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Large-Scale Two-Dimensional Cascade Modeling of the Odra River for Flood Hazard Management

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Abstract: Large-scale two-dimensional hydrodynamic modeling at high resolution is still rarely performed because of its high computational cost and the lack of topographical data for some areas. Despite this, such modeling has been performed for the Odra River, the second largest river in Poland. This river has a high potential for flooding, which has been severely experienced many times in history, most recently in 1997 and 2010, when floods caused large losses. Since then, many different types of activities have been executed in order to reduce the risk of flooding. The paper presents a 2D modeling concept created during these activities. Given that the river valley is up to several kilometers wide, and consists of many complex topographical features and hydrotechnical facilities, a cascade of 25 2D models in MIKE21 software was developed. It covers a 600 km long section of the Odra River and an area of 5700 km^2 in total. A regular grid resolution of 4–6 m was used in the modeling. The models were applied for numerous purposes, first for the elaboration of flood hazard and flood risk maps for larger cities, and then for the verification of historic flood data and stage–discharge relations at gauge stations, as well as the verification of design discharges via flood routing. Other important uses were the evaluation of the effectiveness of flood mitigating works, including the feasibility study for the Racibórz reservoir, and the assessment of flood hazard due to embankment failure or ice jamming. Selected applications, as well as practical aspects of the model's preparation and use, are presented.

Keywords: two-dimensional hydrodynamic modeling; model cascade; flood; Odra River

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1. Introduction

Flood risk analysis has gained much attention globally due to the increasing frequency and magnitudes of flood disasters in most coastal and riverine areas [1,2]. The year 2023 has seen severe flooding in southern Europe, and a catastrophic flood that killed thousands of people in the city of Derna in Libya. As a result, flood hazard assessment has become a key step in flood risk analysis, which in turn translates into emergency planning, flood risk management strategies, and mitigation and protection measures to improve the resilience of communities living in flood-prone areas [3].

It is widely accepted that a key tool for understanding and predicting flood behavior, as well as for choosing the best course of action for managing the risk of flooding, is flood modeling [4]. Detailed hydrodynamic models that solve the full de Saint-Venant equations are a powerful tool for investigating both the natural flood hazard and the impact of man-made alterations and interactions in the river system, such as reservoirs, polders, and dikes. There are many modeling approaches and numerical tools. Numerical models can be based on simple empirical formulas, conceptual hydrological frameworks, or detailed hydrodynamic solutions. A systematic overview of models for determining flood propagation and inundation is provided by Maranzoni et al. [3], Bates [5], Teng et al. [6], Kumar et al. [7] and Hill et al. [8].

The dimensionality of the model is one of the first and basic choices to make. However, this choice (whether it should be a one-dimensional (1D), two-dimensional (2D), or a combined model (1D/2D)) is still problematic and questionable [9]. Hydraulic 1D models can predict flood propagation in channels and narrow valleys with reasonable accuracy and good efficiency [6,10,11]. In most cases concerning natural rivers, 2D flow patterns are predominant, and therefore the use of 1D approaches is a sort of simplification, which can be seen to be either more or less successful [12]. More complex software packages can simulate quasi-2D situations as a series of interlinked channels (e.g., Willems et al. [13]). Even with this ability, 1D modeling is still only appropriate for modeling well-defined and constant flowpaths; the model cannot match the flexibility of the 2D and 3D modeling necessary for representing complex channel/floodplain interactions [14]. Moreover, such quasi-2D solutions may eventually become more complex, both in terms of numerical schemes and data pre- and post-processing, e.g., when creating 3D water surfaces for inundation mapping (discontinuity problems).

Therefore, 2D or hybrid 1D/2D approaches can be more viable or necessary for wide floodplains and complex terrain regions with elevated roads, secondary dikes, levees, buildings, and other obstacles [9,15–19]. In all of these approaches, correct topographical representation is a key aspect, as it brings the model closer to reality and allows water volumes and river conveyance to be correctly modeled [20]. Generally speaking, creating a topographic representation of river systems is a challenging task because of issues associated with interpolating river bathymetry, as well as integrating this bathymetry with surrounding topography. For example, Cook and Merwade [21] and Falter et al. [22] showed that the flood inundation area not only reduces with improved horizontal resolution and with vertical accuracy in the topographic data, but also when incorporating river bathymetry in the topography data. Therefore, a more detailed geometry has a significant impact on the hydraulic modeling results, not only concerning the extent of flooding, but also regarding the distribution of flow velocities and bottom shear stresses. These velocities and stresses are also important for estimating the potential of risk and for the mapping of hazard zones [23]. This is of particular importance in urban areas. Fewtrell et al. [24] concluded that the model's resolution has to be set up to the characteristic scale of building size and street width in order to obtain accurate predictions of flooding.

Large-Scale 2D Models

The practical application of 2D flood inundation models has often been limited by the computation time and processing power of standard desktop PCs when attempting to resolve flows using the high-resolution grids that are necessary to replicate urban features [24]. Two decades ago, large-scale high resolution applications were rare, and hydraulic modelers often dealt with tens of km^2 [25]. In such cases, mesh sizes were equal to thousands, or even hundreds of thousands of computational cells. According to Hill et al. [8], all searched 2D modeling has been completed at a scale of <100 km^2, with a majority being focused on assessing the impact of natural flood management sites on locations directly downstream of sites rather than the whole catchment. For large scales, i.e., river or basin scales, 1D modeling is normally executed [26–28]. Nevertheless, 2D models have recently been applied more often, even in prognostic modeling. This is due to the fact that large-scale predictions of streamflow and inundation maps are very useful for operational disaster information systems [25,29–31]. Relevant to the goal of regional-scale flood modeling at high resolution, large-scale hydrological models have also been coupled to flood inundation models, and these also have the capability of being driven by climate model outputs. For example, model cascades have been run over the Ohio River basin in the USA [31], or the Elbe River basin in Germany based on 1D for river network and 2D for hinterland inundation at a "relatively high resolution of 100 m" [22].

Hybrid 1D/2D models have recently received a lot of attention and can be a good choice when the size of the main channel is relatively small compared to the floodplains, and also when simulating flows ranging from low to high. In this approach, the water flow in a main channel or river network is calculated using 1D models in cross-sections capturing the geometric details more accurately, but at discrete distances, while the flow in the flood domain relatively realistically captures the 2D model. In the case of dam breach applications, hybrid models are used to derive 1D-based breach outflow hydrographs, whereas 2D models are used for flood plain modeling and the generation of inundation maps for areas downstream of a dam [32,33]. Such solutions significantly reduce the computational demand. Schumann et al. [25] proposed a flood inundation forecasting model for large scales (i.e., domain sizes ranging from several tens of thousands of km^2 to millions of km^2). For this, a hydrodynamic component with a simplified version of the shallow water equations that neglects advection and complemented this formulation with a subgrid structure for simulating flows in channels much smaller than the actual grid resolution of the model was implemented. Kiesel et al. [29] proposed the consecutive application of three models: a hydrologic model, a 1D hydraulic model, and a 2D hydraulic model with scales of 50 km^2, 9 km, and 230 m (reach), respectively. Pasquier et al. [34] aimed to evaluate the sensitivity of a complex coastal environment to different sources of flooding. A 1D/2D approach using the new tools made available in HEC-RAS version 5.0 was found to be appropriate for flood mapping in this context. It accurately reproduced the flow of water in both large floodplains and urban areas, while at the same time reducing computational requirements. Lower simulation run times enabled a larger modeled area to be covered. Due to the increasing coverage of land by fine-resolution LiDAR data in the UK, there are better conditions for using 2D modeling [8,34].

