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Philippe Gourbesville
Guy Caignaert *Editors*

Advances in Hydroinformatics

Models for Complex and Global Water Issues—Practices and Expectations

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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, for 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 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, a number of 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, etc. 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. Despite the difficult situation related to the COVID crisis and the related constraints, the SimHydro 2021 conference, following the five previous editions, has contributed to this objective by providing a platform for exchanges and discussion for the different actors in the water domain through an innovative hybrid mode combining on-site and online attendance. The exercise was challenging for participants and organizers who had to invent a new way to present, to share and to exchange through various protocols. If the pandemic situation has popularized the use of video conferencing platforms and developed the requested skills to ensure an efficient online presentation, the on-site participants have all underlined the interests of the synergy during the coffee and the lunch breaks, especially under the sunshine of the French riviera.

SimHydro is a permanent cycle of conferences held every 2 years, hosted by Polytech Nice Sophia and organized 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 in Sophia Antipolis, France, from 16 to 18 of June 2021. The conference was jointly organized by the Société Hydrotechnique de France (SHF), the Association Française de Mécanique (AFM), Université Côte d'Azur/Polytech Nice Sophia and with the support of the International Association for Hydro-Environment Engineering and Research (IAHR), the Environmental & Water Resources Institute (EWRI) of the American Society of Civil Engineers (ASCE) and the Canadian Society for Civil Engineering (CSCE). Several sponsors also supported the conference: CNR, IRSN, EDF, DHI France and SETEC-HYDRATEC. The conference attracted 220 delegates from 38 countries who participated in 30 sessions where 124 papers were presented. The programme was organized around fourteen main themes:

1. Hydro-environmental issues and extreme situations
2. Uncertainties and data assimilation
3. AI solutions for water
4. Intensive computing for hydraulic simulations
5. Extreme in hydraulics: how to deal with?
6. Decision support system and models: concepts, design, challenges, implementation and operation
7. Real-time management and models
8. Hydraulic structures and networks: real-time operation
9. Scale models in hydraulics and their place and complementary in simulation concepts
10. Modelling methods and tools for floods management
11. 3D multi-phase flows (experiments and modelling)

12. Hydraulic machinery
13. Diphasic flows and cavitation
14. Modelling in ecohydraulics and morphology.

The general theme of the conference was focused on "Models for complex and global water issues—Practices and expectations". 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 represent 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 ongoing European Research projects and to the catastrophic ALEX storm event affecting the French and Italian catchments in October 2020.

The ALEX storm was targeting several upstream sectors in mountainous catchments on the French Riviera and in Italy on the 2 of October 2020. The recorded extreme rainfall volumes—among the ten most intense events never recorded in France—have generated massive runoff associated with sediment transport. The magnitude of the processes has produced major morphological changes and induced the destruction of many communication infrastructures and buildings. The recovery phase was complex with key questions on how to rebuild and, more widely, on the uses to promote in the mountainous upstream part of the catchments. The session was gathering feedback from local population, victims, first responders, meteorologists, insurance representatives and decision-makers. The session was organized in order to maximize the return of experience for the modeller's community.

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.

In order to contribute to this dialogue and to provide useful references, following the successful previous experiences of 2012, 2014, 2017 and 2019, the organizers of SimHydro 2021 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 ongoing developments and the state of the art taking place in three major sections that are:

- numerical methods and uncertainties;
- flood modelling and mitigation actions;
- advanced modelling 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.

This volume represents the sum of the efforts invested by the authors, members of the scientific committee and members of the organizing 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
August 2021

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Contents

Part I
Numerical Methods and Uncertainties

Numerical methods are a fundamental component of hydroinformatics solutions. The recent developments within the theoretical aspects associated to the availability of massive computing resources have open the door to new developments that are highly promising for the modellers involved within the water sector. This part gathers papers that are exploring new numerical approaches and analysing their added values. At the same time, several papers are questioning how good are the produced models i.e. how certain is the quality of solution of the original equations given the algorithm and software applied. Problems of methods for a number of years have been rather occulted by engineering community because of the everyday use of commercial software and an unfortunate idea that entered the minds of many, namely that now everything can be modelled and that modelling solves all problems. New methods and algorithms were developed and known mainly by research community and were not massively employed because of commercial software easy to obtain and offering user-friendly interfaces. The situation evolved over the last decade and, precisely, SimHydro conferences allow each time the projection of new methods towards engineering community through a number of specific papers like those found in this part.

