated with the competition among uses. The limited water resources request from the modern societies to review some of the historical paradigms traditionally used and to promote new approaches for a sustainable management. The combined complexity and vulnerability of large urban environments request a deep understanding of water uses and environmental synergy. At the same time, water related natural hazards are contentiously straightening modern societies that have to adapt and implement a more resilient environment. In parallel, in the industrial sector, the search for a high level of efficiency for hydraulic machinery requests to simulate complex processes. Under all these situations, the models currently used represent only partly the physical phenomena involved, the scale of the processes, the hypothesis included within the different numerical tools, etc. The design and the operation of relevant models represents a challenging task for the modeller who is responsible of the knowledge part of a global system that is dedicated to support the decision makers.

Within general themes of the conference, topics like coupling of models, data assimilation and uncertainties, urban flooding, data and uncertainties in hydraulic modelling, model efficiency and real situations, new methods for numerical models, hydraulic machinery, 3D flows in the near field of structure, models for complex phenomena have been covered. The conference, by attracting researchers, engineers and decision makers, has promoted and facilitated the dialogue between various communities especially with several special sessions frequently linked to on-going European Research projects.

Exchanges with participants have been very fruitful on crucial questions related to the crisis management during extreme flood events, the needs for operational forecasting systems, the state of the art in research and development in the domain of numerical fluid mechanics, the stakeholder's capacity to understand results, the means for dialogue directly or indirectly between the stakeholders and the model developers, the information's exchange between stakeholders and developers.

To contribute to this dialogue and to provide useful references, following the successful previous experiences of 2012, 2014, 2017, 2019 and 2021, the organisers of SimHydro 2023 have decided to elaborate this book. This volume gathers a selection of the most significant contributions received and presented during the conference. The objective is to provide the reader with an overview of the on-going developments and the state of the art taking place in two volumes that are:

- Flood modelling and mitigation strategies;
- Advanced modelling solutions.

These two themes were selected in an obviously way based on the submitted papers. As in the previous SimHydro editions, the food modelling issue is still mobilizing widely the community and numerous innovative approaches have been presented. In a similar way, new modelling solutions are now progressing in various sectors with the availability of massive computational resources and efficient communication networks and solutions.

Obviously, all dimensions of these themes cannot be covered in a single book. However, the editors are convinced that the contents may contribute to provide to the reader essential references for understanding the actual challenges and developments in these areas of the hydroinformatics field.

These two volumes represent the sum of the efforts invested by the authors, members of the scientific committee and members of the organising committee. The editors are also grateful for the dedicated assistance of the reviewers who worked tirelessly behind the scene to ensure the quality of the papers. We hope this book will serve as a reference source on hydroinformatics for researchers, scientists, engineers and managers alike.

Sophia Antipolis, France
February 2024

Philippe Gourbesville
Guy Caignaert

Volume 1. Flood Modelling and Mitigation Strategies

During the last decade, within the context of climate change, floods were the leading natural hazard at the worldwide scale. Floods impact both individuals and communities, and have social, economic, and environmental consequences. Flood management represents a major issue for modern societies. The growing sophistication of human environments—urban and agricultural—has induced a higher vulnerability that has to be managed to minimize impacts on both the population and economic activities. In many regions of the world, the need for a better understanding of the flood processes associated to an efficient warning service is frequently underlined. Availability of information to the public appears as one of the major mitigation actions.

The papers included within this volume present different aspects of flood modelling, from hydrological analysis to complex hydraulic models introducing emerging solutions for data fusion and management. The observed situations are analysed, and new approaches are proposed with the ambition to better represent the complexity of the processes and to provide operational tools that can support the various decision-making processes. Several papers describe the growing need for efficient solutions that can integrate and cover the diversity of multiple infrastructures that should be coordinated in their operation to deliver the best service. Among the modelling approaches, the availability of computational resources opens the door to deployment of various AI solutions that can be combined with deterministic approaches and can significantly improve the quality of the produced results. For the mitigation strategies, the use of reservoirs against flood processes remains a key topic in many regions of the world and improvements are proposed through various operational approaches.

In the recent decades, the flash flood has become one of the major natural disasters in the world. The proportion of casualties and social and economic losses caused by flash flood disaster is high and shows a continuously increasing trend. During the SimHydro 2023 conference, a special session was dedicated to flash flood events and was jointly organized with the Flash Flood Program (FFP) initiated by China Institute of Water Resources and Hydropower Research (IWHR), China and Polytech Lab of Université Côte d'Azur, France. Several papers within this volume are directly coming from this session and underline both difficulties to address the extreme processes and to formulate relevant mitigation actions supported by relevant models. The magnitude of the challenges is clearly exposed and requests to review some of the modelling paradigms to deliver operational forecasts that can be used by field operators and first responders who are mobilized during major crisis. Within the FFP actions, an online session was also organised jointly on the 9th of November 2023, within the Smart Water Grid International Conference (SWGIC) organized in Incheon, South Korea.

In addition to the classical mitigation measures, the nature-based solutions are gaining significant interest from the international community. Sustainability concept and limited financial resources for infrastructures maintenance are on the agenda in many countries. The nature-based solutions appear as an alternative option that can be embedded within a more holistic approach regarding flood mitigation.

The need for a holistic approach for floods impacts analysis is a challenge for Hydroinformatics systems that are obviously key tools for assessing efficiency of mitigation measures and demonstrating their local added value within the decision-making process. Several papers are addressing this challenge and formulate innovative approaches with various study cases. Obviously, several reported experiences are at their early stage and will request further developments and tuning. The objective to deliver operational systems able to support the decision-making process both for mitigation measures definition and real time management support remains a major task for the modeller community.