Nevertheless, performing 1D/2D modeling also has disadvantages. In attempts to cover larger areas, coarser models are not able to represent the smaller-scale floodplain dynamics and connectivity [35]. It is necessary to avoid the double modeling of water volumes and conveyance in the main channel, and, in case of SOBEK modeling, a 2D grid cell should be approximately as wide as the riverbed or wider but not smaller. Another important issue is that the method of overflowing the 1D channel has to be defined beforehand [36]. Similar issues are valid for MIKEFLOOD hybrid modeling. Exchange processes between the main channel and floodplain (lateral weirs are normally used for connection) may be prone to distorted representation, and in turn induce numerical instabilities. Hybrid models, when compared to 2D models, are more complex in terms of their structure and use, which is not always compensated by the shorter time of the computational phase. Therefore, as an example, an upgrade of the hydraulic models for the transboundary Lusatian Neisse River (in Polish—Nysa Łużycka) will be executed by the Saxony and Brandenburg states of Germany. It will involve changing the current 1D or hybrid MIKE FLOOD models into full 2D models (HYDRO_AS-2D) with an increased flexible mesh resolution. For the Polish part of the Lusatian Neisse River, it has also been found that the full 2D model (MIKE21) provided better flooding estimates than previous quasi-2D (MIKE11) or hybrid 1D/2D (MIKE FLOOD) models of similar grid size [37].

It is stipulated that reduced-complexity approaches are often sufficient for providing satisfactory results with regards to the extent of inundation when compared to more complex schemes [20]. However, in studies for which the hydraulic variables are used for hazard assessment throughout the flooded area, a more accurate approach should be used [38]. In particular, information on the propagation of the flood wave, water depths and velocities, and the rate at which the water level rises, is very important for emergency planners in charge of evacuation. Moreover, it is also crucial when estimating the potential loss of life. Still, further analyses are required in order to evaluate other important parameters that are necessary for assessing the flood hazard. For example, in steep upstream areas and next to dyke breach locations, flow velocity is a very important factor for determining flood damage. For this reason, accurate and local assessments of flood hazard in each point of the domain should require the use of 2D fully-dynamic models that are also capable of simulating flows, including supercritical, accurately [39,40].

Taking the above into consideration, the paper presents the unique concept of 2D modeling for a large area. This area includes a 600 km long section of the Odra River, for which a series of complementary interlinked hydrodynamic models in a cascade arrangement was prepared using commercial MIKE21 software. The research was initiated more than

10 years ago in order to provide new numerical tools that help to resolve multiple scientific and practical problems related to the river's hydrology and flood hazard management. The paper aims to describe the achievements and experience gained during that time. Several relevant case studies are presented. In addition, various aspects related to the acquisition of data and the solving of problems that occur during the development and use of 2D models are described.

2. Case Study—The Odra River

The Odra River has its sources in the Czech Republic. It then flows through the south-west of Poland, forms a border between Poland and Germany, and finally meets the Baltic Sea via the Szczecin Lagun (Figure 1). It is 854 km long (with 742 km in Poland), and its catchment area comprises ca. 33% of the territory of Poland [41].

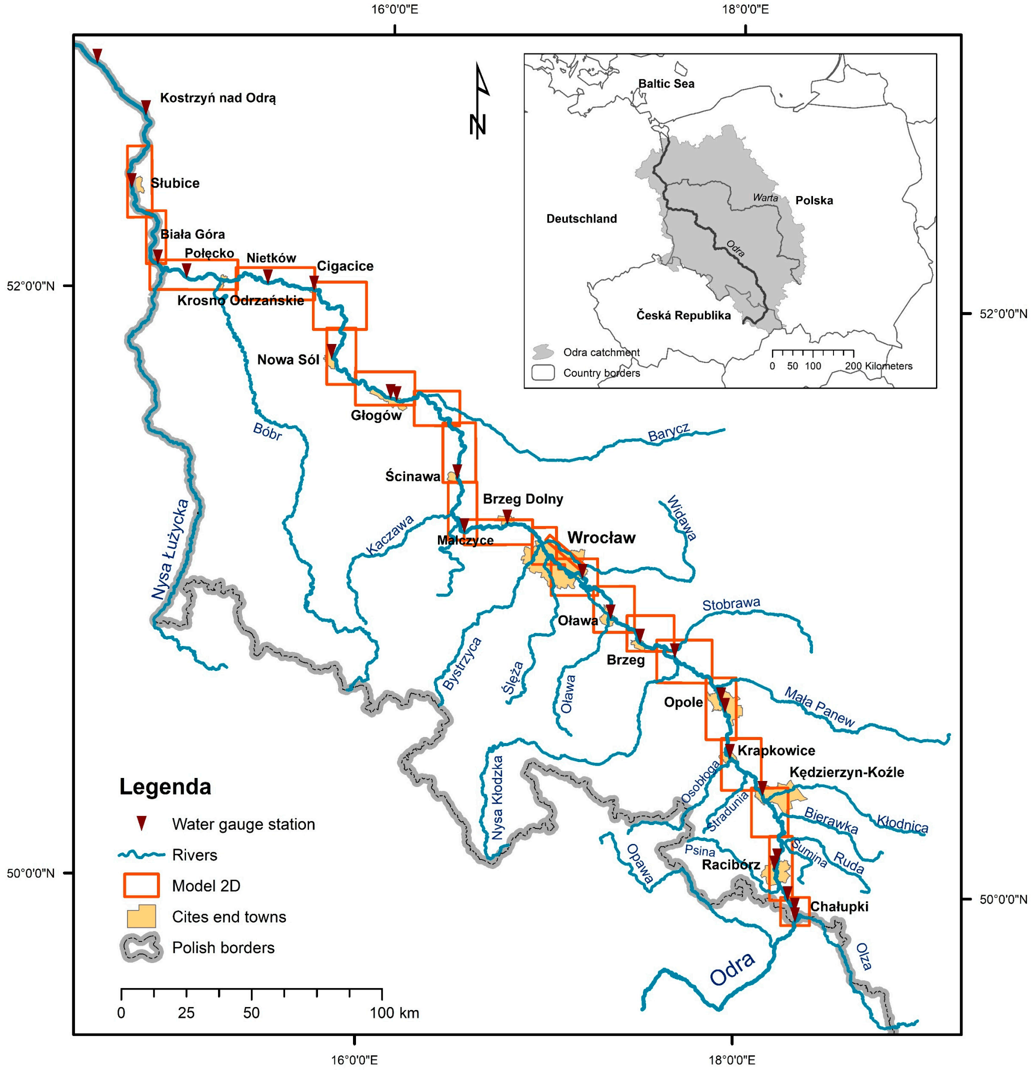


Figure 1. The cascade of the MIKE21 models for the upper and middle course of the Odra River.

It is a regulated river, and its systematic regulation began in the 19th century. This regulation involved cutting off meander bends in order to shorten the length of the riverbed, as well as the building of groins to ensure favorable conditions for navigation and to enable the free movement of sediments without creation of pools and riffles. In the 20th century, the section from 98.1 m to 302 km was canalized using 25 barrages. The Odra Valley is up to 5 km wide, and along the entire Odra River, there is a system of polders and a system of flood embankments running at various distances from the riverbed (most often located at a distance of 200–500 m). There are navigation channels and water nodes with relief channels (in the cities of Racibórz, Opole, and Wrocław). Below Malczyce, the river flows freely—it has numerous groins, bends, and crossings with roads, i.e., bridges.

The mean annual discharge downstream changes from 41 $m^3 s^{-1}$ in the upper course to 535 $m^3 s^{-1}$ at the river mouth. The river has a high potential for flooding, which has happened many times in its history, most recently in 1997 and 2010. These floods, in the densely populated and intensively used river valley, caused human and animal casualties, as well as material losses worth billions PLN [42,43].

Due to the above, many activities of a different type and scale have been executed to reduce the risk of flooding [44,45]. In 2007, the Odra River Basin Flood Protection Project was implemented. The main objective of this project was to enhance flood protection for areas located in the Odra Valley, from Racibórz downstream to Wrocław. This objective was achieved by the construction of the Racibórz dry polder and improvements to the flood control structures and facilities of the Wrocław Water Node designed to increase the flood carrying capacity of the Odra River channels through and around Wrocław. The Project provided flood protection for the population living in Racibórz, Kędzierzyn-Koźle, Krapkowice, Opole, Brzeg, Oława, and Wrocław, as well as other towns and villages located in the Odra valley in three voivodeships (regions): Śląskie, Opolskie, and Dolnośląskie [46].

