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Philippe Gourbesville
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Advances in Hydroinformatics

SIMHYDRO 2012 – New Frontiers of Simulation

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SIMHYDRO 2012 – New Frontiers of Simulation

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Preface

Modeling 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. The emerging environment populated with new generation of sensors, using cloud computing resources, is challenging the current practices of modeling and request innovation in methodology and concepts for a real integration into the decision-makings processes.

With respect to these issues, however, still a number of questions remain open: coupling of models, data acquisition and management, uncertainties, use of 3D CFD, models for complex phenomena, and for large-scale problems. All those points are continuously explored and investigated by researchers, scientist, and engineers. Like in all scientific domains, most recent and advanced developments have to be discussed and shared. The SimHydro 2012 conference contributes to this work by providing a platform exchanges and discussion for the different actors of the water domain.

SimHydro is a permanent cycle of conferences held every 2 years, hosted by Polytech'Nice Sophia Antipolis and organized by the Société Hydrotechnique de France (SHF) and its European partners. It aims, as the subject, recent advances in modeling and hydroinformatics and at the participation and exchanges at European scale (it is open for all other researchers and participants but the purpose is to maintain a specific platform for the region that was a birthplace of both domain). That is why the SimHydro language is English.

The latest SimHydro conference was held in Sophia Antipolis, France, from 12 to 14 September 2012. The conference was jointly organized by the SHF, the Association Française de Mécanique (AFM) and the University of Nice Sophia Antipolis/Polytech Nice Sophia and with the support of IAHR, Eau, and DREAM clusters. The conference has attracted 171 delegates from 38 (although most of them European) countries and who have participated in 14 sessions where 86 papers have been presented. The program was organized around three main themes:

- New trends in modeling for marine, river, and urban hydraulics;
- Stakeholders and practitioners of simulation;
- 3D CFD and applications.

Within (?) these general themes, topics like coupling of models, data assimilation and uncertainties, urban flooding, data and uncertainties in hydraulic modeling, model efficiency and real situations, new methods for numerical models, hydraulic machinery, 3D flows in the near field of structure, and models for complex phenomena have been covered. The conference, by attracting researchers, engineers and decision makers, has promoted and facilitated the dialog between communities with round tables where needs and expectations have been discussed. Exchanges have been very fruitful on crucial questions related to sources of uncertainty in modeling, the state-of-the-art in research and development in domain of numerical fluid mechanics, the stakeholder's capacity to understand results, the means for dialog directly or indirectly between the stakeholders and the model developers, the information's exchange between stakeholders and developers.

In order to contribute to this dialog and to provide useful references, the organizers of SimHydro 2012 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 to the reader a global overview on the on-going developments and the state-of-the-art taking place in three major themes which are:

- The data and uncertainties in hydraulic modeling for engineering and some specific applications of modeling;
- The new numerical methods and approaches for modeling systems;
- 3D computational fluid dynamics and applications.

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 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, scientist, engineers, and managers alike.

Sophia Antipolis, October 2012

Philippe Gourbesville
Jean Cunge
Guy Caignaert

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Data and Uncertainties in Hydraulic Modeling for Engineering, Specific Applications of Modeling

Introduction to Part I: Data and Uncertainties in Hydraulic Modelling for Engineering, Specific Applications of Modelling

Philippe Gourbesville, Jean Cunge and Guy Caignaert

In this first part, it gathers a global overview of the ongoing developments and applications of hydroinformatics tools and methods in engineering projects. The various chapters provide to the reader a good idea about the various methodologies applied today to investigate some complex phenomena which have to be carefully understood during engineering projects. Most of the applications are based on numerical models which are currently widely used and applied within projects. However, as underlined and demonstrated by Jean Cunge in the first introductive chapter, it is essential to keep in mind the reality of the physical processes that we try to represent with our models and which reflect only a partial dimension of the complex reality under a specific set of conditions. The chapters in Part I show how models could be properly implemented and may provide relevant results.

A major emerging field for hydroinformatics is linked to the assessment in real time of the status of a hydrosystem. Irrigation networks, water distribution systems, and rivers are complex systems which request a constant monitoring and control in order to ensure efficiency and safety in the case of flood warning issue for example. The data mining and control methods, initiated mainly in the industrial domain, have massively invaded the water domain and are today integrated within the systems which are applied for real-time operations. This trend is constantly supported by the growing performances and the availability of the computing resources. The possibilities offered by the parallel computing and the access to high-performance computing resources allow today to run in real time

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some of the most sophisticated deterministic models, which can assist the decision-making process. At the same time, the new facilities do not solve all difficulties and the difficult issues of the uncertainty remain a central question for all applications. In the chapter, different approaches are presented in order to quantify uncertainties and to express them to public. This last point still represents a major challenge for the engineering community which has to communicate to the public on sensitive subject like dam break.

If the numerical models are widely used and performed in many engineering project, some specific cases may request the use of physical and scale models. The complexity of processes especially when physical processes like sediment transport are involved represents a limit of the existing deterministic models and is associated with a large uncertainty. The physical experiment associated with the numerical simulations may significantly help to improve the quality of the simulations by reducing the uncertainty. This type of approach represents a sector where progresses and experiments could support the efficiency of the models. In a similar way, the coupling of models—1D and 2D—demonstrates a clear improvement of results. However, if this approach is being now more and more applied, there is a need to work on the definition of the exchange terms between the two types of models.

