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Editorial

Advances in Dam-Break Modeling for Flood Hazard Mitigation: Theory, Numerical Models, and Applications in Hydraulic Engineering

Francesca Aureli [1], Andrea Maranzoni [1,*] and Gabriella Petaccia [2]

[1] Department of Engineering and Architecture, University of Parma, Parco Area delle Scienze 181/A, 43124 Parma, Italy; francesca.aureli@unipr.it
[2] Department of Civil Engineering and Architecture, University of Pavia, Via Ferrata 3, 27100 Pavia, Italy; petaccia@unipv.it
* Correspondence: andrea.maranzoni@unipr.it

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1. Introduction

Despite significant advancements being made in recent decades (e.g., [1–3]), dam-break modeling is still an active field of theoretical and applied research, which is of great interest to hydraulic engineers. Flooding induced by the collapse of a dam has potentially catastrophic consequences in downstream areas, both in terms of human and economic losses [4]. In addition, the vulnerability of older dams to extreme hydrological events is increasing due to structural deterioration or inadequate spillway capacity [5]. Similarly, the exposure of urban areas to flooding is globally increasing as a consequence of urban development [6].

In this context, robust and efficient numerical models which enable the accurate simulation of dam-break flows on real-world topography are effective and useful tools for the assessment of flood hazard and risk associated with dam-break events (e.g., [7]). In fact, flood hazard assessment is a fundamental prerequisite to designing prevention and mitigation measures to reduce the number of people affected by water-related disasters and improve living conditions in urban areas. This objective fits perfectly with Goal 11 of the United Nations' 2030 Agenda, which aims to make cities and communities safe, resilient, and sustainable [8].

Experience and knowledge based on historical dam-break events [4], along with the availability of physical model data [3], allow modeling tools to be validated, constantly improved, and used with confidence in dam-break flood hazard and risk mapping activities. Robust and reliable climate and hydrological models also represent a strategic predictive resource in the definition of future hydrological scenarios under climate change [9].

In light of these premises, the Special Issue entitled "Advances in Dam-Break Modeling for Flood Hazard Mitigation: Theory, Numerical Models, and Applications in Hydraulic Engineering" aims to collect contributions regarding (a) recent advancements in the theoretical analysis of dam-break flows; (b) recent advancements in numerical schemes and techniques used to model dam-break flows on real-world topography; (c) new laboratory experiments and test cases for the validation of numerical models; and (d) practical applications of dam-break numerical models to real-field cases for flood hazard and risk assessments.

Recent contributions in the literature on these themes are analyzed and discussed in this editorial, highlighting the topics on which scientific research on dam-break modeling is currently most focused. Unfortunately, some of these topics were not addressed by the contributions presented in the Special Issue. A final comment is made on this fact.

2. Overview of the Papers Included in the Special Issue

The contributions to the Special Issue are listed and summarized in Table 1. They are also briefly presented in the following four subsections, each of which covers one main theme addressed in the Special Issue.

Table 1. Summary of the contributions to the Special Issue (https://www.mdpi.com/journal/water/special_issues/dam_model_flood_hydraulic, accessed on 16 February 2024).

(1) Contribution Number	(2) Contribution Reference	(3) Contribution Type	(4) Research Topic	(5) Research Focus	(6) Research Results
1	Aureli et al. (2021)	Review	Real-world dam-break modeling. Theme (d)	An overview of documents in the literature concerning historical dam-break events with real-field datasets available for the validation of numerical models; an overview of documents concerning investigations into dam-break flows on physical models reproducing real-world topographies	The analysis of the type and quality of the available data; the division of the retrieved cases into well-documented cases and cases with partial or inaccurate datasets; a help in identifying the test cases most suited to the modelers' needs; the achievement of improvements in data access; the identification of test cases worthy of future research
2	AlQasimi and Mahdi (2022)	Discussion	Real-world dam-break modeling. Theme (d)	A comment on Contribution No. 1 (Aureli et al., 2021) about the classification of the Lake Ha! Ha! dam test case	Due to its serious shortcomings potentially limiting its applicability, the Lake Ha! Ha! dam test case should be classified as a test case with a partial or inaccurate dataset
3	Aureli et al. (2022)	Reply	Real-world dam-break modeling. Theme (d)	A reply to the comment in Contribution No. 2 (AlQasimi and Mahdi, 2022) about the classification of the Lake Ha! Ha! dam test case	Due to the large and complete dataset available in digital format, the Lake Ha! Ha! dam test case could be considered as well documented
4	Aureli et al. (2023)	Review	Experimental dam-break modeling. Theme (c)	An overview of experimental investigations into dam-break flows over a non-erodible bottom for the validation of numerical models with a focus on fundamental dam-break wave physical characteristics; dam-break waves through geometric singularities; impacts against obstacles; dam-break propagation in idealized urban areas; tsunami bores; green water events; dam-break waves of non-Newtonian fluids; dam-breaks in cascade reservoirs; dike-break-induced flows on a lateral floodplain; the collapse of storage tanks and bunds or dike overtopping	The analysis of test conditions and measuring techniques; a help in identifying the most appropriate laboratory test for validation purposes; the achievement of improvements in experimental data access; the identification of physical aspects worthy of future experimental research
5	Maranzoni and Tomirotti (2023)	Review	Numerical dam-break modeling. Theme (b)	An overview of studies in the literature that use 3D hydrodynamic models for the simulation of large-scale dam-break flooding on irregular real-world topography	The analysis of governing equations, numerical methods, and the status of codes; the identification of recent advancements in numerical techniques, modeling accuracy, and computational efficiency; the identification of advantages and limitations of 3D dam-break models compared to 2D shallow-water ones; a help in choosing the most suitable numerical method for the application of interest; the identification of future numerical research directions