The diversity and the availability of data sources especially from the new spatial devices represent opportunities for the data driven approaches. Several papers underline the added values of those newly available data and demonstrate that efficient modelling approaches can be developed and deployed in a systematic way and for affordable cost. This new situation opens the door to a better knowledge of the hydrological processes involved in the floods and inundations development. Within this now data rich environment, the added value of AI based solutions is appearing in a clearer way and will continue to grow in the coming years. The authors underlined the interest to associate and combine various type of models – such as deterministic and data driven – to produce more accurate and reliable results. The selected papers present various successful applications and underline the remaining challenges.

Sophia Antipolis, France
February 2024

Philippe Gourbesville
Guy Caignaert

Contents

Chapter 1
Development of Robust and Efficient Methods for Hydraulic/Hydrologic/Environmental Risk Numerical Simulation

Pilar García-Navarro, Mario Morales-Hernández, Sergio Martínez-Aranda, Isabel Echeverribar, and Javier Fernández-Pato

Abstract Nowadays, the great power of modern computers combined with well-designed numerical models allows to develop computational models able to deal with simulations of several coupled phenomena over detailed complex topography. An efficient and properly calibrated computational model represents a useful tool to provide insight into the catchment dynamics at hydrological and geomorphological levels. In addition, it allows to develop detailed risk management and conservation plans. The challenge of finding a compromise between computational time and level of accuracy and robustness has traditionally expanded the use of depth averaged models (2D or even cross section averaged models (1D) rather than full three-dimensional models for flood simulation. This work presents examples of GPU accelerated 2D shallow-water models for the simulation of flood events, water quality evolution problems and urban flow over non-erodible and erodible bed in real time. In particular, a well-tested and robust explicit first-order finite volume scheme is used to control the numerical instabilities that are likely to appear when used in complex topography. The model is applied to reproduce real events in a reach of the Ebro River (Spain) and a tailing dam in Brumadinho (Brazil) in order to compare simulation results with field data in a large domain and long flood duration allowing an

P. García-Navarro (✉) · M. Morales-Hernández · S. Martínez-Aranda · I. Echeverribar · J. Fernández-Pato
Institute of Water Resources and Hydropower Research (IWHR), Beijing, China
e-mail: pigar@unizar.es

M. Morales-Hernández
e-mail: mmorales@unizar.e

S. Martínez-Aranda
e-mail: sermar@unizar.es

I. Echeverribar
e-mail: echeverribar@unizar.es

J. Fernández-Pato
e-mail: jfernandez@eead.csic.es

P. Gourbesville and G. Caignaert (eds.), *Advances in Hydroinformatics—SimHydro 2023 Volume 1*, Springer Water, https://doi.org/10.1007/978-981-97-4072-7_1

analysis of the performance and speed-up achieved by different GPU devices. The high values of fit between observed and simulated results as well as the computational times achieved are encouraging to propose the use of the model as forecasting system.

Keywords Finite volume methods · Explicit schemes · Wet-dry fronts · Unsteady shallow water flow · Coupled models · GPU computation

1.1 Introduction

To control their impact on the environment and society, management plans are being developed and flow risk modelling is starting to represent an important tool for flood risk maps design. However, detailed flow forecasting is still not as widely used by decision-makers as it could be due to the speed of the simulations [13]. The reduction of computational time when simulating real or practical cases has been one of the most important challenges of computational fluid dynamics (CFD). In particular, when trying to reproduce flood events on a large spatial and temporal domain, the efficiency of the method becomes crucial to make a computational tool affordable and have a practical use. For this purpose, the most common strategies can be divided into two groups: model reduction and computation acceleration. The complexity of a real flow may require the consideration of the three-dimensional (3D) Navier–Stokes equations for the total representation of its nature. However, the prediction of hazards, such as flood events or evolution of pollutant discharges on rivers, does not need such a detail in many cases. Thus, the simplification of the model under shallow water conditions leads to the non-linear shallow water equations (SWE), whose resolution is simpler and faster than the complete equations. Additionally, the assumption of dimensional hypothesis, which allows the modeller to work with one-dimensional (1D) models, can also accelerate the computations. The 1D system can be written as follows

$$\frac{\partial U_{1D}(s,t)}{\partial t} + \frac{\partial F_{1D}(s,U)}{\partial s} = S_{1D}(s,U) \tag{1.1}$$

where the conserved variables, fluxes and source terms are:

$$U_{1D} = \begin{pmatrix} A \\ Q \end{pmatrix}; F_{1D} = \begin{pmatrix} Q \\ \frac{Q^2}{A} + gI_1 \end{pmatrix}; \ldots S_{1D} = \begin{pmatrix} 0 \\ g\left[I_2 + A\left(S_0 - S_f\right)\right] \end{pmatrix} \cdots \tag{1.2}$$

For flood event simulations, the two-dimensional (2D) shallow water system of equations has been demonstrated to be suitable enough to reproduce the flow behaviour [9,12, 27, 28]. Thus, although 3D models are widely extended on other CFD applications, their use for flood events still presents unaffordable times for large-scale events even when using parallelization techniques for acceleration. Additionally, their computational cost is not compensated by the accuracy increment in comparison with simplified models since huge flood events have a natural 2D behaviour. The 2D shallow water flow system of equations can be written as follows [5]:

$$\frac{\partial U_{2D}}{\partial t} + \frac{\partial F_{x2D}(x, y, U)}{\partial x} + \frac{\partial F_{y2D}(x, y, U)}{\partial y} = S_{2D}(U) \tag{1.3}$$

$$U_{2D} = \begin{pmatrix} h \\ hu \\ hv \end{pmatrix}, F_{x2D} = \begin{pmatrix} hu \\ hu^2 + g\frac{h^2}{2} \\ huv \end{pmatrix}, F_{y2D} = \begin{pmatrix} hv \\ huv \\ hv^2 + g\frac{h^2}{2} \end{pmatrix}, S_{2D} = \begin{pmatrix} 0 \\ gh(S_{0x} - S_{fx}) \\ gh(S_{0y} - S_{fy}) \end{pmatrix} \tag{1.4}$$

However, the computational cost may be excessive, especially due to the necessity of small cells in the river bed or in hydraulic structures [4]. This drawback of 2D models has caused over the years an extended use of 1D models for flood simulation [25].