The urban domain with the associated water services represents clearly a new frontier for the development of a new generation of hydroinformatics systems which have to be able to integrate a wide range of aspects like the data collection—sensor networks—the decision-making process, and the public awareness. The growing complexity of the urban environment characterized with the densification process and the need of secured services requests the development of a global information system where hydroinformatics elements have to be integrated. Several applications presented in different chapters demonstrate this emerging trend. The availability of sensors and the implementation of monitoring networks will bring in a flow of data in quantities of few orders of magnitude greater than they have existed up to now and that has to be managed. Acquisition, analysis, and storage are some of the new challenges which request new developments. These subjects, introduced by the new generation of devices and by the availability of data, will drive to review some of the actual paradigms and will lead to question of the very concept of what is information. Quality and sustainability of data will become essential issues which have to be answered with the global integration in the information system. At the same time, the water–energy nexus is also appearing especially when optimization is requested to perform some pumping and distribution operations. This link between water and energy represents, for sure, one of the directions where new developments will take place.

What Do We Model? What Results Do We Get? An Anatomy of Modelling Systems Foundations

Jean A. Cunge

Abstract The chapter is a reminder, a follow-up of the road-map that leads from observation of natural situation to colourful presentation of results of modelling that are supplied to the user and decision makers. It is unfortunate matter of fact that too many people involved in modelling do not know how the very heart of the software they use was conceived and on what physical and mathematical hypotheses it is based. Most of the users do not realise what are the limitations in the validity of the results that may be traced back to the limitations of the stages of this road-map. Using as the departure point and an example 1D modelling, the chapter describes and, up to a point, lists the chain of intellectual activities that can be summarised as follows: observation of the nature (flow); hypotheses concerning main physical phenomena; formulation of physical laws (e.g. conservation laws) for isolated systems where only these phenomena exist; mathematical formulation of these laws (differential, integral, etc., equations); parameterisation of phenomena not described by equations; impossibility to solve the equations; numerical algorithms solutions of which converge to those of equations; interpretation of parameters and approximate solutions obtained from algorithms; interpretation of results. The purpose is to let the users of commercial software to understand how the very heart of the modelling system they use was conceived and why the validity of the results obtained in the end is limited by the hypotheses of the original concept. In conclusions, the following question is put to the reader: can a modeller who is not sufficiently knowledgeable about all the links of this chain tell his "client" what are possible doubts or deviations between what was just simulated and the reality?

Keywords Numerical simulation · Computational hydraulics · De Saint–Venant hypotheses · Numerical solutions · Results of modelling and hypotheses of equations

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1 Introduction

When use of numerical simulation in hydraulics or, in much larger area of water industry and management is considered, one may in legitimate way ask oneself the question: what should a modeller, a user of a commercial modelling software, know about the very heart of it, that is, about how the basic knowledge of physics has been represented in the software he uses and resulted in output pictures he sees (or forwards to his client) on the screen? There are the notions that are introduced in the debate that the present author considers as possibly dangerous if not well understood. One of those is the notion introduced into the hydro technical world by Abbott [1, 2] that there are groups of knowledge providers and knowledge consumers. Unless really well understood (and this asks for careful reading and analysing of the description of these terms in the chapters refereed to), the quick and widely spread conclusion is that the knowledge necessary to model is encapsulated in the software and there is no problem anymore: anybody can model anything with the bought software system. Coming back to knowledge providers and knowledge consumers, the distinction which is supposed to characterise our society, it would be better to talk about technology providers and consumers. Consider an analogy between modeller using commercial software and a car driver. 99 % car drivers in the world have no slightest idea of physical phenomena going in their engine under the bonnet. They have been provided an encapsulated technology package and immense majority of them do not know the principles of explosion engine or diesel one. They learned how to drive but know nothing about scientific and industrial developments that led to this technology and, with a country-dependent variable percentage of killed on the roads, most of drivers are still here, in-spite being knowledge ignoramus. The user is a consumer of the technology that was encapsulated and provided to him by Volkswagen or whatever. I do not feel that he is a knowledge consumer—he has no access to knowledge under any shape to be consumed. It is true that if his ignorance leads to wrong use of this technology, generally the damages are limited (if he runs into a tree) although can be dramatic for limited number of others (if he provokes a head-on collision with other car). The situation is very different with modelling software systems because the modelling results are being used to most important decision concerning investments, structures, management of water systems, etc. Except for very simple situations, a user of modelling software must be indeed knowledgeable about basic hypotheses and physical laws lying as foundations of the software as well as of the methods encapsulated in it. And it can happen that a user of such software who is a technology consumer in the above-described sense of the term, employing the technology "encapsulated" by the "provider", supplies the results and conclusions that provoke, in turn, a catastrophe.

In what follows we shall describe holistically some aspects of one specific area of such "encapsulation" and for one limited class of phenomena only. It concerns the chain of knowledge acquisition and application that leads a creator of the software simulation system to achieve its development. The class of problems taken as example is essentially one-dimensional unsteady free-surface fixed-bed channel flow. In conclusions, we shall repeat the following question to the reader: can a modeller who is not knowledgeable about all the links of this chain tell his “client” what are possible doubts or deviations between what was just simulated and the reality?