Regarding the uncertainty problems, several papers of this part enter conceptual levels that change the category of traditional approach. In engineering project and practice, when modelling is concerned, next to everything is uncertain:

• *First*: do you need a model? A model of what? Do you know the phenomena you wish to model? Hopefully you do not expect that you will discover physical phenomena using models that are solutions of equations that describe these phenomena, what means that the latter are already known!

• *Then*: since known equations describe the physical laws that govern problems of your interest, what is the certainty of their numerical solutions provided by given algorithm?

• *Then*: are the data such as topography and similar sufficiently well-known and introduced in the model to be at the level of required certainty of the results of the latter?

• *Then*: suppose you are interested in flooding issues, and you use some industrial simulation software, are you sure that if through some tuning of resistance coefficients you could reproduce past observed flood then the results for exceptional catastrophic ungauged flood will be as good? And if not, how good?

• *Other level of uncertainty*: how certain are information concerning possibility of catastrophic dyke breaking along the river as compared to uncertainty of results obtained from possibly best modelling of open channel flow system? What is uncertainty of the conclusion of studies face to the question of a decision-making manager: "when, at which discharge observed upstream, should I evacuate cities and industries situated in lateral valley protected by dykes that can break?". Here we are not any longer at the level of uncertainty of the results of modelling but at the level of uncertainty of consequences of decisions that, nevertheless, are based or conditioned by the results of the models. In other terms uncertainty in water resources management and engineering becomes the subject of overall approach and traditional sensitivity studies (Monte Carlo and similar) of the given model results are standard peripheral activity. Over the SimHydro editions, this general approach has gained interest and mobilized numerous teams in various contexts.

Numerical methods and uncertainties remain core components of SimHydro conferences and are now entering the real-time application dimension. Obviously, the topic will be enriched with new developments and applications in the coming years.

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August 2021

Chapter 1
Local Downscaling of Shallow Water Simulations

Pascal Finaud-Guyot and Vincent Guinot

Abstract We present a method for the downscaling of low-resolution flow simulations in urban areas. The purpose is to reconstruct some flow variables over fine grids (cell size 1 m or less) from upscaled flow simulations over very coarse grids (cell size 10–50 m). The flow variables under consideration are the water depth and the norm of the unit discharge. These are two widely accepted indicators in flood hazard assessment. The method is assessed in the framework of perfect upscaling, whereby the coarse grid flow variables are exact averages of the fine grid simulation results. A simple reconstruction approach is used: the flow variables are transformed using a power law. The transform of the flow variable over a given cell in the high-resolution grid is computed as a linear combination of the transforms of the flow variables over the coarse resolution grid. The degrees of freedom in the method are the power of the transform, the number of coarse grid cells (called the neighborhood size) and the linear combination coefficients. The method is fitted by minimizing the RMSE between the exact (known) high resolution solution and the reconstructed one. The results show that (i) reconstructing the water depth is easier than reconstructing the unit discharge, (ii) flows involving shocks yield larger reconstruction errors that those involving rarefaction waves, (iii) the method is better when trained for a specific wave propagation direction.

Keywords Urban floods · Hazard mapping · High resolution reconstruction · Perfect upscaling

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1.1 Introduction

High Resolution (HR) flood risk mapping over large urban areas is increasingly needed. Applications range from real time flood risk management to urban development scenario appraisal [1]. The threat to lives and goods is a function of highly local factors, such as water depth, flow rate or the duration of exposition to floods [2]. Two-dimensional shallow water models are considered as a reference approach to the modelling of free surface flows in urban areas. However, the typical size of relevant hydraulic details in the urban environment is 0.1–1 m, which implies using a meshing density of 10^6–10^{10} computational points/cells/elements per square kilometer [3]. While the advent of HR data acquisition means makes geometry characterization increasingly easier [4], using HR models increases the required CPU time. The computational burden may be relieved by using so-called upscaled models, that operate over Low Resolution (LR) grids and provide CPU time gains over 2 to 3 orders of magnitude. In such models, the urban geometry is described in statistical terms, using areal or linear indicators such as porosities [5–7], building coverage ratios or conveyance reduction factors [8, 9]. The price to pay for the increased speed is the subsequent loss in the resolution of the hydraulic flow variables. As mentioned above, this is not compatible with the needs of detailed flood hazard mapping.