For the numerical resolution of the 1D model, the use of an upwind finite volume method based on the Roe's scheme that relies on average values of the characteristic celerities (see Fig. 1.1) has been reported useful and robust [3,25], the expression for the 1D updating at each cell i is

$$U_i^{n+1} = U_i^n - \frac{\Delta t_{1D}}{\Delta s}\left[\left(\sum_{m=1}^{2} \tilde{\lambda}^{+} \tilde{\gamma}\, \tilde{e}\right)_{i-1/2}^{m} + \left(\sum_{m=1}^{2} \tilde{\lambda}^{-} \tilde{\gamma}\, \tilde{e}\right)_{i+1/2}^{m}\right]^n \tag{1.5}$$

where Δs is the 1D grid size, $\lambda^{\pm m}$ are the Jacobian eigenvalues (with ± superscripts denoting the upwind discretization) are the Jacobian eigenvectors and are wave coefficients. Expression (1.5) represents the time updating each time step at each cell with the in-going contributions, as depicted in Fig. 1.1. Since the numerical scheme has an explicit nature, the time step size must be limited by the Courant–Friedrichs–Lewy (CFL) so that

$$\Delta t_{1D} = \text{CFL} \min_{i,m}\left(\frac{\Delta s}{\left|\tilde{\lambda}^{m}_{i+1/2}\right|^n}\right), 0 \le \text{CFL} \le 1 \tag{1.6}$$

The 2D upwind explicit scheme can also update the cells according to the in-going contributions of the fluxes and source terms of the neighbouring cells (see Fig. 1.2). However, since the flow is computed on a 2D framework, the expression uses as many contributions as edges per cell and the area of cell i, Ω_i, instead of Δs. If a generic edge between cells i and j is called k, the problem is projected onto k and the matrix eigenvectors basis. Finally, the updating equation in a triangular mesh is [24]

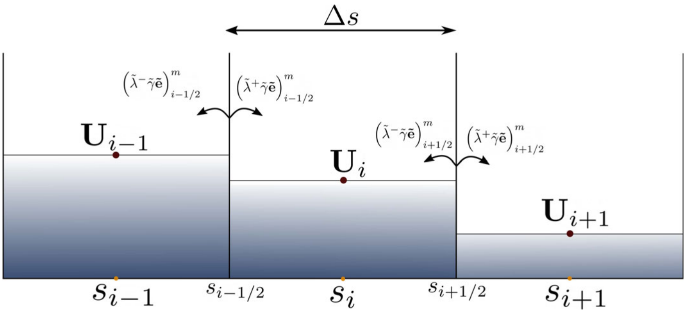


Fig. 1.1 Sketch of the updating 1D scheme

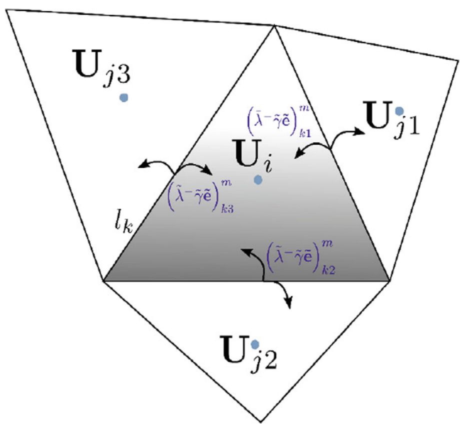
$$U_i^{n+1} = U_i^n - \frac{\Delta t_{2D}}{\Omega_i} \sum_{k=1}^{NE} \sum_{m=1}^{3} \left[\left(\tilde{\lambda} - \widetilde{\gamma e} \right)_k^m l_k \right]^n \tag{1.7}$$

where m = 1, ..., 3 stands for the number of eigenvectors (or variables) and k runs the number of involved neighbouring walls (with NE = 3 in the triangular case). Again, the time step has to be limited through the CFL condition:

$$\Delta t_{2D} = \text{CFL} \min_{m,k} \left(\frac{min(\chi_i, \chi_j)}{\left| \overset{\sim m}{\lambda_k} \right|^n} \right), 0 \leq \text{CFL} \leq 1 \tag{1.8}$$

Alternatively, some researchers have proposed 1D–2D coupled models to combine a 2D representation on the floodplain and a 1D numerical schematization for the main channel [1, 18, 19]. These models may lead not only to a reduction of the simulation time but also to a more accurate representation of the river channel flow, whose

Fig. 1.2 Sketch of the updating 2D scheme



main velocity direction and geometry are better captured. Nevertheless, even though these combined models present a speed-up in comparison with full 2D models, when dealing with large-scale events they still may present a high computational cost.