2 Chain of Concepts and Steps Leading from Hypotheses to Results

2.1 Observation of the Nature (Flow): Hypotheses Concerning Main Physical Phenomena

Observation of the flow in any natural or even artificial stream, especially during flood, leads to the conclusion of incredible complexity of details next to impossible to understand or to describe. However, if the local detailed small scale is replaced by the scale of several hundred metres or more the main ideas are obvious: the flow has one privileged direction, the water is subject to gravity forces and also to inertia forces and there certainly exists a resistance to the flow causing energy dissipation. Moreover, our interest (should we say engineering or macroscopic?) is mainly in knowing what is the free-surface elevation (stage) and discharge along the observed reach and not in details. Since the area of the wetted cross section A is defined by the water stage y (depth h) then, if the flow has a privileged direction, it is useful to imagine brutal simplification that the water velocity is also directed along this axis. In other words, one assumes that the longitudinal velocity u is so important with respect to the transversal one than the latter can be neglected. Rough observation shows that water velocity at a given point does not vary much with the depth and, if the cross section is compact and the width reasonable, that the elevation of the free surface across the stream does not vary much neither. These observations led De Saint–Venant to the set of basic hypotheses that are very far from reality but which nevertheless concern essence of phenomena of engineering interest and decisive to overall description of the flow. The hypotheses are listed in the sequel and it is obvious that they can be true only for an idealised situation (Fig. 1):

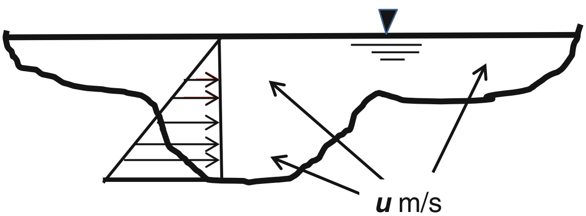

Fig. 1 De Saint–Venant hypotheses

1. Uniform longitudinal velocity u at every point of the cross section.
2. Transversal free surface at any section horizontal.
3. Hydrostatic pressure distribution along each vertical.
4. Head losses can be represented by Chèzy-type formula valid in steady flow.

2.2 Formulation of Physical Laws (e.g., Conservation Laws) for Isolated Systems Where Only These Phenomena Exist: Mathematical Formulation of These Laws (Differential, Integral, etc., Equations)

The simplified, idealised situation is concerned: a flow along inclined channel of constant slope and a cross section $A(y)$. A classic approach is to analyse a control volume contained spatially 'between two verticals distant Δx one from another and temporarily between two instants separated by time Δt. The control volume is supposed to be an isolated system between two cross sections distant Δx and between two instants separated by the time Δt volume of water of which (with balance due to inflow and outflow) as well as the energy must be conserved. These two conservation laws are the foundation from which it is possible to draw mathematical equations. For the volume, it is obvious: if during time interval Δt there is more water discharge Q inflowing into the control module then outflowing, then the elevation y and cross section A will increase. For the energy, because of its dissipation, the sum of potential and kinetic energies decreases over the distance Δx and varies with time. The kinetic energy is expressed in terms of time and space variations of section-constant velocity $u = Q/A$. The decrease in the total energy is equal to its dissipation over the distance Δx. Assuming that ($\Delta x \rightarrow 0$; $\Delta t \rightarrow 0$) one obtains two equations known as De Saint–Venant equations:

Conservation of the volume within an infinitely short control volume:

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0; \quad Q = uA; \ A = A(y) \tag{1}$$

And conservation of the energy within this volume:

$$\frac{1}{g}\left\{\frac{\partial u}{\partial t} + \frac{\partial}{\partial x}\left[\frac{u^2}{2}\right]\right\} + \frac{\partial y}{\partial x} = Ku|u| \tag{2}$$

where $K = K(n, h)$, h = depth, n = empirical parameter of energy dissipation (or resistance to the flow).

2.3 Parameterisation of Phenomena Not Described by Equations

Antoine Chézy was the first one to note that in a long channel of constant slope the "initial flow velocity …diminishes or augments rapidly enough to reduce to a uniform and constant velocity which is due to the slope of the channel and to gravity, of which effect is restrained by the resistance of *friction* against the channel boundaries". And further on: "…velocity due to gravity…is only uniform when it no longer accelerates, and gravity does not cease to accelerate except when its action upon the water is equal to the resistance occasioned by the boundary of the channel; but the resistance is as the square of the velocity because of the number and the force of the particles colliding at the given time; it is also a part of the perimeter of the section of the flow which touches the boundary of the channel" [3]. Everything is said. Chézy used the *concept* of friction analogy to describe the energy dissipation: there is a resistance (energy dissipation) that until today we do not know how to formalise its exact mechanism (which is the turbulence). Its scale and complexity are not in proportion with our purpose: to describe the flow over "engineering" length. Hence, the need to parameterise these complex mechanisms keeping essential factors in: resistance is proportional to the square of the velocity and to the wetted perimeter or, inversely, the velocity u is proportional to the square root of the slope S and hydraulic radius R. This is the Chézy formula:

$$u = k\sqrt{SR} \tag{3}$$

Note that the coefficient k is the parameter that replaces the description of the process of energy dissipation (something we still cannot pretend to know well and to be able to formulate correctly). Note also that while in De Saint–Venant equations k is the only one empirical and subjective parameter, the Chézy formula (and then its follow-ups such as Manning or Strickler formulas) is valid but for steady-state flow. Thus, De Saint–Venant hypothesis that "the resistance law is the same as for steady-state flow" may in certain situations be questionable.