Therefore, some form of downscaling is required in order to retrieve HR flow fields or hazard indicators from LR ones. Downscaling is frequently used in the field of climatology and meteorology, see e.g. [10–12]. To our best knowledge, it has emerged only recently in the field of flood hazard mapping.

In [13], a local subgrid model was used to downscale the simulation results of a parallelized, upscaled model. In [14] a global downscaling method was proposed, whereby the HR solution is reconstructed over the entire computational domain using the LR solution over the entire computational domain too. Principal Component Analysis (PCA), also called Proper Orthogonal Decomposition (POD) [15], was used to reduce the complexity of the information in both the HR and LR solutions. The POD features of the HR solution were then downscaled from the POD features of the LR solution using an Artificial Neural Network (ANN). The structure and coefficients of the ANN were optimized by training the ANN over a set of (HR, LR) simulation couples.

This communication presents a local downscaling method that allows HR risk indicators (the water depth or the unit discharge vector) to be reconstructed from LR simulation results. The method is local in space and time, that is, the HR, downscaled variable at a given point of interest is reconstructed as a linear combination of the transformed LR variables in the cells surrounding this point. The proposed approach lies somewhere between [13] and [14] in terms of method complexity. As in [14], the feasibility of the approach is tested under the assumption of perfect upscaling. This paper is organized as follows. Section 1.2 gives an outline of the method, including the HR model, the LR one and the downscaling approach. Section 1.3 presents the results on two types of cases. The first is an idealized urban layout, over which the propagation of 1D flood waves is simulated. The purpose is to determine the amount of training required by the method to achieve a given downscaling accuracy for different flow scenarios. The second test case is a field-scale application reported in [16]. Section 1.4 is devoted to concluding remarks.

1.2 Methods

1.2.1 Upscaling Versus Downscaling

Consider a domain of space Ω over which a HR model is available in the form of a system of differential equations:

$$\mathbf{L}_{\mathrm{HR}}(\mathbf{u}_{\mathrm{HR}}, \varphi_{\mathrm{HR}}) = 0 \tag{1.1}$$

where $\mathbf{L}_{\mathrm{HR}}$ is a differential operator, φ_{HR} is a vector containing the model parameters and $\mathbf{u}_{\mathrm{HR}}$ is the HR flow solution. Upscaling is understood as a filtering problem [17] whereby (1.1) is transformed into an equation in the form:

$$\boldsymbol{L}_{LR}\left(\boldsymbol{u}_{LR}, \boldsymbol{\varphi}_{LR}\right) = 0 \tag{1.2}$$

where the differential operator $\mathbf{L}_{\mathrm{LR}}$, the solution $\mathbf{u}_{\mathrm{LR}}$ and the parameter vector $\boldsymbol{\varphi}_{\mathrm{LR}}$ are defined over a LR space (and possibly time) grid. Downscaling is the reciprocal transformation, whereby (1.2) is used as a starting point to retrieve the elements of (1.1).

There is not a unique way of upscaling the flow model (1.1) into (1.2). Two main paths are available from the literature:

(a) Parameter upscaling: $(\mathbf{L}_{\mathrm{LR}}, \mathbf{u}_{\mathrm{LR}}) = (\mathbf{L}_{\mathrm{HR}}, \mathbf{u}_{\mathrm{HR}})$, $\boldsymbol{\varphi}_{\mathrm{LR}} \neq \boldsymbol{\varphi}_{\mathrm{HR}}$. In this case, the governing equations and the flow variables are identical on both the LR and HR grids, only the parameter vectors are different. This is the case in e.g. groundwater flow modelling, when an equivalent macroscale hydraulic conductivity field is sought from a highly variable one on the microscale. Both HR and LR models use Darcy's flow equation, with the hydraulic head as a state variable, only the hydraulic conductivity differs from the HR to the LR model.

(b) Model upscaling: $\left(\mathbf{L}_{\mathrm{LR}}, \mathbf{u}_{\mathrm{LR}}, \boldsymbol{\varphi}_{\mathrm{LR}}\right) = \left(\mathbf{L}_{\mathrm{HR}}, \mathbf{u}_{\mathrm{HR}}, \boldsymbol{\varphi}_{\mathrm{HR}}\right)$. In this case, the LR and HR governing equations are different, they may operate on different flow variables and the parameters are usually different in both models. An example is that of the Navier–Stokes equations than can be upscaled into Darcy's flow equation using homogenization processes [18].