On the other hand, there exist other techniques which are focused not on the number of operations to compute depending on the model and its dimensions but on the speed to manage all those operations. Based on parallelization techniques that divide the computing workload into different cores that solve the scheme simultaneously, different technologies can be found. One of the most common strategies is Open Multi-Processing (OpenMP), that accelerates the calculations depending on the number of cores, which depends on the number of Central Processing Units (CPUs) available. Beyond this, high-performance computing (HPC) generally refers to the practice of aggregating computing power in a way that delivers much higher performance than one could get out of a typical desktop computer or workstation in order to solve large problems in science or engineering. In particular, schemes can be implemented to run on graphics cards (GPUs), which may contain up to thousands of cores in the same device and work together with only one CPU (Fig. 1.3). The implementation of 2D models on GPUs was extended a few years ago and several 2D models running on a Graphics Processing Unit (GPU) can be found. They offer computational speed-ups turning 2D models into affordable tools for flood forecasting [2, 12, 26, 27, 29]. Additionally, if several GPU devices are used, the acceleration may be even higher. However, in addition to the large computing facilities required, the communication time penalty is not always worth it for a large number of GPUs, requiring efficient implementations [21].

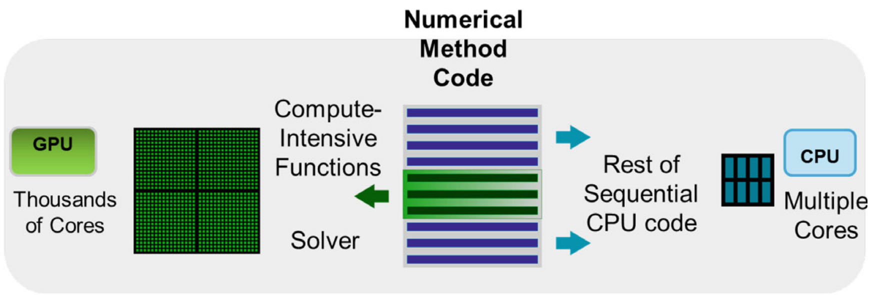


Fig. 1.3 Sketch of the computational work load

1.2 Unsteady Hydraulic Flows

1.2.1 River Flooding

1.2.1.1 Application of a GPU-2D Model

The Ebro River basin is managed by the Ebro River Basin Authority (Confederación Hidrográfica del Ebro-CHE) (www.chebro.es). They provided all the topography details as well as hydraulic data from the gauging stations along the basin. The river basin is located in the North- East of Spain (Fig. 1.4) and has an extension of 85,362 km^2. Many urban areas of different size can be found near the river together with areas dedicated to agriculture and farming. It is a river with an average discharge of Q = 400 m^3/s that increases up to 2500 m^3/s when flooding occurs (return period between 1 and 2 years). The present work is restricted to the physical domain in the middle part of this river (Fig. 1.4), which is the most affected by floods. It is a 125 km river stretch limited by two gauging stations: Castejón de Ebro upstream and Zaragoza downstream. As inlet boundary condition, the hydrographs provided for the measurements at Castejón gauging station are used. The gauging curve (water surface level vs. discharge) provided from measurements in Zaragoza gauging station is imposed as outlet boundary condition. The rest of the boundaries are chosen far enough not to be reached by the flow. The total computational domain chosen encompasses a total extension of 744 km^2. A calibration process is crucial to set up the model with the most suitable computational mesh and the proper roughness values. When dealing with domains of the size presented here this process could turn unaffordable due to the large amount of simulations that are needed and the high computational times. The numerical model robustness and the GPU implementation play an important role in this process.

A computational mesh is built mapping the terrain elevation from the DTMs. In order to reach a compromise between speed of calculation and accuracy of results triangular adaptive meshes in space are used so that the cells are small where we need much detail of the flow (riverbed, levees, etc.), and large in areas far from the riverbed where practically water does not arrive hardly ever always paying attention to their regularity. In particular, edge sizes ranging from 5 m (near river bed) to 150 m (at boundaries) were first imposed. The mesh was designed starting by the requirement to have enough river bed resolution (at least 10 cells at a typical cross section). The mesh calibration process was made with an event occurred in 2015 (see Fig. 1.5) focusing on flood extension. As not only discharge and elevation data at certain stations, but also maps with the maximum extension of the flooded area were supplied, both a qualitative (using visual exploration) and a quantitative comparison between computed and measured flooded area were used to detect the necessity to refine the mesh near levees. This led to the final mesh containing 867,672 triangular cells. Figure 1.6 highlights the differences between final (b) and initial (a) meshes that were generated for the representation of a levee in the floodplain. The figure shows how a local refinement is needed to capture narrow levees. During this process, around

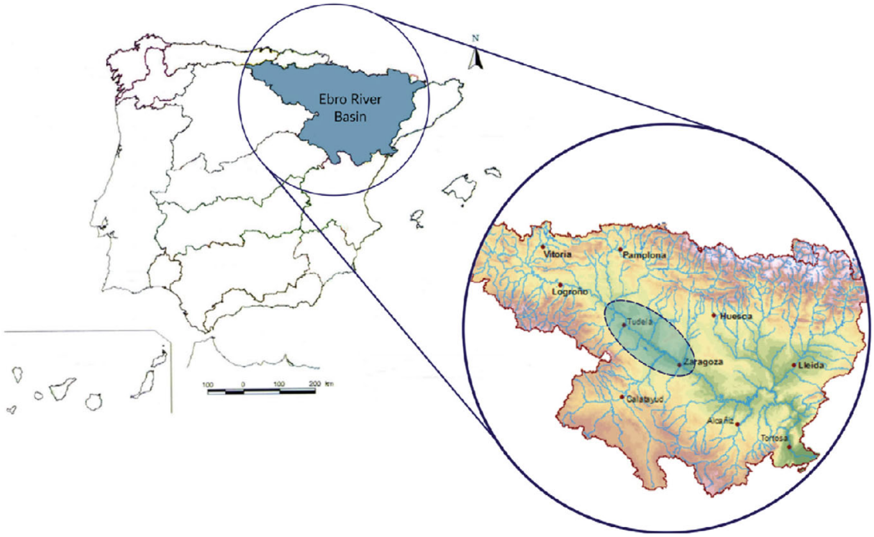


Fig. 1.4 Middle part of the Ebro river object of the study and location of relevant towns

20 simulations were needed to achieve a proper mesh. A trial and error calibration process was carried out to achieve a coincidence between peak values of the measured hydrographs at Tudela and Zaragoza together with the analysis of travelling times.

