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ODRA2D – TWO-DIMENSIONAL CASCADE FLOOD MODELLING FOR THE ODRA RIVER – DEVELOPMENT AND APPLICATIONS

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ABSTRACT

Aim of the study

Development of new hydrodynamic numerical tools for simulations of the flow in the Odra River valley for the flood hazard assessment and management.

Material and methods

Use of the MIKE21 software for model building. Geospatial (ArcGis) topographical data processing and analysis for model inputs and outputs. Extensive use of remote sensing data (digital terrain model and orthophoto maps) combined with traditional data sources.

Results and conclusions

A cascade of twenty-five MIKE21 models was developed to cover a nearly 600 km long section of the Odra River. The models were used in different studies, including: the assessment of flood hazards with regards to various scenarios, the assessment of flooding due to ice jamming and breaks in embankments, the evaluation of the effectiveness of flood mitigating works within the complex water system of the city of Wrocław, the verification of historic flood data and stage-discharge relations, and also the verification of design discharges.

Keywords: the Odra River, 2D hydrodynamic modelling, flood hazard assessment

INTRODUCTION

The Odra River is the second largest river in Poland and is among the top 15 biggest rivers in Europe. It has its sources in the Czech Republic, flows through the south-west of Poland, and forms a natural border between Poland and Germany along its lower course (Fig. 1). The river has a high potential for flooding, which has been seen many times in its history; 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 (Ligenza et al., 2021).

Since then, many activities of varying type and scale have been executed to reduce the risk of flooding. Recent nationwide actions, which are compliant with EU policy regarding floods, involved the development of flood hazard maps and flood risk management plans. These activities also included the assessment of the efficiency of different flood countermeasures – both technical and non-technical. For this purpose, a reliable prediction of the "discharge-water level" relationship, which can be obtained with the use of modelling, is required.

The article presents the numerical modelling of a 600-kilometer section of the upper and middle

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course of the Odra River. Due to long-lasting man-made works, the river has been much transformed, and is now characterized by an extensive system of embankments and polders; a large number of barrages/weirs and navigation channels; and also complex water systems, such as the one in the city of Wrocław. The river's main channel was regulated using groynes.

Therefore, next to a traditional one-dimensional modelling (which has been used for the Oder River since the 1980s), a new approach based on a two-dimensional (2D) model was used to provide the best solutions for solving complex hydraulic problems. The aim of the paper is to present the experiences and achievements from over a decade of work concerning the application and the use of 2D models, encompassed in a cascade. The advantages of using such models in various contexts related to flood management are highlighted.