In the field of free surface flow, the model upscaling approach is the most widely used one, with porosity models and similar approaches [3, 5, 6, 8, 9, 16, 19]. Such models are derived using volume averaging approaches [20] by defining:

$$\langle \mathbf{u} \rangle(\mathbf{x}, \boldsymbol{t}) = \frac{1}{\boldsymbol{D}(\mathbf{x})} \int_{\boldsymbol{D}(\mathbf{x})} \mathbf{u}_{\boldsymbol{HR}}(\mathbf{x}, \boldsymbol{t}) \boldsymbol{dD} \tag{1.3}$$

where **X** is the space coordinate and D(**x**) is an averaging domain centered around **x**. In most finite volume implementations of porosity models, the averaging domain is the LR computational cell. The averaging domains thus form a partition of the solution domain. It should be stressed however that this approach is not the only possible one and that other filters than (1.2) may be used. If the upscaling is perfect, then the LR solution coincides with the exact average (1.3) of the HR variable at all points.

1.2.2 Problem Position

The HR model considered in the present work is the 2-Dimensional (2D) shallow water model:

$$\frac{\partial \mathbf{u}}{\partial t} + \frac{\partial \mathbf{f}}{\partial x} + \frac{\partial \mathbf{g}}{\partial y} = \mathbf{s} \tag{1.4a}$$

$$\mathbf{u} = \begin{bmatrix} h \\ q \\ r \end{bmatrix} \quad \mathbf{f} = \begin{bmatrix} q \\ \frac{q^2}{h} + \frac{1}{2} g h^2 \\ \frac{qr}{h} \end{bmatrix} \quad \mathbf{g} = \begin{bmatrix} r \\ \frac{qr}{h} \\ \frac{r^2}{h} + \frac{1}{2} g h^2 \end{bmatrix} \quad \mathbf{s} = \begin{bmatrix} 0 \\ gh\left(S_{0,x} - S_{f,x}\right) \\ gh\left(S_{0,y} - S_{f,y}\right) \end{bmatrix} \tag{1.4b}$$

where g is the gravitational acceleration, h, q, r are respectively the water depth and the x- and y- unit-discharges, $S_{0,X} = \partial z_b / \partial X$ and $S_{f,X}$ $(X = \{x, y\})$ are respectively the bottom and the energy slope in the X-direction. z_b is the bottom elevation and $S_{f,X}$ is calculated using the Manning formula:

$$S_{f,X} = n_X^2 \left(q^2 + r^2\right)^{1/2} u_X h^{-7/3} \tag{1.5}$$

where n_X (respectively u_X) is the Manning coefficient (respectively the velocity) in the X-direction. The shallow water model is solved using a classical explicit finite volume algorithm [21]. The upscaled solution is obtained from a perfect upscaling procedure, that is, by taking the LR upscaled variable equal to the average of the HR one over each cell of the finite volume LR grid:

$$\mathbf{u}_{LR}(\mathbf{x}, t) = \langle \mathbf{u} \rangle_i (\mathbf{x}, t) = \frac{1}{\Omega_i} \int_{\Omega_i} \mathbf{u}_{\mathrm{HR}}(\mathbf{x}, t) d\Omega_i \quad \text{for} \quad \mathbf{x} \in \Omega_i \tag{1.6}$$

where Ω_i is the ith computational cell in the model.

The objective of the present work is to derive HR flood hazard indicators using only the LR solution defined by Eq. (1.6). The flood hazard indicators retained in the present study are the same as in [14]: the water depth and the norm of the unit discharge are considered as two widespread danger indicators [22] [23]. A hazard variable vector $\boldsymbol{\psi} = [h, \boldsymbol{\theta}]^T = \boldsymbol{\psi}(\mathbf{u})$ is thus defined as in [14], where $\mathbf{q} = [q, r]^T$ is the unit discharge vector. The purpose is thus to derive the HR hazard indicator from the LR one. Note that Eq. (1.6) cannot be applied directly to the norm of the unit discharge because the norm of the unit discharge is not a conserved variable. The following formula is used instead:

$$\boldsymbol{q}_{LR} = \left(q_{LR}^2 + r_{LR}^2\right)^{1/2} \tag{1.7}$$

where q_{LR} and r_{LR} are computed using(1.6).