Table 1. *Cont.*

(1) Contribution Number	(2) Contribution Reference	(3) Contribution Type	(4) Research Topic	(5) Research Focus	(6) Research Results
6	Říha et al. (2020)	Original research	Numerical dam-break modeling. Themes (b) and (d)	A study focused on dam-breaks of small embankment dams in a cascade (overtopping and piping); the comparison of empirical formulae and 2D SWE simulations through HEC-RAS 2D; the attenuation of the peak discharge; the analysis of the case study of the Tetřeví Stream and Čižina River (Czech Republic)	Peak discharge attenuation is influenced by the flood volume, slope, and morphology of the floodplain and increases with the distance from the breached dam. Empirical formulae derived for a single dam break may underestimate the peak outflow by up to 10% in the case of a dam cascade
7	Cantero-Chinchilla et al. (2020)	Original research	Theoretical and numerical dam-break modeling. Themes (a) and (b)	A study focused on a VAM (vertically averaged and moment equation) model for the simulation of dam-break waves; the analysis of non-hydrostatic pressure effects; validation against available experimental data	Discussion of the role of the perturbation parameters in overcoming the limitations of the classic shallow water model; discussion of the complex and necessary interplay between the dynamic component of fluid pressure and the modeling of the velocity profile in producing accurate solutions for dam break flows. Acceptable agreement between numerical predictions and experimental data is shown
8	Ahmadi and Yamamoto (2021)	Original research	Theoretical and experimental dam-break modeling. Themes (a), (c), and (d)	A study focused on the outflow discharge equation for a sudden partial dam-break; verification based on the historical Malpasset dam-break event; application to the hypothetical collapse of the Amagase dam (Japan)	Discussion of the effect of the breach shape; the evaluation of a breach-shape coefficient via laboratory experiments; the integration of the outflow discharge equation in a 2D model. A simple and effective equation is proposed
9	Gaagai et al. (2022)	Original research	Numerical dam-break modeling. Theme (d)	A simulation of the floods resulting from the Yabous dam breach (Algeria) through HEC-RAS 1D; a sensitivity analysis on breach parameters (breach slope, width, and formation time)	The provision of flood inundation maps; the discussion of the effect of breach parameters on flooding variables and the effectiveness of the modeling tool for the simulation of the dam-break wave propagation
10	Bello et al. (2022)	Original research	Numerical dam-break modeling. Theme (d)	A statistical definition of the most influential dam breach parameters and assessment of their influence on the released maximum discharge	The most influential breach parameter on the maximum discharge is the breach formation time, followed by the final breach width and height. The statistical definition of breach parameters strongly affects the maximum discharge magnitude uncertainty, therefore influencing the estimation of the flood risk associated with the breaching, the delimitation of flooded areas, and the preparation of emergency action plans
11	Melo and Eleutério (2023)	Original research	Numerical dam-break modeling. Theme (d)	A study of the impact of the rheological variability and the non-Newtonian behavior of stored materials on the results of the modeling of flooding caused by mining tailings dam collapses	The variability of rheological parameters significantly affects flooded areas, maximum depths, and arrival times. The Bingham model may be applied as a first approximation as it leads to conservative results. The Herschel–Bulkley model proved to be more efficient for probabilistic analysis, with a smaller range of uncertainties and better probability distribution, improving the evaluation for risk management purposes