All the flood event simulations were carried out with different GPU devices. The required computational times are shown in Table 1.1 together with the real flood duration. In order to compare the level of speed up, it is worth mentioning that the 21-day flood event is computed in 21 days when a 12 CPU cores (Intel Xeon X5650) is used. Although a 12-cores parallelization is used, the computational time results unaffordable when trying to have a tool with prediction on-line purposes. For more details, see [4].

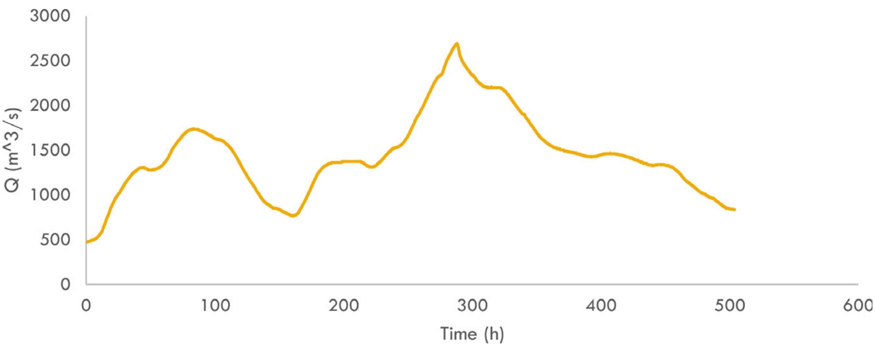


Fig. 1.5 Upstream flow hydrograph of the 2015 event

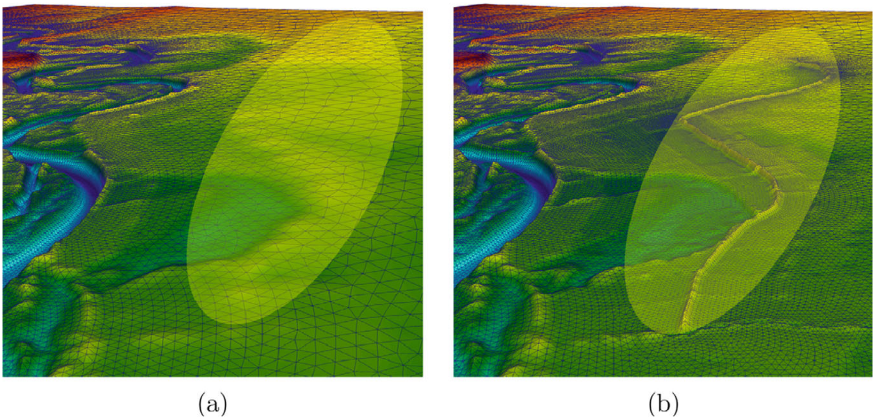


Fig. 1.6 Wrong (**a**) and correct (**b**) representation of a levee on the floodplain comparing calibrated (**b**) and non-calibrated (**a**) meshes

Table 1.1 2D model computational times for the Ebro flooding case

Processor	Computational time	Real time (days)
CPU Intel i7-10700F	> 40 days	21
CPU	21 days	21
CPU—12 cores	21,27 h	21
NVIDIA GTX 780	16,36 h	21
GeForce GTX Titan Black	10,40 h	21
NVIDIA Tesla K40	10,25 h	21
NVIDIA GTX 1080 Ti	> 40 days	21

1.2.1.2 Application of a GPU 1D–2D Model

Coupled 1D–2D models emerged as an efficient solution for a two-dimensional (2D) representation of the floodplain combined with a fast one-dimensional (1D) schematization of the main channel. At the same time as high-performance computing (HPC) has appeared as an efficient tool for model acceleration. As a second example, a previously validated 1D–2D Central Processing Unit (CPU) model is combined with an HPC technique for fast and accurate flood simulation. In the previously validated coupled model running on CPU [20], the main river bed is modelled so that the whole framework works as a pure 1D model when channel overflow does not occur. During a flood event, the terrain adjacent to the river bed becomes inundated and a 2D model is used for the representation of the velocity field evolution on the floodplain. By means of an appropriate geometric link, the 1D and the 2D models are coupled. They are both based on the SWE and solved using a finite volume explicit upwind first-order numerical scheme with approximate Roe solvers that are able to