Recent nationwide actions, which are compliant with EU policy regarding floods, included the development of flood hazard maps and flood risk management plans. These activities also comprised the design and assessment of the efficiency of different flood countermeasures—both technical and non-technical. For this purpose, reliable hydraulic modeling tools were necessary for predicting the discharge–water level relationship, flood inundation maps, and flood risk maps.

3. The Concept of Two-Dimensional Flood Modeling

Parallel to 1D modeling, work on the development of 2D modeling for the Odra River was also undertaken. It began in 2011 as part of the nationwide project called "IT System against Extraordinary Threats" (https://www.isok.gov.pl/index.html, accessed on 15 November 2023). At that time, a digital terrain model (DTM) for the main Polish rivers and their tributaries began to be developed. Moreover, data concerning land cover and land use were acquired, and new aerial photos capturing the whole catchment areas of rivers were also taken. These new data, together with processing systems (GIS) and hydraulic modeling software (MIKE by Danish Hydraulics Institute—adopted for wide use in Poland by a governmental water authority), formed the basis for a new quality of numerical flood modeling.

The methodology adopted at that time for preparing flood hazard and flood risk maps assumed the obligatory development of 2D models for cities with a population of over 100,000. In the case of the Odra River, this concerned the cities of Opole and Wrocław (120,000 and 700,000 inhabitants), for which the first 2D models were developed. Afterwards, due to the significant degree of hydraulic complexity during high waters, subsequent 2D models for the cities of Racibórz, Kędzierzyn-Koźle, and Brzeg were also prepared. This is when the concept of covering the entire course of the upper and middle Odra River (up to the city of Słubice) with 2D models in the form of a cascade was introduced.

For this purpose, MIKE21 software (version 2011) was used [47]. The MIKE FLOOD hybrid model was also often applied for modeling the small tributaries of the Odra River. However, for the Odra River itself, the full 2D solution was chosen due to the following reasons: a more realistic and continues momentum and mass exchange between the main channel and flood plain, an easier model set-up, uniform model structure, and model outputs over the whole computational domain, facilitating the management and postprocessing, and, importantly, higher numerical stability when compared to the hybrid model. Therefore, when developing the first models, as well as the overall concept, the optimal resolution of the individual models was sought. The types of tasks to be solved, and their accuracy in relation to the necessary calculations, were taken into account. This in turn determined the size of the models, as well as their number and location.

The Odra's main channel has a width ranging from ca. 30 m (upper course) to 100 m (lower course). A regular 4 to 6 m grid resolution was used to represent the existing bathymetry conditions, including the presence of groins and numerous hydraulic structures. It also relatively well simulates the flow over the entire area. Hydraulic models are not only sensitive to topographical data, but also to the choice and fundamental design of boundary conditions [34]. Therefore, when establishing the boundaries of the models, it was attempted to designate these boundaries perpendicularly to the river valley. In addition, the model ranges were delineated in a way that the mouths of the tributaries were not close to the boundaries, and therefore were not affected by boundary conditions. Furthermore, neighboring models overlapped in order to minimize the influence of boundary conditions on the calculation results. In multiple cases, boundary conditions were set separately for the channel part between the levees, and for the floodplains beyond it. Neighboring models supplemented each other with data concerning the boundary conditions with regards to separated flows and water levels, in particular cross-section parts, especially during the simulation of extreme floods.

It was assumed that the individual models had about 10 million calculation cells (max. 12.1 million), which allowed up to 34 km long river sections and an area up to 380 km^2 to be covered. The increase in the resolution of the grid not only requires a larger number of computational cells, but also a shorter computational time step due to the need to satisfy the Courant criterion. The calculation time step was usually 0.75–1 s. In the Wrocław and Opole models, the time step was reduced to 0.5 s. due to encountered numerical instabilities, especially in the vicinity of water structures. In fact, coping with numerical instabilities was one of the most difficult modeling issues, and required compliance with the rules for preparing computational bathymetry. The calculation time was also kept within reasonable limits. The present version of MIKE21 is supported by 4 core parallel computations. With a shared 16 core processor, it was possible to run 4 models at once. A model with ten million cells was run with a ratio of modeled time to computer time of 1:3–5, depending on the wetted area (inundation extent). Therefore, a 2–3 day flood hydrograph needed approximately 7–10 days of work from an efficient desktop from the beginning of the previous decade (i.e., HP600 with Intel® Xeon® CPU E5620 @2.40 GHz, and a RAM of 8 GB). A longer computation time was used in special cases. To facilitate the execution of consecutive scenarios, a "hot start" procedure was used, which utilized previous results for further computation, and significantly shortened the computation time both in steady and unsteady flows.

As a result of present conditions, assumptions, and compromises, 25 individual models were created in order to fully cover the Odra River from the Polish and Czech Republic border (19.0 km) to the city of Słubice (603 km) on the border with Germany (Figure 1).

4. Model Set-Up

The MIKE21 flow model is a finite difference model that has constant grid spacings in the x- and y-directions, and therefore the model area has to be rectangular. The model is based on the depth-averaged Saint–Venant equations, which describe the evolution of the water level and two velocity components under the assumption of incompressible flow, uniform density, and hydrostatic pressure. The mass conservation and momentum equations that were used in the model may be found in reference [48], as well as in software documentation [49].

4.1. Bathymetry

The computational bathymetry is based on two sets of data. For the river and linked channels, the cross-sections covering the river bottom and banks were measured at different distances, ranging from hundreds of meters to ca. 1.0 km. In the vicinity of hydraulic structures, additional cross-sections were made in 2012. Simultaneously, aerial laser scanning (LiDAR) was executed in order to provide a digital terrain model (DTM) in two standards—the 1st or 2nd standard (for cities). It had the following parameters: a density of 4–6 points per m^2 (for the 1st standard) and 12 points per m^2 (for the 2nd standard); an average vertical position error of 0.10 m; and an average horizontal position error of 0.4 m. Based on these point data, a DTM raster with a resolution of 1 m by 1 m was supplied.

Hydraulic models are sensitive to the quality of topographical data, but their implementation into the model bathymetry is equally important. It is important that no falsification of the actual flood-relevant topography is introduced during the integration of rasters, i.e., the transition from a raer of higher to lower resolution. Therefore, a dedicated interpolation procedure was elaborated in order to preserve the actual elevations of the embankments. For the main channel, a cross-section to cross-section interpolation procedure was used to create a 3D numerical model within the water surface limits of the DTM. This procedure was even applied for the channel networks [50] or groin-regulated river sections (see Figure 2). Both parts of the bathymetry, i.e., for the floodplains and river channels, were then merged. All of this was done using ArcGIS (v. 10), which created files that were ready to import to MIKE21. The main channel topography and the embankment elevations were then checked by comparing them with geodesy longitudinal profiles or cross-sections.

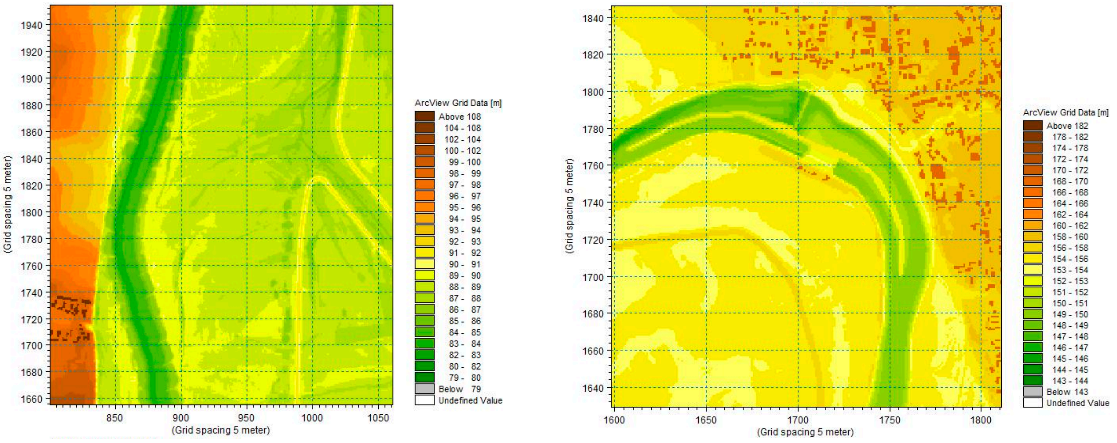


Figure 2. Bathymetry of the model, which was obtained by merging the integrated raster for the floodplain with the raster obtained from the interpolation of the cross-sections for the part of the main channel covered with water—groins regulating a section near Ścinawa (**left**); and the Groszowice barrage near Opole (weir and the navigation channel with a lock (**right**)).