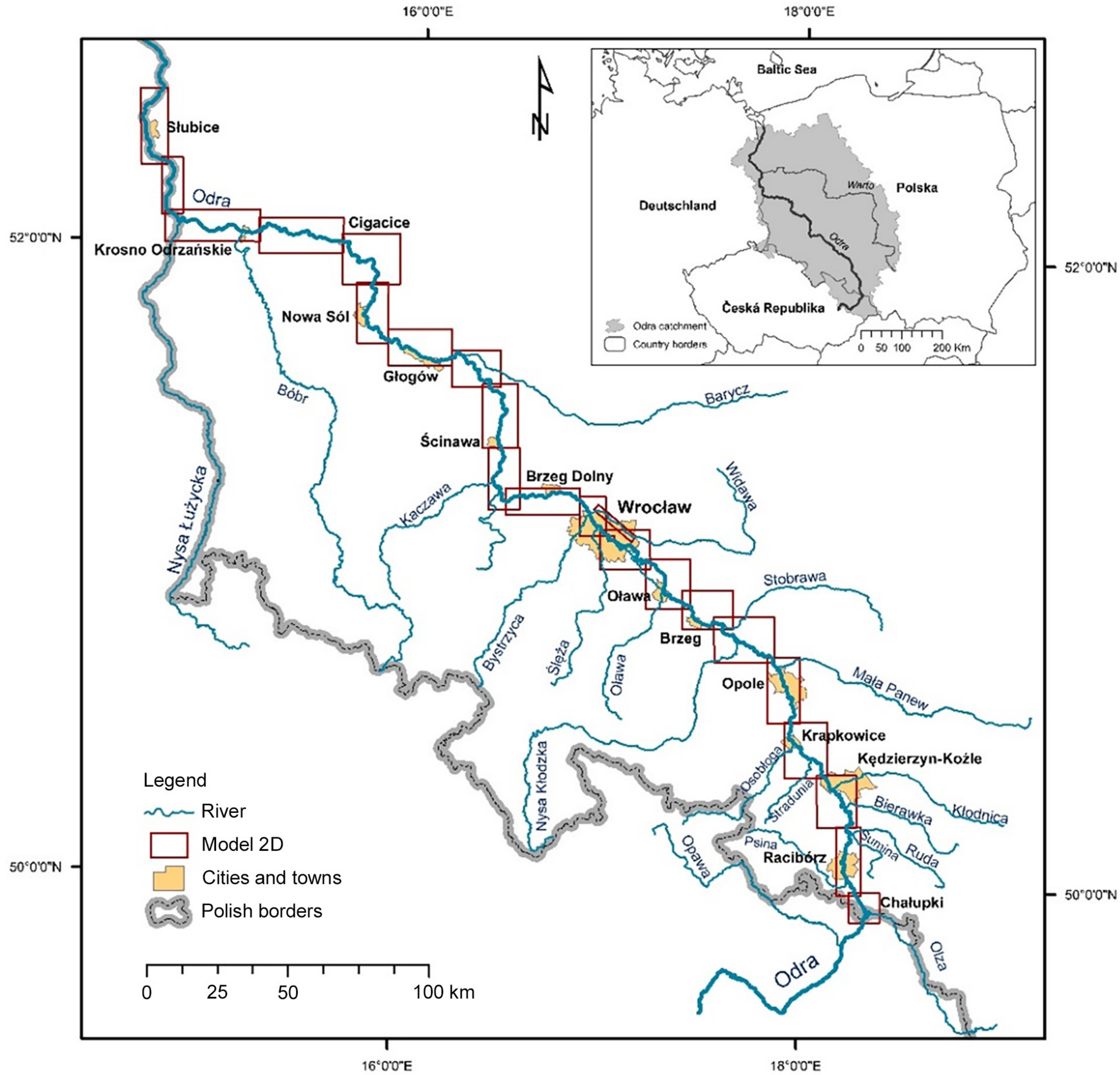

Fig. 1. The cascade of MIKE21 models for the upper and middle course of the Odra River (source: own elaboration)

THE CONCEPT OF TWO-DIMENSIONAL FLOOD MODELLING

Work on the development of two-dimensional modelling for the Odra River began in 2011 as part of the nationwide project called "IT System against Extraordinary Threats" (in Polish: Informatyczny System Osłony Kraju przed Zagrożeniami Nadzwyczajnymi – ISOK, https://www.isok.gov.pl/index.html). At that time, a digital terrain model (DTM) for the main Polish rivers and their tributaries began to be developed on a large scale until almost complete coverage of the entire country was obtained. These new data, together with their processing systems (GIS), formed the basis for a new quality of hydrodynamic modelling, including 2D modelling.

The methodology adopted at that time for preparing flood hazard and flood risk maps stipulated the requirement to develop 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 (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 Oder River (up to the city of Słubice) by 2D models in the form of a cascade was planned. When developing this concept, the feasibility of the project was taken into account, i.e. the availability of software and hardware that would affect the calculation cost. This in turn determined the size and resolution of the models, as well as their number and scope. Hydraulic modelling was executed using MIKE21 software (version 2011) from the Danish Hydraulics Institute (DHI, 2011). When establishing the range and boundaries of the models, because of their rectangular computation grid, it was assumed that these boundaries would run perpendicularly to the river's valley, which was not always possible. The ranges were determined in such a way that the mouths of the tributaries were not close to the boundaries of the model, and therefore were not affected by boundary conditions. Neighbouring models overlapped in order to minimize the influence of boundary conditions on the calculation results.

In most cases, the size of the regular computational grid (square) in the used hydrodynamic software was 5 m, and in the lower course of the river it typically increased to 6 m. The main channel of the river has a width of ca. 30 m (in the upper course) to 100 m (in the lower course). Therefore, the adopted grid allows for a relatively good simulation of the flow conditions as well as topographic and hydrotechnical details. It was assumed that the models had about 10 million calculation cells. It is worth noting that the increase in the resolution of the computational grid results in a larger number of computational cells, coupled with a shorter time step due to the need to satisfy the Courant criterion. The calculation time step was usually 0.75–1 sec. In the Wrocław and Opole models, the time step was reduced to 0.5 sec. due to numerical instabilities, which occurred particularly in the vicinity of water structures. Coping with numerical instabilities was one of the most difficult modelling issues, as it required experience and compliance with the rules for preparing computational bathymetry. The calculation time was also kept within reasonable limits. Depending on the scenario, the calculation time was different, e.g. the simulation of a part of a flood wave (2–3 real days) required 3–7 days of work of an efficient desktop (from the beginning of the previous decade) with four-processor support (Intel® Xeon® CPU E5620 @ 2.40GHz). A longer computation time was used in special cases.

As a result of the adopted assumptions, and also some compromises, 25 individual models were created in order to fully cover the Odra River from the border with the Czech Republic (km 19.0) to the city of Słubice (km 603) (Fig. 1, Tab. 1). All models, however, could be supported and fed by the neighbouring ones with the calculated boundary outputs.

MODEL SET UP

The MIKE 21 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, describing 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 DHI (2017).