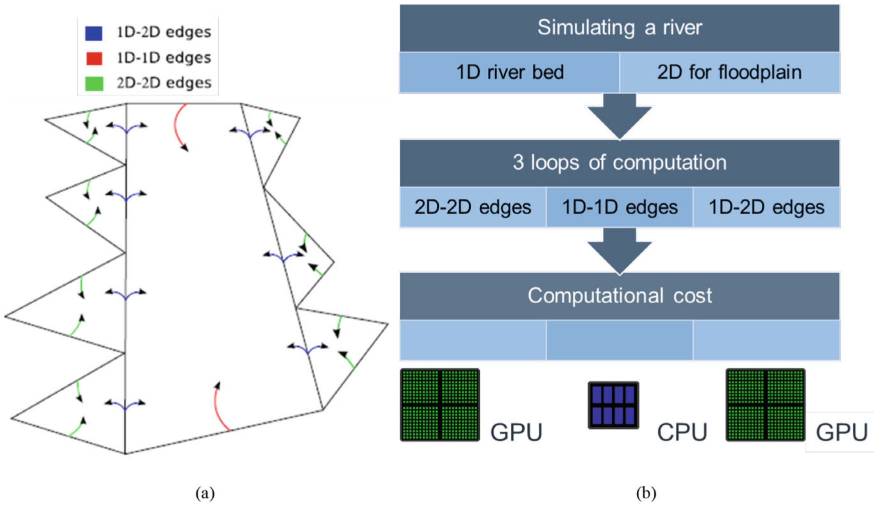


Fig. 1.7 Coupling estrategy (**a**) and computational workload (**b**) for the 1D–2D HPC model

deal correctly with wet/dry fronts, advance over dry beds and transient flows over irregular topography [5, 20, 23].

Due to the speed of 1D schemes, a hybrid CPU/GPU model that runs the 1D main channel on CPU and accelerates the 2D floodplain with a Graphics Processing Unit (GPU) is presented as sketched in Fig. 1.7. Since the data transfer between sub-domains and devices (CPU/GPU) may be the main potential drawback of this architecture, the test case is selected to carry out a careful time analysis.

The coupled model is applied to a 125 km long stretch of the Ebro River (Spain) that encompasses a surface of 392 km^2. Two different historical events are propagated over the mesh and the same speed-up analysis is carried out to study the performance of the model under realistic conditions with complex and non-homogeneous floodplains. Two upstream hydrographs events of different duration and peak discharge were considered. The shortest, E1, corresponds to a 2010 flood event that lasted 5 days reaching 2000 m^3/s. The second one, E2, stands for the 2015 event that lasted 21 days and, containing two peaks, reached more than 2500 m^3/s. The geometry of the case also determines the proper number of 1D cells. In this case, the curvature of the river forces the necessity of small values of Δs within the 1D framework, leading to 2201 1D cells on the river bed. On the other hand, the E2 event consumes more time due to its own hydrograph duration. The transfer time is not so predominant and the floodplain and coupled edges (all computed on GPU) have a strong influence on global time. Finally, due to the extent of the flooded area where small cells are required to represent the levees and the high consumption of the 1D model, simulation times are higher than could be expected according to the idealized case previously simulated.

The results reveal the speed-up dependency on the 2D mesh, the event to be solved and the 1D discretization of the main channel. Additionally, special attention must be paid to the time step size computation shared between sub-models. In spite of the use of a hybrid CPU/GPU implementation, high speed-ups are accomplished in some cases. The interest of the present analysis resides in the study of the combination of efficiency in the model and on the architecture of the parallelization, as the speed-up of the coupled model is not that obvious due to its particular hybrid implementation. This implementation is based on combining CPU and GPU algorithms for each of the subdomains and the necessity of data transfers. Having a 1D–2D fully GPU model could be a possibility depending on the application. However, in the cases of interest in the present study, the fast 1D frameworks and the high involvement of the floodplain in flood events place this hybrid model in an interesting position to be studied for cases where the main river does not represent a large proportion.

1.2.2 Coupling Unsteady River Flow and Water Quality

In this study, a 2D shallow water flow solver integrated with a water quality model is presented. The interaction between the main water quality constituents included is based on the Water Quality Analysis Simulation Program. Efficiency is achieved by computing with a combination of a Central Processing Unit (CPU) and a Graphics Processing Unit (GPU) device. This technique is intended to provide robust and accurate simulations with high computation speedups with respect to a single core CPU in real events. The proposed numerical model is evaluated in cases that include the transport and reaction of water quality components over irregular bed topography and dry–wet fronts, verifying that the numerical solution in these situations conserves the required properties (C-property and positivity) [10]. The model can operate in any steady or unsteady form allowing an efficient assessment of the environmental impact of water flows. The field data from an unsteady river reach test case are used to show that the model is capable of predicting the measured temporal distribution of dissolved oxygen and water temperature, proving the robustness and computational efficiency of the model, even in the presence of noisy signals such as wind speed.

Depth-averaged transport equations for 10 scalar variables are used in the present work to evaluate the physical, chemical and biological processes of interest in rivers. The equations for the WASP water quality state variables considered—ammonium nitrogen ϕ_1 (NH_4), nitrate nitrogen ϕ_2 (NO_3), inorganic (ortho) phosphorus ϕ_3 (IP), phytoplankton ϕ_4 (A), Carbonaceous Biological Oxygen Demand ϕ_5 (C-BOD), dissolved oxygen ϕ_6 (DO), organic nitrogen ϕ_7 (ON), organic phosphorus ϕ_8 (OP), temperature ϕ_9 (T) and total coliform bacteria ϕ_{10} (TC) can be written in conservative form as

$$\frac{\partial(h\phi_s)}{\partial t} + \frac{\partial(hu\phi_s)}{\partial x} + \frac{\partial(hv\phi_s)}{\partial y} = E_x \frac{\partial}{\partial x}\left(h\frac{\partial\phi_s}{\partial x}\right) + E_y \frac{\partial}{\partial y}\left(h\frac{\partial\phi_s}{\partial y}\right) \pm R_s(\phi_s, p) \pm f_s \tag{1.9}$$

where ϕ_s is the depth-averaged concentration of the s state variable (s = 1, 2, ..., 10). E_x and E_y are the diffusion–dispersion coefficients in the x and y directions, respectively, R_s is the rate of change in the substance concentration due to the physical, chemical and biological processes as a function of each concentration ϕs and the p model parameters. The description of these processes of degradation of organic material, growth and death of algae, nitrification, hydrolysis of organic nitrogen and phosphorus, re-aeration, sedimentation of algae, phosphorus and nitrogen, sediment uptake of oxygen are detailed in [10]). The set of state variables with their conversion processes form a matrix of size NP × ST where NP is the number of processes and ST is the number of chemical species. Finally, f_s are point and non-point sources of each species. It is worth noting that, since most of the kinetic coefficients depend on the temperature, the proposed model calculates the water temperature among the set of water quality variables (ϕ_9) whose transport is influenced by atmospheric radiation and sensitive heat fluxes in the heat balance. The 2D shallow water equations were discretized using the previously described finite volume scheme. For the scalars transport equations, the conservative procedure described in [17, 22] was followed.