The final steps of the computational bathymetry preparation involved the implementation of buildings, as well as hydrotechnical and other structures, by adjusting the ordinates of corresponding grid cells. In the case of buildings, this procedure was automated by using the land data. In turn, hydraulic structures were implemented manually in order to ensure the appropriate representation of their geometry in the model with a given resolution of the computational grid (Figure 2).

4.2. Roughness

The roughness parametrization is another crucial aspect of the model's preparation [36]. The uncertainty in Manning's n roughness estimates has a considerable impact on model accuracy, and for overbank flow events, obtaining more representative floodplain n values is more important and labor intensive than estimates of main channel roughness. Werner et al. [51] aggregated detailed information on land use types to form one, two, or five classes of floodplain roughness. The model's performance with regards to the calibration data showed that as the number of floodplain classes increases, sensitivity to these roughness values decreases, given allocation of prior roughness values on the basis of constituent land use types and associated roughness values found from the literature.

By knowing the above, a raster of the initial roughness was prepared on the basis of land cover data and aerial photos, including up to 15 roughness classes: the river channel, open surface waters, grassland, bushes and tree areas, paved surfaces, roads, etc. The roughness parameters (expressed by the Strickler coefficient M = 1/n) were preliminarily determined on the basis of guidance, e.g., from [51–53]. For grasslands, the M value was set to 17–25 $m^{1/3}$ s^{-1}, for forests and bushes to 8–10 $m^{1/3}$ s^{-1}. For the main channel, the results of studies by Szczegielniak [54] and Banasiak et al. [55] were useful. For instance, the change in the Mannings coefficient in relation to the change in the flow rate and water depth was known and depended on the topography of the alluvial bed (consisting primarily of sand). The topography of the riverbed can change from ripples to dunes (even the early stage of washed out dunes at high flows). The measured M-values ranged from 34 to 40 $m^{1/3}$ s^{-1} for the main channel of the straight river section.

4.3. Calibration

The Odra River is relatively well monitored by 20 gauge stations, for which hydrometric measurements are systematically carried out. During the great floods in 1997 and 2010, measurements were also conducted that provided a lot of important data. These data concerned water levels, flow intensity, the extent of the flood, high water marks in various locations, and information about breaches in the embankments. Particularly valuable measurement data were obtained for the Wroclaw Water Node.

The calibration and validation of models are most often carried out on the basis of the hydrographs of water levels and flows. For this purpose, reliable and high-quality data are necessary. Unfortunately, complete, or at least satisfactory, sets of such data are rather rare for large floods [56]. Hydrographs of water levels are usually available for gauge stations (unless gauge stations are damaged or destroyed during floods). In turn, discharges (especially for conditions beyond the hydrometric measuring range), which correspond to these hydrographs, are subjected to significant uncertainty, or are even speculative.

Therefore, the calibration of the models was of a complex nature, and involved both adapting the model to the results obtained in situ, and verifying them according to the knowledge obtained from the models. Due to the fact that Institute of Meteorology and Water Management—National Research Institute (IMWM-PIB) carries out hydrometric measurements as part of its responsibilities, it was also possible to use the source data of the measurements, e.g., a review of the files concerning flow measurements carried out using the ADCP method for the flood from 2010. The uncertainties and inconsistencies in the measured flood data were explained, also based on valuable consultations with the people responsible for the measurements [57].

The implemented calibration process was mainly based on the use of the rating curves (within the upper zone of water levels) from individual gauge stations and the high water marks in different locations. The simulation time was also important. Carrying out simulations for a full hydrograph of the Odra River wave (lasting several to a dozen days) would require weeks of computer work, whereas performing quasi-steady or unsteady calculations for just a part of the flood hydrograph was feasible.

In addition, the ADCP flow data were used to validate the partitioning of the flow between the floodplain and the main channel. The measured velocity vectors were also used to compare the calculated velocities in the main channel and floodplain, and to adapt the roughness in several cross-sections. This was necessary for the models of Opole, Brzeg, and Głogów [58].

5. Rating Curves and Verification of Flood Peak Discharges

The maximum flows of historical floods are very important hydrological data. The flood in 1997 was the largest recorded flood in the history of the Odra River, which catastrophically affected three countries: the Czech Republic, Poland, and Germany. After this flood, many hydrological studies were carried out in order to obtain and supplement knowledge about this event [59,60]. These studies perfectly documented the course of the flood. However, in quantitative terms, they were uncertain and seen to be controversial, in part at least. Only after 2010, after implementing the above-mentioned program of actions, it became possible to better determine the hydraulic conditions of this flood. This was thanks to new available data and tools.

It is worth noting that until 1997, flow assessments for the Odra River were based on measurements taken within the range of 1200–1500 $m^3 s^{-1}$, whereas during the flood in 1997, the flows reached values of 3000–4000 $m^3 s^{-1}$. The data concerning the flood from 2010 turned out to be of great analytical support, with maximum flows along the Odra River ranging from 1800 to 2200 $m^3 s^{-1}$. The water levels were similar to those in 1997, but there were less embankment breaches and a much smaller extent of the flood (most of the water flowed between the embankments). These new data filled the gap between the previous data and the 1997 flood data, which in turn allowed for better verification and calibration of hydraulic models, and the correction of hydrological studies.

Figure 3 shows two examples of the calibration/verification of the flow rating curves. In the case of the Krapkowice gauge station, the measurement result in 1997 deviated significantly from the established trend. The conducted measurement probably did not include the total flow, which also happened during the measurements from 2010. Verified flood flows from 2010, i.e., the measured one and the maximum one that is associated with the neighboring water gauge sections (Opole and Koźle, thus respecting the continuity principle), indicate that the rating curve must be consistent with the final simulation results (Figure 3a). The almost straight-line nature of this curve within its upper range is due to the narrowing of the river valley and the presence of an embankment and a railway bridge (1500 m below), which caused a damming effect. This example shows that a number of factors must be taken into account in order to determine Q_{max} (in this case, it was estimated to be equal to approximately 3500 $m^3 s^{-1}$ for H_{max} from 1997). In the case of the Brzeg Dolny cross-section, the compliance of the results of the 2D model simulations and the in situ measurements was obtained quickly, which in turn allowed for the extrapolation of this curve (Figure 3b). The breach in the embankment that occurred above the gauge station was taken into account. Thanks to this, the uncontrolled flow was also determined, due to which the estimation of the entire maximum flow was made more precise (from the value of 3200 to approximately 3500 $m^3 s^{-1}$).