Table 1. *Cont.*

(1) Contribution Number	(2) Contribution Reference	(3) Contribution Type	(4) Research Topic	(5) Research Focus	(6) Research Results
12	Xue et al. (2023)	Original research	Numerical dam-break modeling. Themes (a) and (b)	A novel 1D model for the simulation of open-channel flows with variable width and topography; its application to rectangular channels with variable widths; verification against steady and unsteady flows with a reference solution; validation against experimental data	The implementation of new conservation and non-conservation terms allowed the authors to achieve satisfactory results in the simulation of selected test cases concerning dam-break and steady flows
13	Martínez-Aranda et al. (2023)	Original research	Numerical dam-break modeling. Theme (b)	A 2D finite-volume model of bedload sediment transport in non-equilibrium conditions during dike erosion or dam breach; its validation against experimental data of dike overtopping and dam-breach opening	A non-equilibrium bedload transport model is preferable compared to an equilibrium model in morphological dam-break modeling over a mobile bed
14	Silva and Eleutério (2023)	Original research	Dam-break flood risk assessment. Theme (d)	A study on the effect of the integration of early warning and evacuation systems in flood risk assessment in terms of loss of life; the analysis of the case study of the hypothetical Pampulha Lake dam breach (Brazil) using 2D hydrodynamic modeling coupled with an agent-based life loss model	The determination of an optimal time for warning issuance; the discussion of the crucial role of preparedness and the perception of mobilization for the minimization of the potential for loss of life; the discussion of a possible optimization strategy based on differencing alerts and actions in different sectors of the downstream area
15	Akgun et al. (2023)	Original research	Dam-break flood risk assessment. Theme (d)	A comparison of the 2D and 3D modeling of dam-breach flow with Flow3D software; validation against available experimental data; application to the case study of the hypothetical failure of Tuzluca dam (Turkey); the assessment of loss of life for different scenarios (overtopping and piping)	Discussion of the impact of breach geometry and failure time on expected casualties; 2D modeling is more practical and less time-consuming than 3D modeling, which, on the other hand, is more accurate and hence suitable for small-scale simulations

2.1. Advancements in Theoretical Analysis of Dam-Break Flows

Three papers address theme (a), providing valuable contributions to the theoretical analysis of dam-break flows.

Cantero-Chinchilla et al. (2020) [Contribution No. 7] proposed a new vertically averaged and moment equation (VAM) model to overcome the limitations of the classic shallow water equation (SWE) model in the simulation of dam-break waves over a wet bed. The importance of including the effects of non-hydrostatic pressure and the vertical flow velocity profile in the dam-break model was investigated and assessed by comparing numerical results of the VAM and SWE models with experimental data available in the literature.

Ahmadi and Yamamoto (2021) [Contribution No. 8] proposed a new, simple equation to predict dam-break outflow discharge in the case of a partial dam-break event. This equation can be used as an inflow boundary condition in the hydrodynamic modeling of dam-break wave propagation in downstream areas. Among the strengths of the proposed equation, there are few input parameters regarding the dam and the modeling of a partial breach through a percentage failure of the structure. The authors validated the equation against experimental data, investigated the effect of the breach shape, and, finally, showed the results obtained for selected real-field case studies.

Xue et al. (2023) [Contribution No. 12] proposed a one-dimensional (1D) model for the simulation of open-channel flows in rectangular channels with variable widths and non-flat bottoms. The shallow water momentum equation was rewritten in a convenient conservative form by introducing a pressure term in the numerical flux and a non-prismaticity term in the source term. Satisfactory results were obtained in validation and verification tests concerning dam-breaks and steady flows.

2.2. Advancements in Numerical Modeling of Dam-Break Flows on Real-World Topography

Regarding theme (b), Říha et al. (2020) [Contribution No. 6] used a simplified parametric model for piping and overtopping embankment dam erosion with parameter optimization based on a Monte-Carlo sampling procedure in order to predict the outflow discharge hydrograph. Standard 2D shallow-water modeling was adopted to simulate the dam-break wave propagation in a cascade dam-break flood.

Martínez-Aranda et al. (2023) [Contribution No. 13] applied a recently developed 2D finite-volume bedload transport model in equilibrium and non-equilibrium conditions to study dam breach and dyke erosion processes. The benchmarking of the non-equilibrium model based on dyke erosion and dam breach opening laboratory tests reproducing highly unsteady flows showed improved results compared with the classical equilibrium approach, despite the careful calibration of the exchange parameters required, especially in the regions where complex unsteady processes occur.

The papers by Cantero-Chinchilla et al. (2020) [Contribution No. 7] and Xue et al. (2023) [Contribution No. 12] also deal with relevant numerical issues in dam-break flow models. In particular, Cantero-Chinchilla et al. (2020) [Contribution No. 7] used a three-step semi-implicit hybrid finite-volume–finite-difference scheme for the numerical solution of the VAM equations. Xue et al. (2023) [Contribution No. 12] solved the 1D SWE model via a two-step upwind scheme based on the random choice method and the Harten, Lax, and van Leer (HLL) approximate Riemann solver.

Maranzoni and Tomirotti (2023) [Contribution No. 5] performed a comprehensive literature review inherent to theme (b) since it is focused on three-dimensional (3D) hydrodynamic models for the simulation of large-scale dam-break flows on irregular real-world topography. The authors discussed the advantages and limitations of the 3D models (in terms of complexity, accuracy, and computational efficiency) compared to conventional two-dimensional (2D) ones.