1.2.3 Proposed Downscaling Approach

The proposed downscaling formulae are based on the following principle. Assume that the kth component $\psi_{\mathrm{HR}}^{(k)}$ of the HR hazard variable vector $\boldsymbol{\psi}$ is sought at the location $\mathbf{x}$ at time t. It is computed using the LR hazard variables over a limited number of cells of the LR mesh. Let $\psi_{LRi}^{(k)}$ be the value of the kth component of the LR hazard variable (here $k = 1, 2$) over the ith cell of the LR grid. Denoting by N_k the set of neighbouring LR cells used in the downscaling reconstruction, the following linear combination is proposed:

$$\left(\psi_{HR}^{(k)}\right)^{p_k}(x, t) = \sum_{i \in N_k} \alpha_i^{(k)} \left(\psi_{LRi}^{(k)}\right)^{p_k} \tag{1.8a}$$

$$N_k = N_k(\mathbf{x}),\ p_k = p_k(\mathbf{x}),\ \alpha_i^{(k)} = \alpha_i^{(k)}(\mathbf{x}) \tag{1.8b}$$

where p_k is a positive power performing a non-linear transformation and the $\alpha_i^{(k)}$ are weights. As specified by Eq. (1.8b), the size of the neighbourhood (i.e. the set of LR cells used to reconstruct the HR risk indicator), the weights and the power in the reconstruction formula are all functions of the hazard variable to be reconstructed (for instance reconstructing h does not necessarily require the same number of cells as reconstructing $\mathbf{q}$). Moreover, they also depend on the location $\mathbf{x}$ of the HR hazard variable to be reconstructed. The degrees of freedom in the formula are the size $N_k(\mathbf{x})$ of the neighbourhood, the $N_k(\mathbf{x})$ weights and the power $p_k(\mathbf{x})$.

The optimal values for these $N_k(\mathbf{x}) + 2$ degrees of freedom are found by minimizing the difference (i.e. the modelling error) between the reconstructed hazard variable $\psi_{\mathrm{HR}}^{(k)}$ and its exact value $\psi^{(k)}(\mathbf{u}_{\mathrm{HR}})$ computed from the known HR variable

$\mathbf{u}_{\mathrm{HR}}$. The error for the kth component of the hazard indicator vector is thus location-dependent. Its root mean squared average over time is the objective function to be minimized via the optimization procedure:

$$E^{(k)}(\mathbf{x}) = \left(\frac{1}{T}\int_0^T \left(\psi_{HR}^{(k)}(\mathbf{x},t) - \psi^{(k)}(\mathbf{u}_{HR}(\mathbf{x},t))\right)^2 dt\right)^{1/2} \tag{1.9}$$

where $[0, T]$ is the time interval.

1.2.4 Training Sequence

Prior to training, a number of HR simulations with various combinations of initial and boundary conditions are carried out over a given computational domain Ω over a time interval $[0, T]$. For each simulation, an HR solution $\mathbf{u}_{\mathrm{HR}}(\mathbf{x}, t)$ is thus available over the $\Omega \times [0, T]$ space–time domain. Each HR solution is averaged into a LR solution $\mathbf{u}_{\mathrm{LR}}(\mathbf{x}, t)$ over a coarse grid using Eq. (1.6). Therefore, for every simulation, a pair $\left(\boldsymbol{\psi}_{\mathrm{HR}}(\mathbf{x}, t), \boldsymbol{\psi}_{\mathrm{LR}}(\mathbf{x}, t)\right)$ of HR and LR hazard vectors is available over $\Omega \times [0, T]$. These are divided into three sets (Fig. 1.1): a calibration, validation and training sets, the roles of which are detailed hereafter.

The model operation sequence is the following.

Step 1:For each HR hazard variable to be reconstructed at a given location $\mathbf{x}$, a number of possible neighbourhood sizes are proposed.

Substep 1.1 (calibration): for every neighbourhood size, the reconstruction formula (1.8a) is calibrated by minimizing the error given by Equation (1.9).
Substep 1.2 (validation): for each neighbourhood size, the calibrated reconstruction formula (1.8a) is run over the validation set. The validation performance is evaluated by computing the modelling error as in Eq. (1.9).

Step 2 (operational use): The neighbourhood size N_k that gives the smallest validation error is retained.

Substep 2.1: the coefficients $\left(p_k, \alpha_i^{(k)}\right)$ are calibrated again using both the calibration and validation sets.
Substep 2.2: the predictive performance of the model is evaluated using the modelling error as given by Eq. (1.9).