2.4 Impossibility to Solve the Equations and Conditions of Existence of the Solutions

To solve the problem as stated by De Saint–Venant means to find two *continuous differentiable* functions of independent variables $u(\mathrm{x}, \mathrm{t})$ and $y(\mathrm{x}, \mathrm{t})$ satisfying Eqs. (1) and (2). It must be kept in mind of a modeller that such *solution would be the description of the situation limited by the hypotheses and not the full description of real-life flow*. Hence, it is not possible to expect from the solution anything more (e.g., nonuniform velocity repartition, information on transversal slope of free-surface or transversal velocity component). Moreover, we cannot solve these two equations. Indeed, the two De Saint–Venant equations are a system of two non-linear partial differential equations of hyperbolic type. The problem is that mathematics do not know how to solve *exactly* such equations. If we consider a simple partial differential equation such as:

$$\frac{\partial f}{\partial t} + a\frac{\partial f}{\partial x} = 0; \quad f(x,0) = f_0(x), \ -\infty < x < +\infty \tag{4}$$

then we know that there exists exact, "analytical" solution for this equation:

$$f(x,t) = f_0(x - at) \tag{5}$$

But for De Saint–Venant equations such solution is not available has not been found by mathematicians. Let us consider a space (*x, t*) and half space of it $t > 0$. Then, it has been proved that *if* there exist initial conditions smooth enough, that is, if at the time $t = 0$, there do exist functions $u(x, 0)$ and $y(x, 0)$ *and* their derivatives, then the *existence* of solutions for some time interval $0 < t < T$ can be proved. This is what we call the *initial well-posed problem*: we know that solution exists but we cannot find it under exact closed form. Hence, there is necessary to seek an approximate (numerical) solution. Situation is even more complicated when finite length of the stream is considered (*x* segment is $x_0 < x < x_L$). It is still possible to prove that the solution exists for $0 < t < T$ within these space limits but the *mixed problem* (initial and boundary conditions) must be well posed. That means that appropriate boundary conditions and continuous solutions of Eqs. (1) and (2) must be given at the boundaries $x = x_0$ and $x = x_L$ for all $t > 0$. The case of unsteady subcritical flow and upstream boundary condition provides an illustration of the fact that things are not as simple as they may look or be presented. While imposing $u(x_0, t)$ or $y(x_0, t)$ corresponds to well-posed problem, it can be proved that imposing a rating curve $Q(y)$ at the upstream boundary $x = x_0$ makes the bounded solution of the problem impossible while the same type of condition (rating curve) at the downstream boundary $x = x_L$ is correct from mathematical point of view. Note, however, that in hydrology practice rating curve function $Q(y)$ is typically single valued and, hence, it corresponds to a *steady*-state flow. When such rating curve is the downstream-imposed boundary condition, it introduces errors to the solution of the *unsteady* flow Eqs. (1) and (2). In other words, the solution with such downstream boundary condition does exist, but in fact, it is not the solution of the original equations! The conclusion and warning is that the Eqs. (1) and (2) alone do not suffice our purpose even if we assume that reality obeys De Saint–Venant hypotheses: the initial and boundary conditions formulated in terms of the independent variables $u(x, t)$ and/or $y(x, t)$ make integral part of the problem that is known as a *mixed* (initial and boundary values) *Cauchy problem*. And, again, it is not the solution that we can find but only conditions of its existence.

2.5 Numerical Algorithms Solutions of Which Converge to Those of the Equations

In order to deal with the difficulty, we have to *replace* Eqs. (1) and (2) and their boundary conditions by some other systems that we *can* solve. This may be justified only if we can prove that the solutions of such surrogate systems are not very far from the solutions of original equations—those are what we called approximate numerical solutions.

Since we wish only to point out to the conceptual track of creation of the heart of modelling systems, we shall here limit ourselves to just one of various numerical methods of approximation, namely the finite difference methods (FDM). The FDM of integration of systems of differential, integro-differential or integral equations of mathematical physics consist in transformation of derivatives into difference ratios and of integrals into the summations. In practice that means a transfer from the infinite space of functions of continuous arguments to the finite space of grid-functions and transformation of the equations of continuous functions into algebraic equations for which exist numerical methods to find approximate solution.

Note the original equations are replaced by algebraic equations, and then, the latter are solved approximately. Two questions are to be answered:

- Is the system of algebraic equations well posed, that is, can it be solved even approximately?
- How to be sure that after such double stage the approximate solution of algebraic systems is not too "far" from the analytical solutions (which cannot be found) of the original systems. And is it possible to reduce the difference between the two?

The grid-functions are the networks or grids of enumerable computational points and *the approximate solutions are sought at these discrete points*. Such approach is convenient in practice, but it introduces difficulties to prove mathematically the convergence of the FDM results to those of the original equations because the approximating grid functions (solution of FDM) and continuous approximated functions (solution of differential equations) are defined in different spaces having different norms. Using more descriptive approach to the problem, consider as in Fig. 2 a grid of computational points distant Δx_i one from another and the Δt_n time intervals for which the solution is sought. Suppose that indeed the unknown values of originally sought continuous functions $u(x, t)$ and $y(x, t)$ are approximated at grid points by FDM approximations $\tilde{u}(x_i, t_n)$, $\tilde{y}(x_i, t_n)$. Suppose now that we refine space grid by using new distance $\Delta x_k = 0.5\ \Delta x_i$. Then, new solution at grid points would be obtained: $\{\hat{u}(x_k, t_n), \hat{y}(x_k, t_n)\}$.