2.3. New Laboratory Experiments and Test Cases for the Validation of Numerical Models

Considering theme (c), Ahmadi and Yamamoto (2021) [Contribution No. 8] performed a new laboratory investigation to collect experimental data for the calibration of the shape parameter appearing in the partial dam-break outflow rate equation they proposed. This contribution is the only one published in the Special Issue that presents new experimental dam-break flow data.

An extensive review of the state-of-the-art experimental investigations into dam-break flows was performed by Aureli et al. (2023) [Contribution No. 4], limited to schematic test cases with fixed, non-erodible bottoms. This survey demonstrated the impressive number of experimental studies conducted in the last century which aimed to provide insight into the physical features of dam-break waves and collect experimental data for the validation of numerical models.

2.4. Applications of Dam-Break Numerical Models to Flood Hazard and Risk Assessment

Most contributions to the Special Issue fall under theme (d).

Říha et al. (2020) [Contribution No. 6] considered a case study concerning a cascade of three small reservoirs along the Tetřeví Stream and the Čižina River in the Moravian–Silesian Region, Czech Republic.

The dam-break outflow rate equation proposed by Ahmadi and Yamamoto (2021) [Contribution No. 8] was coupled with a two-dimensional flood simulation model applied to the Amagase dam (Kyoto Prefecture, Japan) dam-break case study. Consequently, this article also contributes to theme (d), supporting dam-break flood hazard assessment in highly populated areas.

Real-field dam-break case studies were also analyzed by Gaagai et al. (2022) [Contribution No. 9], Bello et al. (2022) [Contribution No. 10], Melo and Eleutério (2023) [Contribution No. 11], Silva and Eleutério (2023) [Contribution No. 14], and Akgun et al. (2023) [Contribution No. 15], who considered hypothetical dam-break events for selected dams in emerging countries. The commonality between all of these studies is that different dam-break scenarios were considered, and the effect of uncertainties in the model parameters was examined through sensitivity analyses to effectively delimitate the floodable areas and assess the risk that threatens the population exposed to dam-break flooding.

In detail, Gaagai et al. (2022) [Contribution No. 9] studied the flooding wave resulting from the hypothetical failure of the Yabous dam (northeastern Algeria). Bello et al. (2022) [Contribution No. 10] considered the dam-break of the Chacrillas dam (central Chile). Melo and Eleutério (2023) [Contribution No. 11] conducted a probabilistic analysis to investigate the sensitivity of tailings dam-break floods to relevant rheological parameters of non-Newtonian hydrodynamic models in a fictitious ICOLD (International Commission on Large Dams) dam-break case study. Based on the case study of the hypothetical failure of the Pampulha Lake dam (Minas Gerais State, Brazil), Silva and Eleutério (2023) [Contribution No. 14] investigated the effectiveness of specific alert systems in the mitigation of potential loss of life in densely populated urban areas. Finally, Akgun et al. (2023) [Contribution No. 15] analyzed different dam-break scenarios for the planned Tuzluca dam (Iğdır Province, Turkey), obtaining results in terms of dam-break flood risk and potential loss of life that are expected to guide the preparation of emergency action plans for the downstream region.

The review performed by Aureli et al. (2021) [Contribution No. 1] fits into theme (d) because it concerns historical dam-break events for which enough reliable information is available to set up real-field dam-break test cases, as well as datasets obtained by experimental dam-break studies on physical models reproducing real-world topography. A comment on this review (AlQasimi & Mahdi 2022; Contribution No. 2) and the subsequent reply (Aureli et al. 2022; Contribution No. 3) discuss the completeness of the available dataset for a specific historical dam-break event (the 1996 Lake Ha! Ha! breakout, Québec, Canada).

3. Recent Developments in Dam-Break Modeling: Gaps and Advancements

3.1. Recent Advancements in Theoretical Analysis of Dam-Break Flows

Dam-break modeling is usually performed through 1D (cross-sectional averaged) or 2D (depth-averaged) shallow water models. In particular, 2D depth-averaged models based on 2D shallow water equations are widely used to simulate the dynamics of a large variety of geophysical surface flows (e.g., [10,11]). However, in many hydraulic applications, such as the propagation of waves over obstacles, flows over spillways, and the motion of undular bores, the hydrostatic pressure assumption can no longer be considered valid [12–14]. Similarly, more complex non-hydrostatic models are required to accurately simulate coastal wave propagation phenomena, such as wave run-up and wave shoaling, due to the need for the reproduction of nearshore dynamics, preserving both nonlinear and dispersive effects [15,16]. In these kinds of flows, vertical acceleration plays a significant role, and a dynamic component affects the pressure distribution. Given the high computational cost of three-dimensional modeling, the development of enhanced non-hydrostatic depth-averaged models overcoming the limitations of the classical shallow water (hydrostatic) models is an active research topic in environmental and hydraulic engineering. For the sake of computational costs, several approaches based on the vertical averaging of the fully three-dimensional flow equations have mainly been investigated, such as the non-hydrostatic extension of shallow water models [17,18] and Boussinesq-type models [19,20], among which are the weighted residuals techniques proposed by Green and Naghdi [21] and widely used in the literature (e.g., [22]), which are precursors of the vertically averaged and moment equations model (VAM) [23]. Given their promising peculiarities, VAM models are currently being studied with the aim of improving numerical techniques and computational efficiency to effectively deal with non-hydrostatic simulations of free-surface flows [24], as well as in the presence of sediment transport [25]. Recent applications of these models also concern dam-break problems [26], as confirmed by Contribution No. 7 to this Special Issue.