A reach of the Ebro River is again considered in the study. It is located between the cities of Alagón and Zaragoza with an approximate length of 40 km. This river reach is used to test the simulation model involving the three hydrodynamic equations and the transport equations corresponding to the ammonium nitrogen ϕ_1 (NH_4), nitrate nitrogen ϕ_2 (NO_3), carbonaceous biological oxygen demand ϕ_5 (C-BOD), dissolved oxygen ϕ_6 (DO), organic nitrogen ϕ_7 (ON) and temperature ϕ_9 (T). A Digital TerrainModel (DTM) of resolution 5 × 5 m to define the topography of the study region together with additional cross-sections provided by the river basin authorities (Confederación Hidrográfica del Ebro, CHE) were used. The roughness coefficient is estimated from the land use [Sistema de Información de Ocupación del Suelo de España (SIOSE)] at a reference scale of 1:25,000. Soil uses and other factors such as the irregularity of the land are analysed to obtain a map of roughness values for the different types of soil. With the previous information, an unstructured triangular mesh was created using 169,918 triangular cells of variable size, more refined in regions requiring a higher level of detail such as the river bed or thin levees. The length of the edges of the cells ranged from 13.0 m (near the river bed) to 159.0 m (limit of the domain).

To reproduce and evaluate a transient event, information on hydrodynamic and quality parameters is required. This information is imposed at the beginning of the calculation (t ¼ 0) as initial condition and at the domain boundaries. Through the monitoring stations managed by the CHE, information is obtained with a periodicity of 15 min for the discharge flow rate, water temperature and dissolved oxygen concentration (the latter measures less frequently on some occasions). In the present case, a 7-day event corresponding to a 2012 flood event (December 18–25) is simulated. The measured discharge hydrograph as well as the measured DO concentrations and water temperatures at Alagón were used as time variable inlet boundary conditions. They are plotted in Fig. 1.11. For the rest of the water quality components, the inlet boundary value was assumed constant. On the other hand, external heat contributions, such as air temperature, relative humidity, wind speed and solar radiation, were obtained from the Sociedad Aragonesa de Gestión Agroambiental (SARGA). Meteorological data are recorded every hour so that when there are no records of the meteorological and chemical variables a linear interpolation is performed.

A quantitative analysis of the DO and water temperature variables gives a root mean square error (RMSE) of 0.338 and 0.549, respectively. There is great difficulty in reproducing in more detail the processes that occur in a reach of the river when there is a lack of regularity in the water quality monitoring by the agencies in charge of management. Although there are techniques that allow the recovery of information, it does not become the final solution because all these techniques require more periodic information in the measurement of state variables present in the quality model [11]. Since the computational load in this case is very high due to 2D hydrodynamic and water quality computation, an efficiency analysis is carried out. When the hydrodynamic and water quality models are both solved with a single CPU processor (Intel (R) Xeon (R) CPU E5-2697 v3@2.6 GHz), the calculation time is 108 h, whereas the same scenario requires 3.75 h when the model is solved on a Tesla K80 GPU device. Therefore, the gain in efficiency when using GPU computing in comparison with CPU is 28.8×. On the other hand, in order to measure the extra time required for the water quality algorithms, an additional simulation has been performed considering only the hydrodynamic model (without any water quality calculations), obtaining a simulation time of 1.76 h. This highlights the great complexity of the solute transport and reaction algorithms.

1.2.3 Coupling Surface Flow and a Drainage Network Flow with Solute Transport

The numerical simulation of fluid dynamics, considering the interaction between surface water and drainage networks, has emerged as a practical tool for preventing and mitigating flood occurrences in urban settings. This is particularly crucial during intense storm events, where the limited capacity of sewer systems can act as a catalyst for flooding. Moreover, to curb the dispersion of pollutants through the drainage network, it is imperative to monitor and control the water quality in both domains. Introducing a pollutant transport component to both surface and sewer hydraulic models enhances the comprehensive analysis of combined water flow.

The presented 2D shallow water model can be generalized including the mass source terms of rain, infiltration and drainage network inflow/outflow as described in [8] apart from including solute transport equations. Then, it can be coupled to the EPA-SWMM drainage network simulation model to run synchronously.

In the context of large domains with intricate topography or street structures, a meticulous spatial discretization becomes essential. Consequently, the number of grid cells is typically extensive, necessitating the utilisation of parallelization techniques for computations. Among these techniques, the use of Graphic Processing Units (GPU) proves highly efficient, capitalising on the parallel processing capabilities of thousands of processors within a single device. In this study, we integrate an efficient GPU-based 2D shallow water flow solver with the Environmental Protection Agency's StormWater Management Model (SWMM). Both models can conduct a thorough transient water quality analysis, considering various pollutants.