Then, the following questions become legitimate:

1. What is the difference between the solutions $\{u(x, t), y(x, t)\}$ and $\{(x_i, t_n)\tilde{y}(x_i, t_n)\}$?
2. What is the difference between the solutions $\{\hat{u}(x_k, t_n)\tilde{y}(x_{k'}, t_n)\}$ and $\{(x_i, t_n)\tilde{y}(x_i, t_n)\}$?
3. Is the solution $\{(x_k, t_n)\tilde{y}(x_k, t_n)\}$ "better" than the solution $\{\tilde{u}(x_i, t_n)\tilde{y}(x_i, t_n)\}$?
4. What means "better"?

Note the reasoning and criteria of being better or not should be with respect to the solutions of the original equations. The results obtained are considered as better or worse not in comparing them with the reality but with the unknown solutions of differential equations.

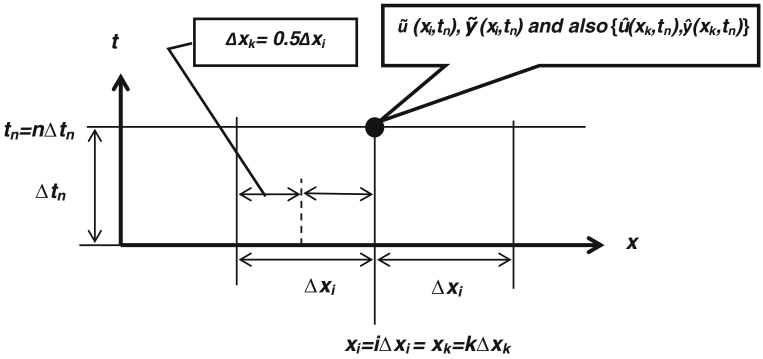

Fig. 2 Grid of computational points

There is no direct way to answer question (1) The question (2) can be answered by running two computations, one with Δx_i and other with $\Delta x_k = 0.5\ \Delta x_i$. But to answer question (3), it is necessary to answer the question (4) first: if one reduces the computational steps dividing them by 2, are approximate solutions converge to the analytical solutions?

The answer is that in general case *it is not true*. To clarify this point, one must take into consideration the way the derivatives in original equations were approximate by finite differences and, hence, how the differential equations themselves were replaced by difference algebraic equations.

Consider simple (as compared with De Saint–Venant Eqs. (1)and (2)) case and the grid (i, n) as in Fig. 2:

$$\frac{\partial f}{\partial t} + \frac{\partial f}{\partial x} = 0; \tag{6}$$

The derivatives can be approximate in various ways for time and space derivatives, for example,

$$\frac{\partial f}{\partial t} \approx \frac{f_i^{n+1} - f_i^n}{\Delta t_n}; \quad \frac{\partial f}{\partial t} \approx \frac{f_i^{n+1} - 0.5(f_{i+1}^n + f_{i-1}^n)}{\Delta t_n}; \tag{7}$$

$$\frac{\partial f}{\partial x} \approx \frac{f_{i+1}^n - f_{i-1}^n}{2\Delta x_i}; \quad \frac{\partial f}{\partial x} \approx \frac{f_{i+1}^n - f_i^n}{\Delta x_i}; \quad \frac{\partial f}{\partial x} \approx \frac{f_i^n - f_{i-1}^n}{\Delta x_i}; \tag{8}$$

Developing grid-functions Eqs. (6), (7) in Taylor series around (i, n) point and substituting in Eq. (6) one finds that differential form Eq. (6) is replaced by a finite difference equation. The unknown values f^{n+1} for each point x_i $i = 1, 2,\ldots,L$ can be then computed with orders of truncation error such as Δx, Δx^2, Δt, Δt^2, or with ratios of these time or space steps. That means that the approximation is each time *consistent* because when $(\Delta x, \Delta t) \rightarrow 0$ then the finite difference equation will tend towards differential form of Eq. (6). *But to maintain the degree of consistent* *approximation for each case, both Δx* and *Δt must decrease simultaneously and their ratio such as appearing in finite difference equation must be kept constant during this process.* Another important problem is *numerical stability* of the finite difference scheme. For example, the use of the first time approximation of Eq. (7) and of the first space approximation of Eq. (8) leads to absolutely unstable numerically finite difference scheme and no valid results for f^{n+1} at point I can be obtained.

The finite difference solution found at the computational grid points *would converge to the solution of the differential equations they approximate but under certain conditions*: the approximation must be consistent, the finite difference scheme must be stable and both differential and finite difference problems must be well posed (including boundary and initial conditions). And if the convergence is thought numerically by repeating computations while refining computational grid (Δx, Δt) $\rightarrow 0$ then the successive computations must maintain the relationship between Δx and Δt obtained from consistent approximation. Now, we can answer the question of grid refining as shown in Fig. 2, namely: if the time step is divided by 2, will the results better? From the computational point of view, no! Indeed the time step should be reduced at the same time in order to maintain consistency of approximation. However, it is obvious that reduce the space step should improve topography representation in our model if the topography is introduced again in new details and this may well be essential.

As illustration of the fact that consistency of the scheme with equation is not enough to ensure the convergence consider the following example [4]. Let the partial differential Eq. (6) with the forward-space consistent scheme:

$$\frac{f_i^{n+1} - f_i^n}{\Delta t_n} + \frac{f_{i+1}^n - f_i^n}{\Delta x_i} = 0 \quad \rightarrow \quad f_i^{n+1} = \left(1 + \frac{\Delta t_n}{\Delta x_i}\right) f_i^n - \frac{\Delta t_n}{\Delta x_i} f_{i+1}^n; \tag{9}$$

Note that the finite difference scheme is consistent with differential equation but numerically unstable.