1.3 Results

The proposed downscaling approach is tested on two different configurations: a synthetic urban layout and a real-world test case.

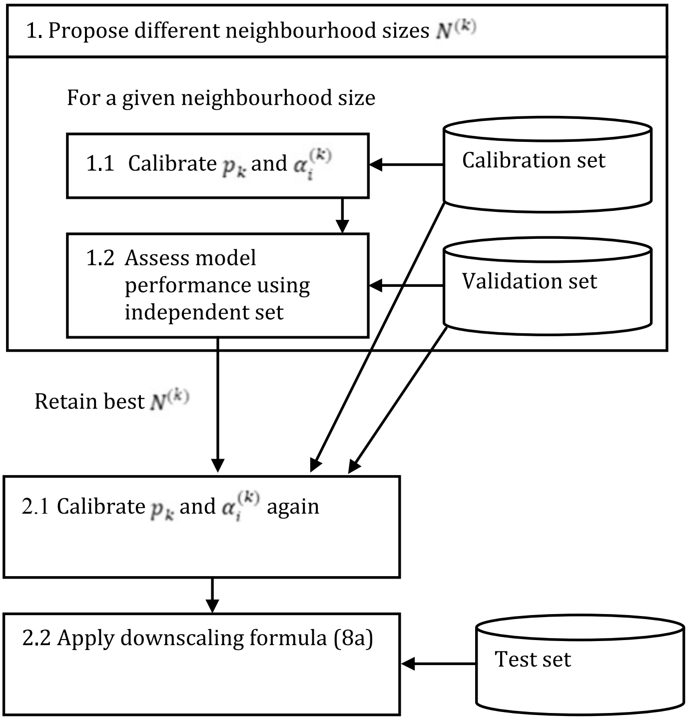

Fig. 1.1 Definition sketch for method training and testing

1.3.1 Idealized Urban Layout

1.3.1.1 Test Case Description

An idealized urban layout configuration is used to assess the ability of the proposed downscaling approach to reconstruct the hydrodynamic variables with a high resolution using the low-resolution results. The geometry is made of a main street bounded by dead-end lateral streets (see Fig. 1.2). The reconstruction method is tested over three crossroads at the middle of the main street and close to the upstream and downstream end.

In the present paper, the bottom elevation is horizontal and the friction is neglected for all the tested configurations. Initially, the water surface elevation z_0 is constant and the velocity is nil over the whole domain. At $t = 0$, the free surface elevation at the left (respectively right) boundary condition is set to z_L (respectively z_R), the other one being kept to z_0. The free surface elevation at the "perturbed" boundary conditions is denoted z_{BC} (correspond to z_L or z_R depending on the test case). This allows to generate different types of waves (rarefaction if $z_{BC} < z_0$; shock if $z_{BC} > z_0$) travelling through the domain from the left to the right boundary conditions (and

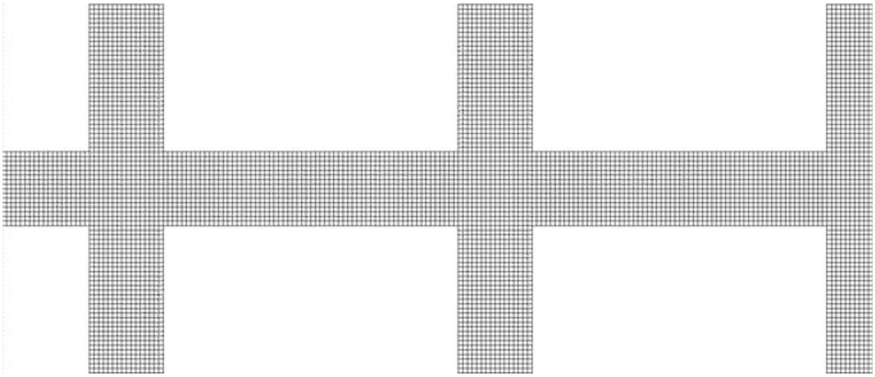

Fig. 1.2 Representation of the idealized urban layout. The represented mesh is the fine one. For the sake of readability, only 3 crossroads over 20 are represented

inversely). The different configurations are summarized in the Fig. 1.3. The triangles (respectively the diamonds) represent the simulation defining the calibration (respectively validation) set. The hydraulic configurations for the test simulations (represented by the circles) are located outside the range of the training domain. The simulation naming is composed of two letters: the first one represents the wave configuration (S for shock wave, R for rarefaction wave); the second letter identifies boundary/initial conditions combination. Simulations a–j (respectively k–t) represent waves travelling from left to right (respectively right to left). The proposed downscaling method is expected to be able to reconstruct the hydrodynamic variables from the LR results on the fine grid including for hydraulic configurations beyond the training domain.