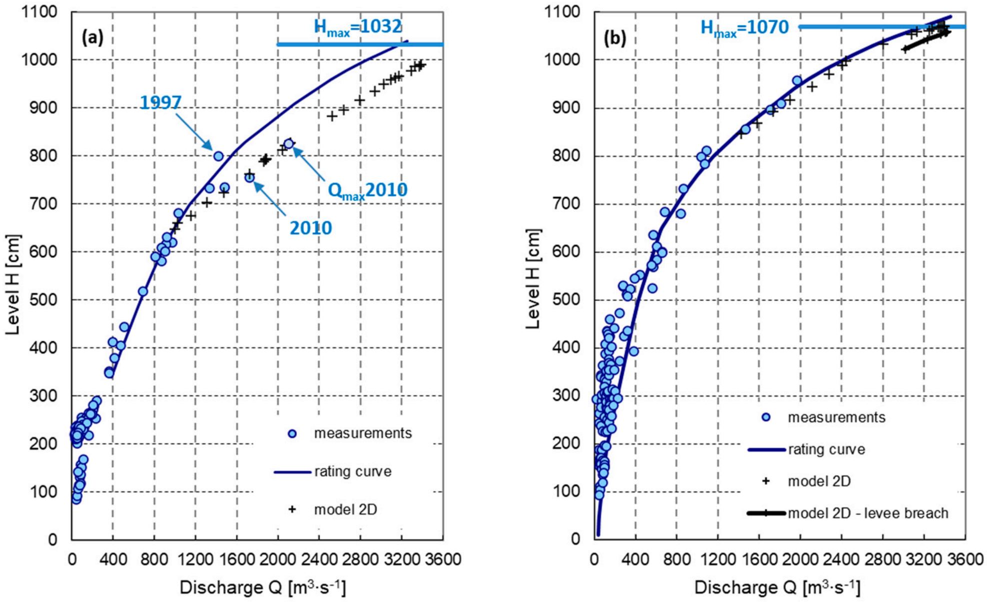


Figure 3. Calibration of the models by fitting the rating curve to the measured and verified flood discharges: (**a**) Krapkowice cross-section—verified rating curve; (**b**) Brzeg Dolny with the analysis of the levee break upstream.

As a result, the verification of the flows was carried out for almost all water gauge stations along the Odra River. Selected values are given in Table 1, which shows large discrepancies between current values and early estimates (up to 35 percent). In addition, the impact of valley retention on the propagation of large flood waves was better determined and understood. This is one of the major outcomes of performing 2D modeling for the Odra River—an outcome that could not be achieved using a 1D approach. More practical benefits are presented in the next section.

Table 1. 1997 flood peak discharges according to past estimates [59] and the current results based on 2D modeling.

	Chałupki (km 20.7)	**Opole (km 152.2)**	**Brzeg (km 199.1)**	**Wrocław (km 242)**	**Ścinawa (km 331.9)**	**Głogów (km 392.9)**	**Połęcko (km 530.3)**
Before	2160	3100 (3500)	3530	3640	3000	3040	3200
Based on 2D model	2950	3400	4200	3900	3000	2300	2250
% change	35.6	9.7 (−2.9)	19.0	7.1	0.0	−24.3	−29.7

6. Applications

6.1. Flood Hazard and Flood Risk Management

The development of the flood hazard and flood risk maps was the primary reason for conducting the numerical flood modeling (including the 1D, 1D/2D, and 2D approaches). Flood hazard maps were meant to cover the areas that can be flooded, whereas flood risk maps were developed in order to show the potential adverse consequences that are associated with different flood scenarios. The Floods Directive in the EU assumes 6-yearly cycles that aim to reduce the risk of flood damage. The first cycle of implementation in Poland was from 2010–2015, with the second cycle covering the period from 2016–2021. Developing and updating flood hazard maps and flood risk maps has a key impact on the safety of inhabitants and material resources in the areas covered by the studies. These maps are also the basis for planning subsequent actions—establishing land development plans by local governments, or planning investments. They are also used as the basis for planning flood prevention measures, such as, e.g., the (re)construction of dikes, polders, or other structures. All interventions were studied in detail within flood risk management plans. The flood hazard and risk maps can be found on the dedicated governmental website [61].

The applied 2D hydraulic modeling was the basis for defining the flood hazards for three scenarios of flooding (with a return period of 10, 100, and 500 years). It also provided data for flow velocity mapping in urban areas. Moreover, it was used to study both flooding caused by the embankment's failure (for a return period of 100 years), and also winter flooding caused by ice jamming. The developed models were also applied in the assessment of the efficiency of individual or mutually related flood protection measures, including the construction of the strategic Racibórz reservoir and the construction or reconstruction of 140 km flood embankments. 2D modeling is especially useful for floods with a long return period—when the water levels rise above the existing embankments. 2D modeling more accurately indicates (when compared to 1D modeling) hazardous "hot spots" and the extent of inundation.

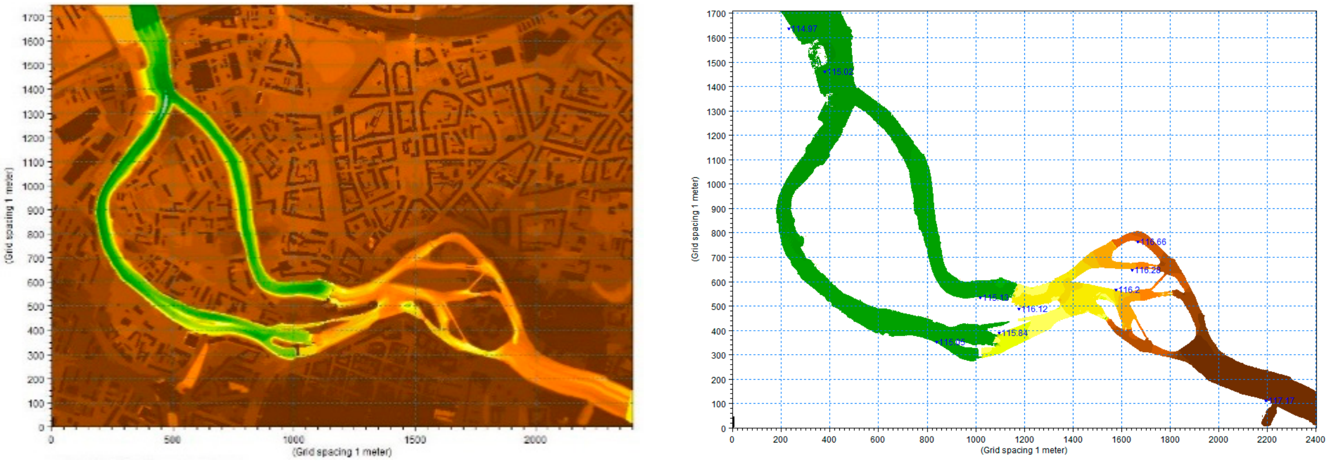
As part of the first planning cycle, six 2D hydrodynamic models were developed and used for flood hazard management. The models covered 105 km of the Odra River and 22 km of the Widawa River (tributary). In the second planning cycle, 14 models covering 370 km of the river were used for the same purpose (primarily for the upper and central Odra). In turn, further downstream, 2D models were also used to prepare a concept for the development of inland navigation on the Odra.

6.2. Modeling of the Wrocław Water Node

The Wrocław Water Node (WWN) was a particular challenge regarding its hydraulic modeling. It is a complex system of river channels and canals, with many hydrotechnical structures. The WWN is part of the so-called protection system for the city of Wrocław, which also includes sections of the Odra River from the gauge station in Brzeg (km 199.1) to the gauge station in Brzeg Dolny (km 284.7). This system also includes the towns of Brzeg and Oława, as well as the polders of Lipki-Oława, Oława, and Blizanowice, including their accompanying inlet and outlet facilities.