As initial conditions for the *differential* equation, we take

$$\text{If } -1 \leq x \leq 0,\ f_0(x) = 1; \quad \text{elsewhere } f_0(x) = 0;$$

The solution of the partial differential equation is a shift of f_0 to the right by t. In particular, for t greater than 0, there are positive values of x for which $f(t, x)$ is nonzero. This is illustrated in Fig. 3. Let us take for difference scheme the initial data as:

$$f_i^0 = 1 \quad for\ -1 \leq i\Delta x \leq 0; \quad f_i^0 = 0\ elsewhere$$

Equation (9) shows that the values of grid-function f_i^{n+1} for $\Delta t/\Delta x = 1$, for $n > 0$ and $i > 0$ will always be zero. Hence, the computed values of grid-function *will never converge* towards the solution of differential equation although the finite difference scheme is consistent with this equation.

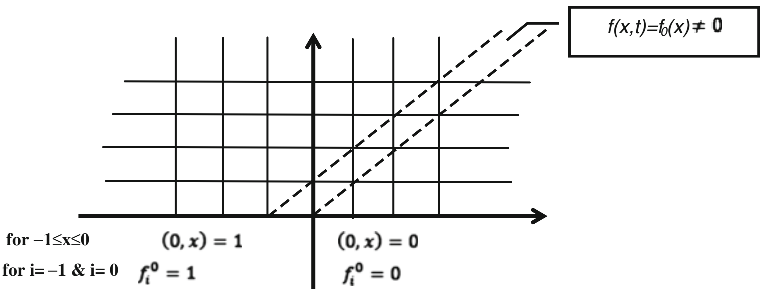

Fig. 3 Consistency alone does not imply convergence

But if instead Eq. (9), the following consistent approximation is considered:

$$\frac{f_i^{n+1} - f_i^n}{\Delta t_n} + \frac{f_i^n - f_{i-1}^n}{\Delta x_i} = 0 \quad \rightarrow \quad f_i^{n+1} = \left(1 - \frac{\Delta t_n}{\Delta x_i}\right) f_i^n + \frac{\Delta t_n}{\Delta x_i} f_{i-1}^n; \qquad (10)$$

then with $\Delta t/\Delta x \leq 1$, the result is stable and correct, and hence, the scheme is convergent.

2.6 Interpretation of Parameters and Approximate Solutions Obtained from Algorithms: Interpretation of Results

As shown above, the only parameter in De Saint–Venant equation is the coefficient *k* in Chézy formula (Eq. 3). The coefficient *k* is the parameter that replaces essentially the description of the process of energy dissipation (something we still cannot pretend to know well and to be able to formulate correctly without including some other parameters). There may be other phenomena that are not represented in Eqs. (1) and (2), for example, subgrid phenomena, but it must be clear that, precisely, they are not represented. Essential point is to understand that as long as we can relate this parameter to the reality (e.g., as long as we can assume that for a sand bed, the value of *k* varies within reasonable and known limits) such parameterisation is useful. If, however, by calibration or "tuning" one finds, through the modelling of past floods for a given river reach that may contain all kinds of obstacles and local head losses, some global value of *k*, then of course such value of the parameter has no physical meaning. In such a case, a modeller is parameterising the situations that are due to unknown factors (not a general situation of the flow in a channel but rather specific situation of resistance encountered in a given reach during a given flood event) and thus jeopardises the predictivity of the model. This is often a price for reproducing past-observed floods with models that do not contain all topography, structures, etc.

The results obtained by above-described procedures are to be interpreted in respect of what these procedures contain. There is no hope to expect that modelling based on the approximate resolution of partial differential equations can supply anything more that the values of grid-functions $\{\tilde{u}(x_i, t_n)\tilde{y}(x_i, t_n), i = 1,2,\ldots L; n = 0,1, \ldots, N\}$ that are approximation to continuous functions $\{u(x, t), y(x, t)\}$. Obvious consequence is that the four hypotheses used to set up Eqs. (1) and (2) are built-in in the results of all 1D modelling systems based on De Saint–Venant equations. Important point is also the fact that the result of simulation is the approximate solution only at the grid points. Nothing can be said about what happens between two grid points unless a complementary hypothesis assuming the continuity of the grid-functions is ensured between the points. Thus, interpolation between the computational points or a search for improvement of the results using higher-order approximation of derivatives through the extrapolation formulas involving several grid points is hazardous. The interpretation of the results must also take into account how the computations were conducted: to refine space grid of computational points in two consecutive computations is not enough to improve the quality of results from one simulation to another.

In general, the interpretation of the results may lead to inaccurate or even false conclusions and, then, policies and decision. Consider the example of flood insurance problems for dwelling on the inundated plain created by 1D-modelled free-surface elevation. As demonstrated, the free surface across the river is computed as horizontal at any time of the flood and computed velocity is uniform within the whole section. This is notoriously false: even if the flow is of one-dimensional character in unsteady flood of reasonable duration the free surface will be higher along the river axis than on the plain, the duration of inundation will not be the same and velocity very different. Nowadays, we often have available the digital terrain models (DTM). Using GIS techniques, it is enough to superimpose the 1D flow model results and DTM to produce illusion of accuracy. There are numerous cases of similar situations, especially when the studies (compulsory in many EU countries) of inundation risks are conducted. The reasons are of two origins: available budgets that push clients to less-qualified service suppliers using cheaper tools and lack of knowledge of the decision makers. How many of everyday users of market-available 1D software think of De Saint–Venant hypotheses when producing "inundation maps" from the colourful results supplied by GUI? Imagine that topography used in a model of an area was manufactured a couple of years ago and that since local forest service built a dirt service road crest of which is 1 metre above original plain elevation. Somebody unable to analyse the results in function of basic hypotheses and of sound knowledge of hydraulics will not be able to seek and find the differences between the results of 1D model and the free-surface elevation observed during last year flood.