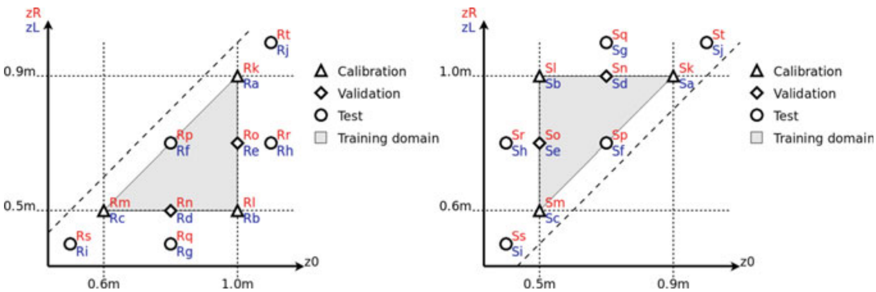

Fig. 1.3 Representation of the tested hydraulic configurations. Left: rarefaction wave, Right: shock wave

1.3.1.2 Influence of the Wave Configuration

This test case investigates the variability of the wave configuration (either shock or rarefaction) that should be represented in the learning set to allow a correct downscaling in any wave configuration. For the sake of simplicity, the considered configurations represent only waves from the left to the right side. Three different combinations of the simulations between the different sets are compared (see Table 1.1). The test set 1 includes hydraulic configurations corresponding to the learning set whereas test set 2 regroups voluntarily "unknown" hydraulics configurations as they were not represented in the learning set. The reconstructed results are expected to be closer form the reference for test Set 1. Test set 2 allows to assess the importance of having a learning set that is as exhaustive as possible.

Figure 1.4 presents the size of the optimal neighbourhood to reconstruct the water depth for combinations R and S. It is recalled that the tested neighbourhood sizes are $N(i) = \{3, 5, 7, 9, 11\}$. The optimal neighbourhood size appears to be smaller when the simulations combination includes shock wave. Smaller neighbourhood is coherent with the discontinuities that appears in case of shock waves. Interestingly, the wave configuration appears to have no significant impact on the optimal neighbourhood size to reconstruct the unit-discharge norm. The optimal size of the neighbourhood also evolves along the street axis. In all the tested configurations, the simulation duration allows the wave to travel through the three represented crossroads. However, the reconstruction coefficients are constant in time. This implies

Table 1.1 Tested repartitions of the simulations to investigate the influence of the wave configuration

Combination	Calibration set	Validation set	Test set 1	Test set 2
Comb. R	Ra Rb Rc	Rd Re	Rf Rg Rh Ri Rj	Sf Sg Sh Si Sj
Comb. S	Sa Sb Sc	Sd Se	Sf Sg Sh Si Sj	Rf Rg Rh Ri Rj
Comb. R + S	Ra Rb Rc Sa Sb Sc	Rd Re Sd Se	Rf Rg Rh Ri Rj Sf Sg Sh Si Sj	

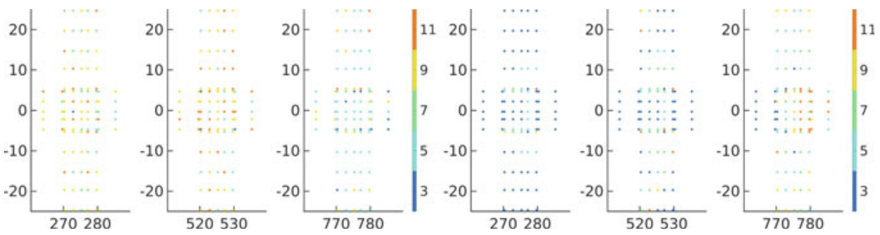

Fig. 1.4 Distribution of the optimal neighbourhood size to reconstruct the water depth. Left: Combination R; Right: combination S. The graphs axis represents the spatial coordinate: the crossroad around the coordinate 275 m (respectively 525 m and 775 m) is the 6th (respectively 11th and 16th) crossroad after the beginning of the model (see Fig. 1.2)