Despite being computationally expensive, 3D models (based on the Navier–Stokes equations or the Reynolds-averaged Navier–Stokes equations coupled with a suitable free-surface-tracking algorithm) are increasingly used in dam-break modeling. Indeed, they overcome the limitations of depth-averaged models and offer a detailed and accurate prediction of flooding dynamics, inherently including the vertical acceleration of fluid and 3D effects due to the flow curvature ([27,28], and Maranzoni & Tomirotti 2023 [Contribution No. 5 to this Special Issue]). The current availability of powerful computational resources allows the efficient use of Computational Fluid Dynamics (CFD) in many hydrodynamic problems, including dam-break flow analysis, even when concerning large-scale applications on real-world topography (e.g., [29–32]). Despite this recent possibility, only one contribution to this Special Issue [Contribution No. 15] reports a 3D simulation (using commercial software) of real-field dam-break flooding resulting from the hypothetical failure of a real dam.

As observed by Maranzoni and Tomirotti (2023) [Contribution No. 5], coupled 2D–3D models can be a valid compromise between simulation accuracy and computational efficiency in dam-break analyses and offer a viable and modern alternative to conventional 2D and 3D hydrodynamic models. Such hybrid models are becoming popular in the hydrodynamic modeling of free-surface flows. According to this approach, hydrostatic shallow water equations are used in regions where vertical accelerations are negligible, while Boussinesq-type or Navier–Stokes equations are adopted in zones where the non-hydrostatic effects are significant [26]. Currently, some CFD software codes allow models to simulate large-scale shallow flows via the 2D depth-averaged model and near-field flows (near structures, obstacles, or topographic irregularities) via a 3D model (e.g., [33]). In general, the portions of the computational domain where each of the two models are applied must be preselected by the user; the interface between the two regions (with the related exchange of hydraulic information) is critical and requires efficient numerical treatment. Research into the development of coupling strategies and algorithms to implement hybrid models is currently active. For example, Sarkhosh and Jin [34] recently proposed a hybrid Lagrangian solver of one-dimensional (1D) shallow water flow and a 2D large-eddy simulation with moving coupling to simulate dam-break flows over frictional beds. However, the application of hybrid models to real-world case studies seems prohibitive.

New, innovative dam-break mathematical models are continually being proposed in the literature, confirming that research in this field is still lively. Surrogate models, which mimic the input–output dynamics of a complex system by simple approximated models, can be adopted as an alternative to physically-based models. Such a modeling approach has recently gained substantial popularity, mainly due to the increasing development of machine learning and artificial intelligence. Surrogate models are based on different possible approaches based on data and intrinsic physics, such as deep neural networks (characterized by a strong ability to catch complex nonlinearity in high-dimensional data), stochastic approaches based on Gaussian processes, reduced-order models or low-complexity models, and hybrid physics models, which combine physics and data-driven methods [35]. Moreover, surrogate models generally possess characteristics that make their use attractive in inverse modeling and in the determination of model parameters through differentiation for optimization purposes. In any case, one of the main motivations behind the development of such models is the reduction in the computational cost compared to conventional physically-based approaches. However, long model training and data generation times, as well as the scarce ability to identify correct solutions outside of the situations for which training was carried out, make these models mainly suitable in scenarios where repetitive simulations are necessary, without including the physics of the process. Physics-Informed Neural Networks (PINNs) have been proposed in the literature to overcome these limitations, embedding physical laws into models' training processes. Promising results have been obtained in dam-break modeling, albeit only concerning geometrically simple situations [36].