3 A Remarkable Example of Limitation of De Saint–Venant Approach

Consider a case of a trapezoidal concrete derivation channel several kilometres long and conveying a steady flow discharge towards a power station, irrigation area, etc. What happens when the gates (or turbines) downstream close rapidly? In classic hydraulics curricula, the case becomes a 1D unsteady flow as downstream positive-steep front wave (discontinuity, roller, bore) propagates upstream the channel. Question is: is it possible with a commercial De Saint–Venant-based code to simulate the situation and define the heights of the dykes along this channel? Still classic answer is yes, and the computed result is as in Fig. 4a. In many (if not most) cases, the real situation is different. Like shown in Fig. 4b (and in Fig. 5), the upstream propagating wave is under the shape of undular bore height of which may be twice of that of steep front wave [5].

In this particular case, De Saint–Venant hypotheses of uniform velocity and hydrostatic pressure are wrong and no commercial software based on such hypotheses can produce acceptable results. And, once the structure built and water spilling out of channel at every manoeuver of the gates, there may occur serious consequences if the modeller or his client do not know hydraulics in depth: the client may well feel that modelling is a humbug, inapplicable to engineering problems. At the very best, the used software would be disqualified.

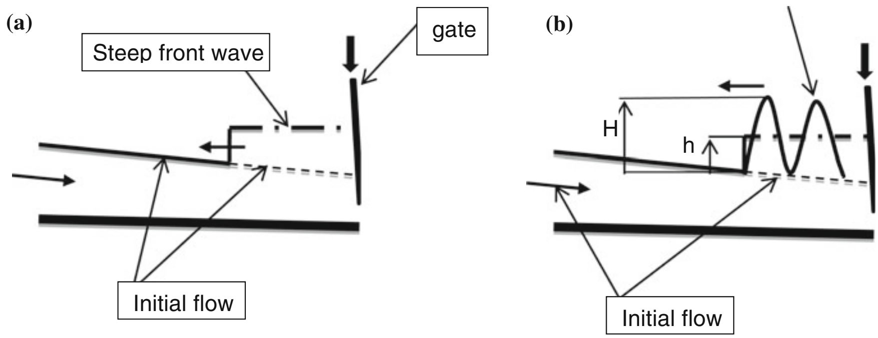

Fig. 4 Closure of downstream gate **a** simulation results from 1D De Saint–Venant-based code (steep front bore of height h), **b** often observed reality—undular bore of height $H = 1.2\text{–}2.1$ h

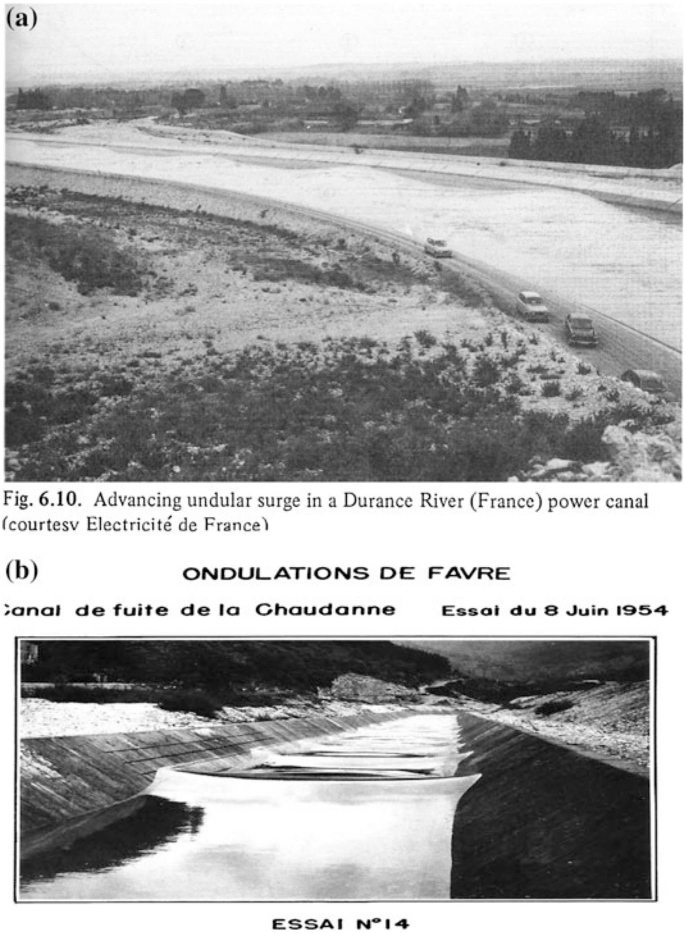

Fig. 5 **a** from [5]. **b** Tests of release in Chaudanne HP station (France), courtesy Electricité de France

4 Conclusions

From mathematical point of view, the results of models are nothing more than, at their best, approximate solution of original differential equations. From the engineering point of view, the interpretation of the results is essential because of the limitative basic hypotheses on which equations are built and because the computer output cannot supply more than these hypotheses allow. If there is a contradiction, an in-depth analysis is necessary. A modeller who is not sufficiently knowledgeable about links of the chain leading from hypotheses to results may not be able to supply his “client” with appropriate conclusions indicating how the original hypotheses and subsequent approximations may make the results differ from the reality. Given that the “client” is typically a decision maker in wide sense of the word: investor, public body, administration, etc., it is important that he realises the situation and makes sure to find necessary and qualified assistance in order not to be at the mercy of the modelling studies supplier.