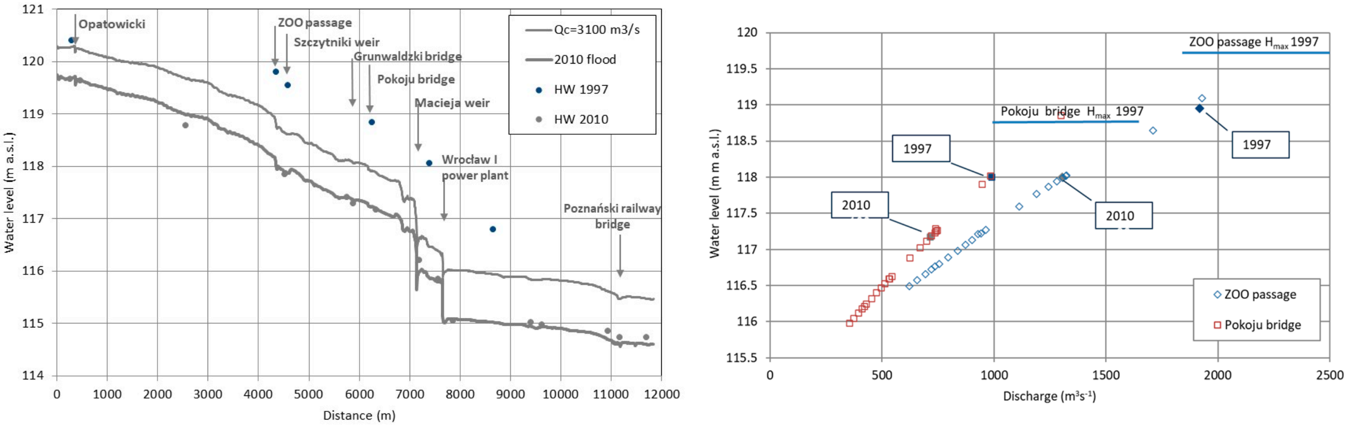
Due to the large area of the Wrocław Water Node, five models were developed: two models for the city of Wrocław, two for the Widawa tributary (including the Odra–Widawa connection canal), and one model with an increased resolution for the City Center Hydrosystem (CCH), which covers the central and oldest part of the city (Figure 4). A careful calibration process was executed to ensure proper model performance [62]. This was possible due to the data from the flood from 2010, which was obtained from the dedicated extensive hydrometric measurements of the flow rate and water levels at critical points of the system. After the calibration, the models were used for a reliable extrapolation of the results to higher flows (500- and 1000-year water), for which the WWN was redesigned after the flood in 1997. Moreover, using these hydrodynamic models, calculations were carried out to verify the maximum flow of that flood. In Wrocław, it amounted to approx. 3900 m^3 s^{-1}, with 3640 m^3 s^{-1} being the figure that was previously established. In fact, the verification of this peak flow was the starting point for the high peak flow verification of the whole Odra River.

In the years 2013–2016, the main part of the modernization of the WWN was conducted. It was a one billion PLN investment that aimed, together with the construction of the Racibórz reservoir on the Upper Odra, to prevent the dramatic effects of the flood that Wrocław suffered in 1997. It is worth noting that the Wroclaw water system was designed at the beginning of the 20th century for the capacity of 2400 m^3 s^{-1}, whereas now its capacity has been increased to 3100 m^3 s^{-1} (design discharge). A number of water structures were reconstructed, the channels were deepened and widened, and the flood embankments were moved, removed, or raised. All completed works were included in the update of the hydraulic model, and new flood hazard maps were developed. At the same time, the effect of these investments on the capacity of the WWN was assessed [63]. It was established that the current capacity of the system is even higher than the designed assumptions that were determined on the basis of the 1D model. However, some negative aspects of the WWN's modernization were also revealed, i.e., the limited effectiveness of some solutions, e.g., adaptations of the City Channel (navigation channel) and the navigation locks of the Rędzin barrage for flood passage. This emphasizes the importance of detailed hydrological and hydraulic analyses when planning such investments.



(**a**) (**b**)

Figure 4. *Cont.*



(**c**) (**d**)

Figure 4. 2D model of the Wrocław City Center Hydrosystem: bathymetry of the 2D model with a grid resolution of 1 × 1 m^2 (**a**), the calculated water level for the 2010 flood (with the measured water levels (ZWW), (**b**)), design water level profile against the flood data (HW) (**c**), and rating curves for selected cross-sections (**d**).

6.3. Dam Break Modeling

As already mentioned, the embankment break scenarios were part of the flood risk assessment. From a methodological point of view, this is not a simple matter. Taking into consideration the hundreds of kilometers of embankment, a large number of potential threats in various locations, as well as different sizes and rates of breaching, can be assumed. In the first planning cycle for the Odra River, 30 cases of breaches in the embankment were considered, with all of them being analyzed using 2D models for a flood occurrence probability of $p = 1\%$. An example is illustrated in Figure 5. In the conducted simulations, the time of outflow through the breach was from 1 to 3 days. The simulations involved the removal of a part of the embankment to its base, and the creation of 80–100 m wide breaches (according to real cases) in selected locations that have the greatest risk of flooding. It is worth noting that MIKE21 software gives the possibility of using dynamic bathymetry, i.e., defining the change of bathymetry from state A to state B according to linear interpolation in a given time. Due to this, it is possible to better simulate the washout of the breach and outflow dynamics. This procedure, however, significantly increases the computer simulation time and the size of output files.

The presented simulation case is of particular interest because it refers to the dramatic situation of an attempt to deliberately break the embankment in this place in order to protect the center of Wroclaw before the peak of the wave in July 1997 (at the expense of flooding the nearby village). It was then, due to opposition and active resistance of the inhabitants, that this situation did not take place, despite the actions of sappers that had already been undertaken [64]. Breaking the embankment would not save Wroclaw, but instead it would cause additional losses for local settlements. This retention area, with hindered outflow, was too small to have a significant effect in the face of such a scale of flooding. This erroneous and fortunately unsuccessful attempt became one of the least positive episodes of crisis management at that time. It resulted from making decisions in conditions of great uncertainty, as well as the ignorance of some authorities. This event also became the basis for a widely known film plot.

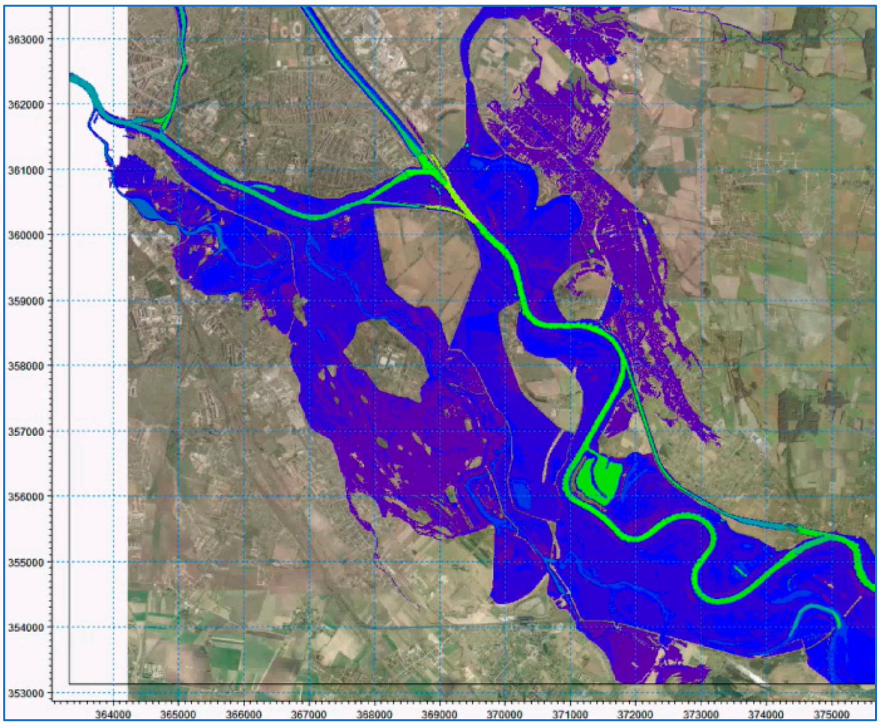


Figure 5. Dam break simulation at Łany near Wrocław (right bank) for a flood of exceedance probability p = 1% (visualization in MIKEVIEW).

6.4. Ice Jam Flood Modeling

Ice phenomena occur on the Odra River, which may cause ice jams and ice jam floods [65]. In 2015, a feasibility study was undertaken in order to assess the possible hazards and mitigation measures. These measures are already in the implementation phase. The main goal of these measures is to restore the regulation works that are over 100 years old, and to improve unfavorable navigation conditions, also for the effective icebreaking.