Several situations regarding the flow exchange between the surface flow and the sewer system can take place: (1) Inflow into non-pressurized sewer, (2) Inflow into pressurised sewer, (3). Outflow over floodplain (wet or dry). Every time step, an internal algorithm compares the values of the surface water depth, pressure head in the pipe and the distance between the bed of the flume and the invert level of the sewer, in order to adequately estimate the exchange discharge in terms of the diameter of the manhole DM, area of the manhole AM, and a coefficient C which accounts for the energy losses at the manhole. The particular form used to formulate the exchange discharge follows closely the formulation suggested in [8].

When coupling two or more numerical models, it is necessary to take into account that the time steps may be different. Therefore, it is necessary to homogenise this value so that the models work in a synchronised way. In this case, since SWMM routing algorithm is based on an implicit method, it has no restrictions on the time step and the surface model (explicit) governs the temporal advance of the simulation, due to stability issues.

The purpose of the case is to test the ability of the coupled model to deal with a combination of several hydraulic/hydrologic phenomena over a huge and complex domain. The study area is located in the city of Santa Fé (Argentina). Figure 1.8 shows the urban map and the delimitation of the study domain (red polygon). Several areas of interest with very different characteristics are considered including a large and complex network of streets and roads, a golf course and an artificial lake connected to an important river (Río Salado) upstream and to a supply channel downstream. An additional injection of water discharge together with two pollutants (TSS and lead) is set in the north part of the domain (see Fig. 1.8). The urban area is provided with a complex drainage network with 152 ground nodes and 147 manholes, shown in Fig. 1.8. A sewer water and TSS inflow is also set at node N8. Figure 1.8 also shows the water discharge and concentration for both pollutants at the surface boundary inlet point, the stage–discharge rating curve used for the river connection and the water discharge and TSS concentration at the sewer node N8. This variety of terrain types lead to the necessity of considering a complex roughness map. The spatial discretization is performed by means of an unstructured triangular and locally refined mesh of approximately 600,000 elements. The mesh refinement is especially careful in the urban area, where the narrowness of the streets requires the use of small triangles in order to obtain an adequate representation (Fig. 1.9).

Regarding the model efficiency, the computational time for a single 6 core CPU simulation is 132.62 h, that for a GPU (Tesla C2075) is 18.05 h whereas for a GPU (GTX Titan Black) is 5.11 h. Hence, speed-up factors computed as the ratio between the six-core CPU time and the GPU time reach 26.5. All the details of the case and some additional considerations on the computational efficiency of the model on GPU can be consulted in [8].

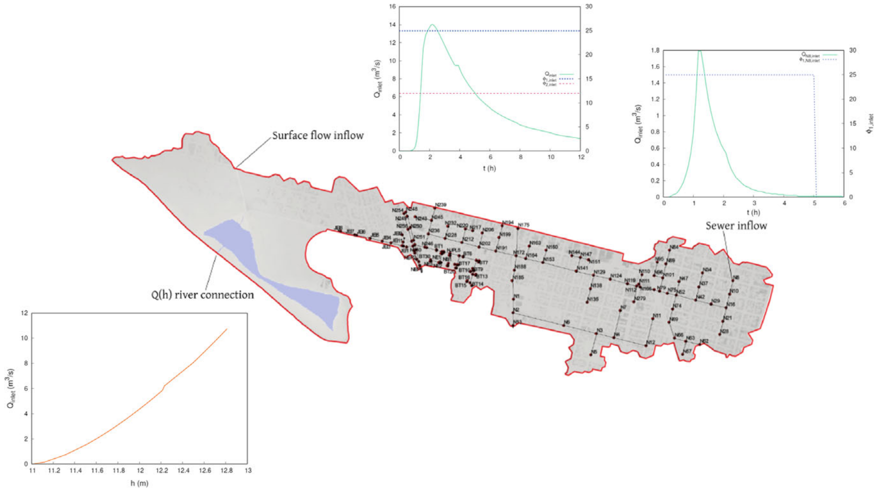


Fig. 1.8 Sante Fe urban flood coupled with drainage

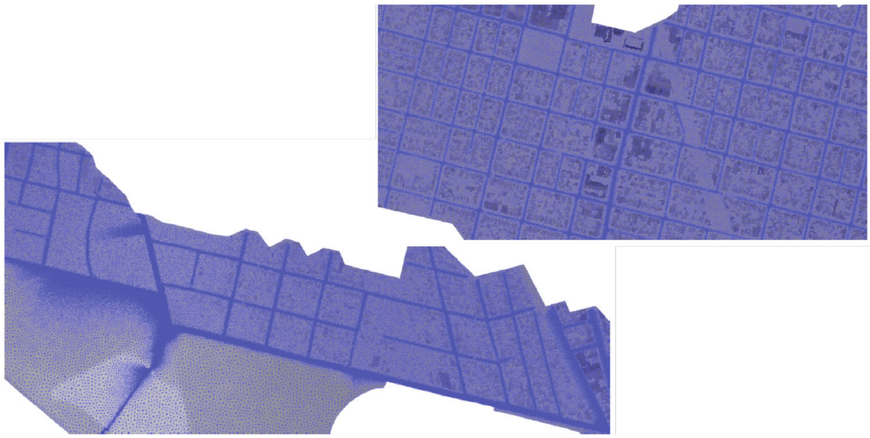


Fig. 1.9 Sante Fe urban flood coupled with drainage: detail of the mesh

1.3 Unsteady Erosive Flows

1.3.1 Formulation of the Problem

Rapid flows of highly concentrated water–sediment mixtures, such as landslides, muddy slurries, debris flows and erosive fast floods, are probably the most challenging and unknown hydro-morphodynamical gravity-driven processes. The fluidized material in motion consists of a mixture of water and multiple solid phases with