References

1. Abbott, M. B., & Vojinovic, Z. (2009). Applications of numerical modelling in hydroinformatics. *Journal of Hydroinformatics, 11*(3–4), 308–319.
2. Abbott, M. B., & Vojinovic, Z. (2012). *Flood risk and social justice*. New York: IWA Publishing.
3. Chézy, A. (1768). Original manuscript of the report prepared for the French Academy of Science contained in the files of the Ecole des Ponts et Chaussée. In G Mouret (Ed), Antoine Chézy: Histoire d’une formule d’hydraulique. Annales des Ponts et Chaussées, (1921–II)
4. Strikwerda, J. C. *Finite difference schemes and partial differential equation* (2nd ed.). Society for Industrial and Applied Mathematics (SIAM), Philadelphia
5. Cunge, J. A., Holly, F. M, Jr, & Verwey, A. (1980). *Practical aspects of computational river hydraulics*. Boston, London, Melbourne: Pitman Advanced Publishing program.

Use of Standard 2D Numerical Modeling Tools to Simulate Surface Runoff Over an Industrial Site: Feasibility and Comparative Performance Survey Over a Test Case

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Abstract Intense pluvial generated surface flow over an industrial facility represents a flood risk requiring an appropriated approach for risk assessment. Runoff over industrial site might have flow regime changes, wild flooding/drying extend, as well as small water deep properties. This makes standard bidimensional (2D) numerical surface flow models use particularly challenging. Indeed, numerical treatment of these properties might not be specifically supported by models. Furthermore, it gets close by their traditional application domain limits. Accordingly, an assessment of this group of numerical tool use for such a purpose needs to be in detailed studied to evaluate feasibility, performance, and relevance of their use in this context. This chapter aims to focus on common 2D numerical modeling tools use for application over an industrial plant test case to simulate surface runoff scenarios. Feasibility of such an approach is hereby studied. Performances and relevance of this attempt are evaluated. Our test case has specificities of real industrial plants in terms of domain extend, topography, and surface drainage structures. Tested scenarios state a uniform net 100 mm 1 h long rainfall event in a context of storm water sewer pipe failure. Selected tested models were a 2D finite differences diffusive wave model and an array of different 2D shallow water equation [2D shallow water equations (SWEs)]–based models. Comparison has been conduced over computed maximal water depth and water deep evolution. Results reveal a feasibility of these tools application for the studied specific purpose. They underline the necessity of a highly fine spatial and temporal

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discretization. Tested categories of average 2D SWEs–based models show in a large extend similar results in water depth calculation. Used indicator of results reliability estimation did not point out major critical aspects in calculation. Limits inherent of these categories of models use for this domain of application are underlined. Relevance of this approach is raised up.

Keywords Flood risk assessment · Surface runoff modeling · Industrial site · 2D shallow water equations · MIKE · TELEMAC

1 Introduction

Flood risk over industrial sites includes surface runoff generated by intense pluvial events. For sensitive industrial sites, this risk has to be assessed as it might lead to issues for industrial activities, environment, and for human protection. A new guide for nuclear power plant protection against flooding risk has been elaborated by the Institut de Radioprotection et de Sûreté Nucléaire (IRSN) for the French Safety Authority (ASN). The guide [1] defines a set of Standard Flood Risk Situations (SFRS) to be taken in consideration for safety assessment of nuclear power plants. This guide notably includes a SFRS defining a framework for intense pluvial generated runoff risk assessment. This SFRS recommends that a plant has to be able to cope with a 1 h long rainfall event with a hundred year return period; meanwhile, sewer system network is considered as locally non-available. Through this SFRS, aim is to consider two possible aspects in safety failure which might occur during an intense rainfall event scenario: (1) a clogging of sewer network access and (2) a possibility of rainfall events occurrence exceeding the return period for which the sewer system has been designed and implemented.

Different approaches for the runoff SFRS application are possible. (1) A spreading of the cumulated rainfall volume over the industrial site might be an approach to consider for flat sites, to identify pounded areas. It has to be noticed that this quantitative approach do not take hydrodynamic aspects into accompt. (2) Using fine topographical data, main drainage path and pounded areas can be identified. This method is rather qualitative and does not integer quantitative aspects. (3) Numerical modeling of runoff as a free surface flow is a practice often used at larger scale for flood risks assessment and might be applied for runoff over high-resolution topography studies. Indeed, gaining ground of standard numerical modeling tools use for surface runoff component modeling at high resolution is observed [2, 3]. At the same time, nowadays techniques for high-resolution topographical data gathering are becoming commonly used. Modern techniques as light detection and ranging (LIDAR) [4] and unmanned aerial vehicle (UAV) photogrammetry [5] can produce digital elevation models (DEMs) with a resolution consistent enough to finely represent surface drainage influencing structures up (e.g., walls, side walks, curbs). Nevertheless, runoff over an industrial site