A crucial step in dam-break modeling and flood risk assessment is the estimation of the outflow discharge hydrograph induced by the dam failure. This information can be imposed as an inflow boundary condition in numerical simulations of dam-break wave propagation [37–39]. In fact, sometimes, dam-break hydrodynamic models do not include the reservoir behind the dam (for example, when the reservoir bathymetric data are unavailable) and rarely incorporate a breach formation model [40]. Dam breach modeling actually requires several parameters to be estimated, mainly related to breach geometry and development. This task can be accomplished through empirical methods (based on the regression analysis of historical dam-break data [41,42]) or physically-based methods (which reproduce the breach formation, e.g., [43]) and is particularly challenging in embankment dams, for which different breach mechanisms are possible (namely, overtopping, piping, and internal erosion), involving several geometric, structural, and hydrological factors [44,45]. Additionally, dam breach parameters are affected by high uncertainty, which propagates to the prediction of breach peak outflow and, consequently, of the inundation extent, flood hazard level, dam-break wave arrival time, and, in general, flood risk [46–49]. The accurate estimate of dam breach parameters is addressed by Contributions No. 9 and 10 in the Special Issue and by recent papers published in the literature which propose innovative approaches [44], thereby confirming that this topic is still relevant and attractive and that there is room for further research in this area [50].

Sometimes, dam-break flow develops over a mobile bed, incorporating large quantities of sediment from the bottom and inducing significant morphological changes. In these cases, geomorphic models which can account for the motion of water and sediment in non-equilibrium conditions and predict contextual changes in bottom morphology are required [51]. Scientific research on this topic is still active (as confirmed by Contribution No. 13 of this Special Issue), although different modeling approaches have been proposed in the recent past in the literature, including variable-density shallow water models (where the mixture of water and sediment is idealized as an equivalent homogeneous continuum [52,53]), two-layer models [54,55], and two-phase models [56]. Such complex models include closure equations with several model parameters, and, hence, they must be extensively validated against experimental data to accurately assess their predictive capabilities [51,57,58].

3.2. Recent Advancements in Numerical Modeling of Dam-Break Flows on Real-World Topography

The hydrodynamic simulation of dam-break flow over irregular, real-world topography requires accurate, robust, and efficient numerical models. Generally, these qualities can be found at an acceptable level in 2D shallow water models, provided that the numerical scheme used to solve the basic equations can cope with the difficulties induced by complex flow phenomena, such as critical transitions, the formation of shocks, and the motion of wetting and drying fronts (e.g., [59–62]). An appropriate treatment of the source terms, allowing the numerical model to satisfy the *C*-property and to be well balanced (i.e., preserving steady and stationary conditions) [63,64], is desirable, if not essential, especially in dam-break analyses over irregular topography, as quiescent water in the reservoir must be preserved until the arrival of the depression wave. Many researchers have focused on the robustness of the discretization of the source term; in this framework, research on this topic is still ongoing [65], and today, upwind schemes are preferred to centered ones [63]. Well-balanced schemes were proved to preserve a steady state even in the presence of geometric discontinuities [66]. For example, in this field, an energy-balanced version of the augmented Roe schemes was introduced [67], where the source term was accounted for by increasing the number of elementary waves.

The numerical treatment of the bottom and friction source terms influences the accuracy and stability of the numerical scheme, especially in the presence of wetting and drying fronts or overland flows due to the very shallow water depths involved (e.g., [68,69]).

Various methodologies have been proposed in the literature to enforce the balance between numerical fluxes and the bottom source term, based on a classic hydrostatic reconstruction strategy [70,71], a surface reconstruction technique [72], the correction of fluxes [73,74], or the incorporation of the bottom source in the numerical fluxes [60,75]. Also, the positivity-preserving property (which avoids the calculation of unphysical negative water depths) and a mass-conservation treatment of the motion of wetting and drying fronts are advantageous in the obtainment of accurate and stable solutions [76–78]. For this reason, the implementation of new formulations of the source terms capable of ensuring the greater accuracy and stability of the numerical resolution schemes is a constant subject of investigation, especially in the context of the development of Godunov-type finite-volume hydrodynamic models. Finally, particular attention is paid to providing new schemes with which to reconstruct the values of flow variables at the boundaries of grid cells and to improve and simplify the discretization of the stiff friction term [79,80].

Conventional finite-element methods (e.g., [81,82]) and discontinuous Galerkin finite-element schemes (e.g., [83]) were also adopted to solve shallow water equations with source terms and constitute a significant research area, especially in dam-break modeling, given their ability to cope with complex geometries and reach high-order accuracies.

A popular modern strategy to solve hydrodynamic governing equations in dam-break modeling, both in 2D and 3D frameworks, is based on meshless particle-based methods, such as Smoothed Particle Hydrodynamics (SPH) [84] and the Moving Particle Semi-Implicit Method (MPS) [85,86]. Such methods offer the advantage of avoiding the construction of a computational mesh and the adoption of complex free-surface-tracking algorithms (e.g., [87–90]). Additionally, Lattice Boltzmann methods (which are based on a discrete form of the Boltzmann equation and simulate flow through collision models of fictitious particles moving on a discrete lattice grid) were applied to shallow water equations [91] but are rarely used in dam-break flooding simulations (e.g., [92,93]), despite their efficiency and flexibility. Therefore, they deserve further research, especially in 3D dam-break flow applications.