The formation of ice jams and their hydraulic capacity are relatively poorly understood phenomena, and there are not many numerical tools to solve such problems [66,67]. MIKE21 software does not offer a direct tool for simulating ice jams. Nevertheless, an ice jam is simulated in a simple and effective manner as an impermeable barrier introduced into the channel at a vulnerable cross-section. Using a "sink and source" tool just upstream and downstream of the "ice barrier" allows for the setting of outflows and inflows at a chosen rate. In the considered case, a flow of 400 $m^3 s^{-1}$ was simulated (the yearly average flow is ca. 200 $m^3 s^{-1}$), with 75, 50, and 25 percent of it being let though the artificial barrier. In this way, various degrees of blocking the flow by an ice jam were simulated. As a result, the remaining flow is collected upstream, in turn causing the water level to rise and backwater to reach the embankment crest. Verifying a number of scenarios allows for the assessment of both the dynamics and reach of the potential ice jam flooding. Such simulations were also combined with the analysis of a dam break in order to obtain a complete picture of the potential depth and extent of flooding. Figure 6 presents a result of such a simulation for the city of Głogów. In this case, the inundation zone beyond the embankments on the right riverbank is large (with a length of more than ten kilometers)—downstream, it reaches the backwater embankment of the tributary. This embankment causes a deep retention basin in the floodplain when the area is supplied with water for a long enough time. Fortunately, most of the city and its industrial zone is located on the left riverbank. Similar modeling was executed for the cities of Nowa Sól and Słubice, with the obtained results being used for a cost-benefit analysis of the project [68].

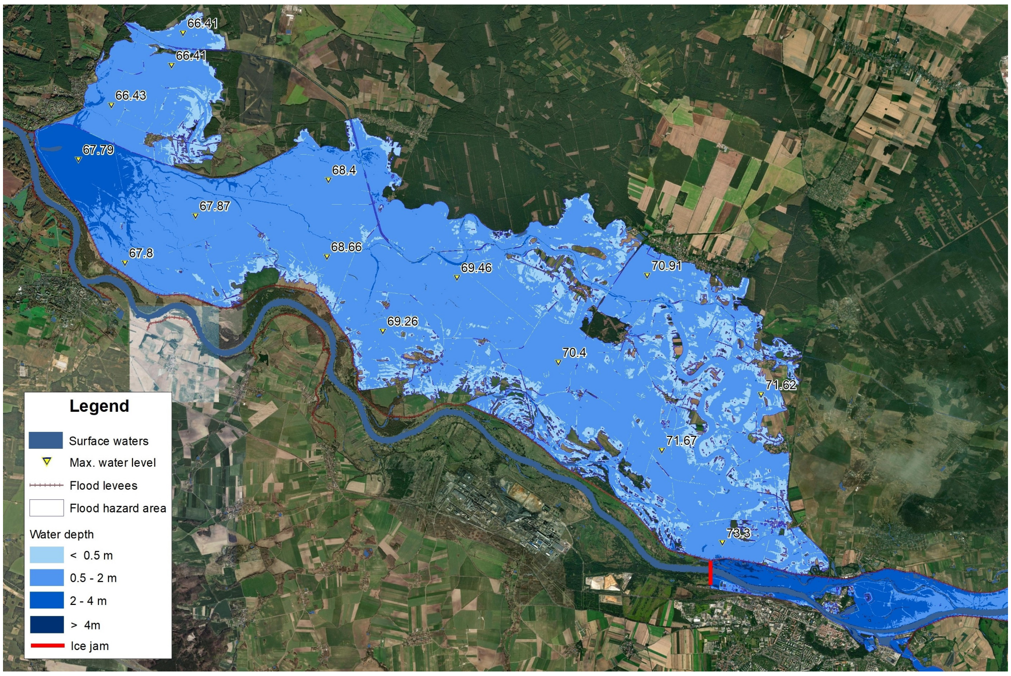


Figure 6. Modeling of flooding caused by ice jams near the city of Głogów [68].

6.5. Feasibility Study for the Racibórz Reservoir

In 2015, the feasibility study for the Racibórz reservoir was updated. During this work, a cascade of 2D models for the upper and middle course of the Odra River was completed. These models were used to re-analyze the impact of the reservoir on the risk of flooding below it, taking into account new hydrological assessments. After calculating the transformation of a wave on the reservoir (using a dedicated 1D model), hazard zones were determined for a 200 km long Odra River section downstream, which reaches the city of Wrocław. Variants with and without the reservoir were considered for 6 flood scenarios that had the probability of occurrence of p = 5, 2, 1, 0.5, 0.3, and 0.2%. This allowed for a detailed analysis of the losses and benefits coming from the construction of the reservoir, and ultimately confirmed the need to construct it. This approach has again significantly improved estimates obtained via 1D modeling in the first feasibility study.

In a more recent study [69] that aimed to obtain a legal permit for the exploitation of the built Racibórz reservoir, an additional 2D model was elaborated. This model covered the whole reservoir area, as well as the area upstream (up to the border with the Czech Republic), and included the polder of Buków that was commissioned for use in 2002. Firstly, this model was used to analyze the transformation of the flood wave in 1997. It was found that the actual flood maximum flow and the volume at the border with the Czech Republic (Chałupki gauge station) must have been much higher than those that were determined after the flood and published by ICPO [60] (cf. Table 1). The next stage involved the simulation of a "worst case" scenario, i.e., the simulation of the passage of a wave that has a very low probability of occurrence, and parameters exceeding those considered in the design. The obtained result is shown in Figure 7. A potential danger for the reservoir in such a scenario is reduced by the fact that the excessive water overflows above the embankment crests (upstream from the Buków polder) and floods the adjacent area (on the right riverbank). This area is an additional storage for the excessive water. However, another problem has been identified, namely a cascade risk related to the possible overloading of the structure (just upstream of the Krzyżanowice gauge) that controls the filling of the Buków polder. The real threat applies to the gabion-reinforced earth dam, which can overflow with water that has velocities of up to 6 m/s. This issue requires further study and adaptation measures.

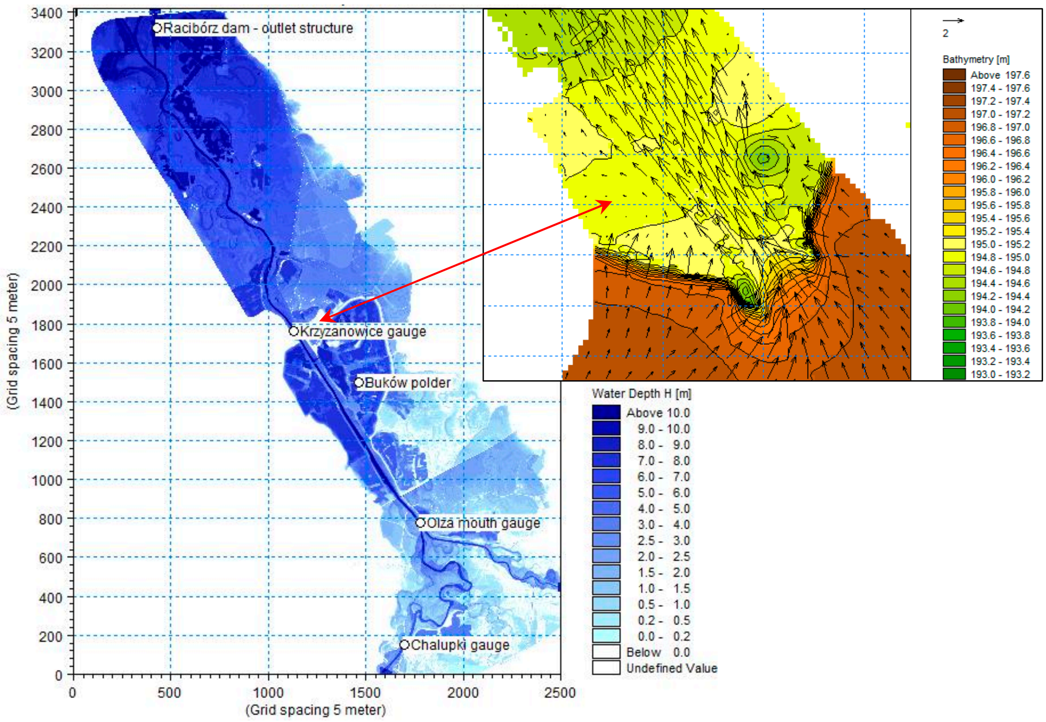


Figure 7. The modeling of the passage of the extreme flood wave through the cascade of the Buków polder and the Raciborz reservoir; right the flow situation around the calibration structure (note local high energy head and velocities—arrow indicates a velocity vector of 2 ms^{-1}).

6.6. Flood Routing and Verification of the Design Discharges

The Odra River has not only been the subject of flood countermeasures, but also actions that aim to develop the Odra River Waterway. These studies also verified the potential and searched for measures to adapt the river to the international navigable class, including plans to build subsequent barrages (Lubiąż, Ścinawa, and others) [70]. Their dimensioning needs scientific calculations, where flood design discharge plays the major role [71]. Design discharges are usually determined based on the statistical approximations and extrapolations of various distributions of the probability of discharges being exceeded. This is in accordance with the applicable hydrological methodologies. However, the predictions of statistical models are inherently uncertain, and it is currently unknown to what extent that uncertainty affects the predictions of the effect of flood mitigation measures [72,73].

Flood routing can be very helpful in estimating flood magnitudes for design purposes. In the present case, 2D flood routing was applied for the subsequent sections of the channelized and free-flowing river sections in order to analyze, as already mentioned, the historical flood propagation, as well as the hypothetical flood waves with a low probability of occurrence (once every 500–2000 years). The modeling showed that the purely statistical approach, which is common in practice, may be significantly misleading in low-probability discharge ranges. This is due to the fact that flood propagation drastically changes under certain conditions, e.g., when the water level rises above the embankment's crest and when additional storage zones are being used (see Figure 8).

Thanks to the use of 2D modeling, more consistent and reliable maximum flows were obtained along the river's course. The differences can reach up to several hundred cubic meters (approx. 20%), which in turn translates into design water level differences of 0.2–0.3 m for p = 0.3% and 0.5–0.8 m for 0.05%. This is obviously important when planning and implementing investments.

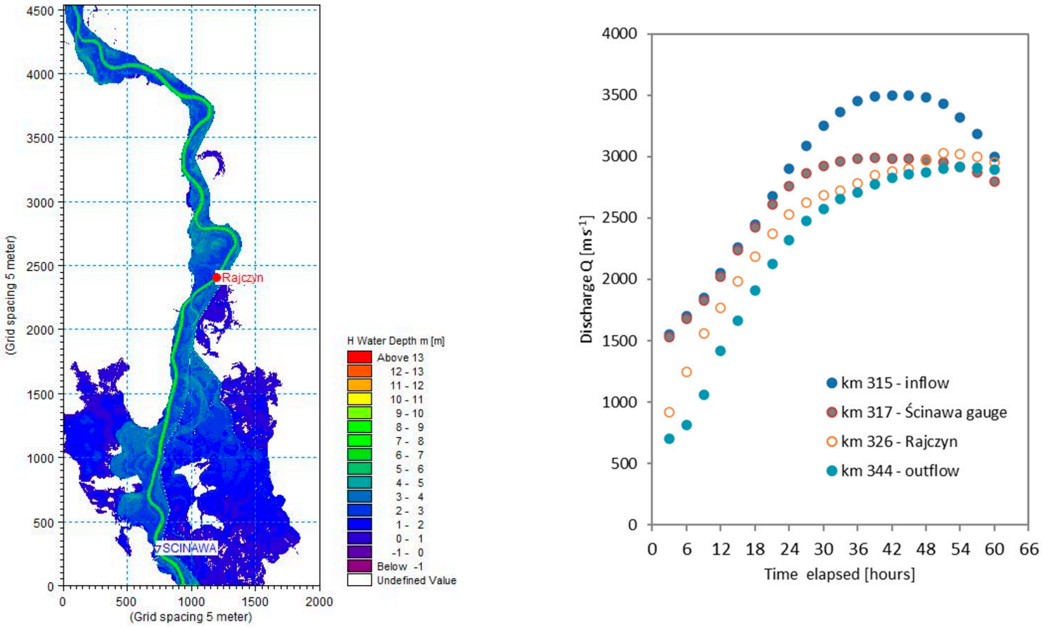


Figure 8. Flood routing for Q_{max} = 3500 m^3 s^{-1}. Maximum capacity of the channel between levees amounts to 2990 m^3 s^{-1}. The remaining water is stored on the floodplain with a length of several kilometers.

7. Future Work

The elaborated 2D models were used multiple times for the assessment of the efficiency of flood protection measures, i.e., the models were updated to be consistent with the actual or design conditions. Similar ones can be used in the future, e.g., for the purpose of constructing new flood embankments between Racibórz and Kędzierzyn Koźle. These investments can easily be incorporated into the model(s), whereas flood hazard maps can be updated (if the impact of these activities on the risk of flooding will be qualified as significant). Other operations related to the current project entitled Odra–Vistula Flood Management Project can also be used in a similar way [46]. This can be done within the ongoing third cycle of the management of flood hazards in Poland.

The uncertainty quantification of predictions and implications for flood mitigation interventions is an important part of hydrodynamic modeling [74]. In fact, despite the considerable effort that has already been made, future work should continue to focus on this aspect of two-dimensional modeling, which contributes to an even better understanding and assessment of the quality of the obtained results, including flood hazard maps.

The presented system of hydrodynamic models is dedicated to simulating floods over large areas. Another goal should involve the improvement of the ability to model transport processes along the riverbed itself, which often have a quite complex configuration. While high-quality LiDAR data were available for the floodplains, the vast majority of the riverbed's bathymetry was based on traditional geodetic measurements of river cross-sections. These discrete data concerning the main channel required the use of a linear interpolation procedure. In the longer term, it is recommended to obtain complete high-resolution bathymetry data of the riverbed, which can be obtained using ultrasonic methods (in some cases, this has already been executed). The implementation of these data in models that are based on a flexible computational grid, and which have an appropriately selected resolution, will allow for a better mapping of both flow conditions in a riverbed and the transport of sediments and pollutants. This last issue has become particularly important after the ecological disaster in the Odra River in 2022, which involved mass fish deaths along its course as a result of blooms of the so-called golden algae (*Prymnesium parvum*). The causes of this phenomenon remain ambiguous and difficult to definitively explain, although water salinity due to industrial releases, combined with high air and water temperature during low flow conditions seems to be the most probable cause of this event [75,76]. The new models can also be used in subsequent projects related to the development of inland navigation.

8. Conclusions

This paper has reviewed flood hazard assessment based on 2D numerical modeling across large river scale, with a focus on spatial process patterns during large hydraulic events. Understanding these processes of flood propagation is not only of scientific interest, but also has enormous practical importance for risk management purposes, including flood forecasting and flood risk assessment in a changing climate conditions. Examples provided include flood protection designs, which has benefitted from the flow studies such as those in Figures 7 and 8. By this, modelers and practitioners may be assisted in selecting the most appropriate flood hazard assessment method for the specific needs and the application of interest, as well as identify references where relevant application examples and case studies can be found. The importance of the quality of hydrological data needed for computer model calibration is also demonstrated. A well-considered (even retrospective) approach, as well as supplementary data collection, can increase the quality of both the original data and the model's performance. As a result, 2D modeling helps the standard of hydrological and hydraulic products to be improved. This justifies the need for spending the necessary costs for developing this modeling, as well as the need for its wide application.

It should be emphasized that investing in high-quality hydraulic simulation tools is an extremely good investment. In turn, savings in this area (possibly excessive methodological simplifications or the lack of competences) may turn out to be expensive. Examples of the effects of these savings, which led to ineffective solutions, may constitute material for a different publication.

The presented approach is based on a rather outdated modeling tool. Improved hydrodynamic software, and an increase in the computing power of computers, enables an even more effective use of 2D modeling in subsequent flood and drought management planning.

In the case of the Odra River, further work is expected to be carried out in two directions: the first is a further quantitative assessment of the uncertainty of flood modeling, and the second is an analysis of water and sediment transport conditions in the river main channel using flexible grid models.

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