3.3. New Laboratory Experiments and Test Cases for the Validation of Numerical Models

The comprehensive review of experimental studies on dam-break flow reported by Aureli et al. (2023) [Contribution No. 4] shows that in the past, an impressive number of experimental investigations were performed on this topic in a variety of test conditions, and many extensive and accurate datasets are available for the validation of dam-break numerical models. However, as observed by the same authors [Contribution No. 4], most datasets are not available in digital format. Hence, the creation of a public repository would be advisable to facilitate access to these data and their use.

Despite the numerous experimental investigations carried out in the past, the experimental approach remains very popular in dam-break flow analysis for the provision of insights into specific physical aspects that are not yet completely clear and for the collection of further experimental data concerning new geometries and test conditions to validate numerical models. In the Special Issue, only one original experimental investigation (on dam-break outflow) appears; however, experimental data available in the literature have been used in several contributions to this collection for validation purposes (Contributions No. 7, 12, 13, and 15). Additionally, some new contributions to experimental dam-break modeling have been published in the literature in the last year (e.g., [86,94,95]). In some of these, dam-break waves are used as incident waves to investigate the features of specific phenomena, such as green water events [96], the propagation of tsunami waves in the swash zone [97], or interaction with floating structures [98]. Non-intrusive measurement techniques are preferably adopted to collect experimental data. Special attention is devoted to imaging techniques that can provide data distributed in a relatively large area with a frequency suitable for rapidly varying flows at the cost of complex calibration procedures and post-processing actions (distortion correction, denoising, etc.) [94].

In dam-break experiments, dam-break waves are typically generated by suddenly removing a lift gate (which can be moved upwards or, more rarely, downwards) or a swing gate. The gate-opening modality can significantly influence the resulting dam-break flow [99] and must be carefully considered during the setup design. In any case, the opening time should be short enough to reproduce a nearly instantaneous dam collapse [100].

It is worth noting that model validation based on small-scale laboratory tests is affected by errors induced by scale effects (see the discussion reported in Contribution No. 4 of this Special Issue). This fact must be considered when applying numerical models to practical problems in large-scale, real-world situations. The impact of scale effects, especially in physical models, deserves further analysis. Similarly, dam-break flows generated by a partial dam-break obtained through partial gate opening [101] or partial gate removal (in both horizontal and vertical directions) [102] are topics worthy of further experimental and numerical investigation.

Finally, further efforts to conduct new experiments into partial dam-break (see Contribution No. 8 of this Special Issue) or breach formation [103], as well as dam-break flows involving sediment transport and morphological changes in an erodible bed or interactions with erodible structures [104], are advisable to collect additional experimental data for validation purposes. Modern non-intrusive, imaging-based measurement techniques are available to this end, allowing the accurate acquisition of water levels, flow velocities, and bottom levels with high temporal and spatial resolution [105]. The contextual measurement of both the free surface and the erodible bottom surface in dam-break flows with distinct 3D characters is an ongoing challenge.

3.4. Applications of Dam-Break Numerical Models to Flood Hazard and Risk Assessment

Most of the contributions in this Special Issue address theme (d), confirming the current considerable interest in the assessment of the hydraulic hazard and risk associated with dam-break flooding in scientific research and practical applications to provide accurate and exhaustive information for use in flood risk management and emergency planning. To this end, the identification of meaningful flood hazard indicators and associated flood hazard classifications is crucial to the correct quantification of flood hazards in areas that would be potentially floodable in the event of a dam failure [106]. Flood damage and life loss models are thus essential to predict the potential impact of a catastrophic dam accident, especially when different flood alert systems or non-structural mitigation measures must be tested or compared (e.g., [107,108]).

However, several uncertainty sources potentially affect the inundation model results and, consequently, decision-making [109]. In dam-break analysis, such uncertainty sources, which include the breaching mechanism, the breach width, the breaching duration, and the reservoir level at the breach time, must be considered in the definition of dam-break scenarios [47,110]. Probabilistic maps, commonly used in the analysis of riverine- or levee-breach-induced flooding (e.g., [111–113]), were recently extended to dam-break flood hazard and risk assessment and were shown to facilitate the informative and comprehensive quantification of the uncertainty associated with flood hazard estimates [47,48].

The need for effective flood risk management is even more urgent in developing countries (it is worth noting that three contributions to the Special Issue consider dam-break case studies concerning dams located in Algeria, Turkey, and Brazil). Climate change may increase the likelihood of dam failures, and the severity of the dam-break consequences may be exacerbated by the increasing exposure and lack of preparedness of the population at risk [108].

The paper by Říha et al. (2020) [Contribution No. 6] highlights the recent interest in cascading dam-break floods and the impact of scenario parameters on the evolution of the inundation process and the related consequences (e.g., [114,115]). Similarly, the article by Melo and Eleutério (2023) [Contribution No. 11] demonstrates the increasing interest in the assessment of flood hazards and risks associated with the potential failure of tailings dams used to store waste materials [116]. As stated by the same authors in the introduction to their contribution, "failures of tailings dams occur at a significantly higher frequency compared to those of water storage dams", and "recent incidents have highlighted the immense destructive potential associated with tailings inundations" or waste soil landslides (e.g., [117]). This is particularly true in emerging countries rich in raw materials, where mining activities are carried out on a large scale and often in the absence of adequate safety protocols. Usually, a mudflow originates from a tailings dam failure, and hydrodynamic simulations must take into account the non-Newtonian behavior of the released material [118]. The influence of the rheological model and the related parameters on the inundation dynamics and the extent of the flood inundation area is a crucial problem on which Contribution No. 11 of the Special Issue focuses. Similarly, non-Newtonian behavior is typically assumed in the simulation of dam-break debris flows based on the single-phase hypothesis [93].

4. What Was Missing

The contributions submitted to the Special Issue highlight the importance of some relevant lines of research in dam-break modeling. However, the absence of contributions concerning new modeling approaches and research currently at the forefront highlights, to some extent, the unpreparedness of the related state of the art towards practical applications.

In this Special Issue, it would have been interesting to host contributions regarding surrogate models applied to dam-breaks. However, the current research does not seem capable of addressing applications of practical interest yet. Due to their high complexity, these models do not currently represent (and probably will not be able to represent even in the short term) a credible alternative to conventional methods such as finite-difference, finite-element, or finite-volume methods. The simulation of naturally complex flows over irregular real-world topography in real-field case studies is not on the horizon yet [36], despite attempts to integrate fundamental physical laws and domain knowledge into the models, thereby trying to ensure generalization capabilities and credible predictions.

No contributions to the Special Issue focused on the theme of dam-break wave propagation in urban areas. However, this remains a very significant topic [119], especially, for example, in light of the application of hydrodynamic numerical models to the study of levee-breach-induced flooding [120], frequently involving densely urbanized lowland areas. An adequate description of built-up areas incompatible with a low spatial resolution (which is suitable for limiting calculation times, especially from the perspective of real-time applications) could be obtained by enhancing the capabilities of simplified approaches (e.g., porosity, 1D-2D coupling, etc.) [121], which therefore prove to be strategic and deserve further research.

A viable option to overcome the limitation related to the computational inefficiency of physically-based models is to accelerate model calculations via high-performance computing (HPC) and graphics processing unit (GPU) technology to reduce model running times. In particular, parallel computing is a valid and widely used method to improve computational efficiency, possibly exploiting GPU computing power and processing capabilities. Reducing the computational time of model executions also allows larger domains to be considered with high spatial resolution and the simulation of flooding dynamics for a longer physical time. Moreover, a large number of model runs for different dam-break scenarios can be performed in sensitivity analyses. Even in the presence of promising runtimes, the scalability in recently proposed multi-GPU codes is still unsatisfactory for a large number of GPUs due to thread divergence for dry cells, poor load balancing between MPI ranks with static decomposition, and, above all, the time consumed by I/O and MPI communication for large-scale problems with respect to the computation time. These times (in the order of minutes each) are difficult to minimize, even in the face of constant effort in this direction. In fact, they do not depend on the number of GPUs and represent the highest percentage of the total runtime when trying to achieve operational purposes. Future perspectives should therefore aim to design optimized I/O parallel algorithms and explore new communication techniques [122]. This line of research is cutting-edge. However, given the high stakes and the very specific topic, researchers interested in this field are likely to turn to more sector-specific journals rather than generalist journals, such as MDPI's *Water*.

5. Conclusions

This Special Issue concerning "Advances in Dam-Break Modeling for Flood Hazard Mitigation: Theory, Numerical Models, and Applications in Hydraulic Engineering" consists of a collection of 15 papers. The topics addressed range from recent advancements in the theoretical analysis and numerical modeling of dam-break flows, both in schematic configurations and on irregular real-world topography, to new laboratory experiments and test cases suitable for the validation of numerical models. Special attention is devoted to case studies in which dam-break modeling is used for flood hazard and risk assessment.

During the three years in which manuscript submission was open, research on dam-break modeling has continued, also through the contributions included in this collection, thereby demonstrating great liveliness and fidelity in its ultimate goal of protection from flood hazards. In fact, under the aegis of the general topic of the total or partial failure of a dam, developments of fundamental importance have originated in the modeling of flooding phenomena, which allow populations to be protected in an increasingly targeted and effective manner from flood risks.

Many foods for thought came from the analysis of the papers included in the Special Issue, and numerous new questions arose from the fact that some relevant aspects of the many topics related to dam-break modeling have been overlooked. As Guest Editors, we hope that the articles included in the Special Issue and the reflections and proposals advanced in this editorial will be useful and stimulating for researchers involved in this interesting research field, which is so rich in history and has profoundly influenced the evolution of hydrodynamic modeling for over a century.

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