Table 1. Parameters of the 2D models for the Odra River (source: own elaboration)

Name	Chainage (km)	River section length (km)	Grid size (m)	No. of cells (10^6)	Model area (km^2)
Chałupki	19–34.7	15.7	5	4.27	107
Racibórz	33.4–69	35.6	5	8.56	214
Raciborz reservoir	19–45.2	26.2	5	8.55	214
Kędzierzyn-Koźle	68.8–102	33.2	5	9.99	250
Krapkowice	100–134.1	34.1	5	12.11	303
Opole	134–162.5	28.5	5	9.95	249
Ujście Nysy Kł.	161–191	30.0	6	9.68	348
Brzeg	186.5–208	21.5	5	9.72	243
Olawa	205–232	27.0	5	10.87	272
Wrocław-1	230–258.5	28.5	5	9.26	231
Wrocław-2	256–273.4	17.4	5	5.14	129
Wrocław-CCH	251.1–254.6	3.50	1	4.20	4,2
Widawa-1	2.8–22.5	19.7	4	2.78	44,5
Widawa-2	21.7–48.3	26.6	4	8.90	142
Brzeg Dolny	273.2–305	31.8	5	8.68	217
Malczyce	299–330.1	31.1	5	9.39	235
Ścinawa	330–360	30.0	5	9.07	227
Orsk	359–385	26.0	5	9.22	231
Głogów	384.5–413.8	29.3	5	11.52	288
Nowa Sól	413.5–443.8	30.3	5	9.63	241
Cigacice	443.2–471	27.8	6	10.20	367
Nietkow	470.5–509	38.5	6	10.38	374
Ujście Nysy Ł.	508.5–549	40.5	6	10.56	380
Rąpice-Urad	546.5–570.5	24.0	6	3.97	143
Słubice	568.5–603	34.5	6	6.99	252

The main part of the model is the geometrical representation of the modelled domain, i.e. computational bathymetry. The bathymetry in the considered case was based on the cross-sections of the river's bed, which were measured in 2012, as well as on a digital terrain model (DTM) that was created in the same year. The DTM was made using laser scanning in two standards: 1st or 2nd standard (for cities). It had the following parameters: a density of 4–6 and 12 points per m^2, an average vertical position error of 0.10 m, and an average horizontal position error of 0.4 m.

The development of the model included the following works: (i) generation of the bathymetry of the main river channel based on the surveyed cross-sections (spaced by a distance of 100–1500 m) with an ArcGIS linear interpolation tool used for the purpose; (ii) generation of the calculation bathymetry with a regular grid resolution of the chosen value by merging the main channel bathymetry with the DEM; (iii) implementation of buildings, hydrotechnical structures, and linear structures (e.g. embankments) by adjusting the ordinates of corresponding grid cells; (iv) preparation of a raster of the initial roughness on the basis of land cover data and aerial photos, where 15 roughness classes were distinguished in total, including the river channel, open surface waters, grassland and tree areas, bushes, paved surfaces, roads, etc.; (v) implementation of boundary conditions, including water level and discharge series.

The roughness parameters (expressed by the Strickler coefficient M = 1/n, where n is the Manning coefficient) were preliminarily determined on the basis of guidance e.g. from Arcement and Schneider (1989) and Morvan (2008). The results of the studies of Szczegielniak (1988), and Banasiak et al. (2014) were helpful in this case. The final M-values, which resulted from the calibration of the model and the evaluation of its performance, ranged from 35 to 40 $m^{1/3}s^{-1}$ for the main channel. For grasslands, the M value was set to 17–25, for bushes it was set to 8, and for built-up surfaces, it was set to 1 $m^{1/3}s^{-1}$. The models were calibrated on the basis of "water level – discharge" relationships (rating curves), which are available for over twenty gauge stations along the river. The computed rating curves were fitted to the measured ones, also taking into account the uncertainty and errors found in the measured flood data as verified (Banasiak, 2019a). Moreover, a set of high water marks for the floods in 1997 and 2010 was used to aid the calibration process. In some cases, the ADV flow data were used (in simulations) for the correct determination of the partitioning of the flow between the flood plain and the main channel (the models of Opole, Brzeg, and Brzeg Dolny) (Banasiak and Krzyżanowski, 2015).

APPLICATIONS

Flood hazard and flood risk management

Pursuant to the Floods Directive (Directive 2007/60/EC) concerning the assessment and management of flood risks, all EU countries are required to create and update flood hazard maps and flood risk maps. Flood hazard maps should cover the geographical areas that can be flooded, whereas flood risk maps should show the potential adverse consequences that are associated with these flood scenarios. These maps form the basis for the preparation of flood risk management plans. The Floods Directive assumes 6-year cycles that aim to reduce the risk of flood damage. The first cycle of implementation in Poland ran from 2010–2015, with the second cycle covering the period 2016–2021. Developing, and updating, of 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 investment projects. They are also used as the basis for planning flood prevention measures, such as e.g. the (re)construction of dikes, polders or other. All interventions were studied in detail within flood risk management plans. The flood hazard and risk maps can be found on the website of the "Wody Polskie" ("Polish Waters") State Water Holding at: https://wody.isok.gov.pl/imap_kzgw/?gpmap=gpMZP.

The 2D hydraulic modelling was the basis for determining flood hazard for three scenarios of flooding, i.e. 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, and winter flooding caused by ice jamming (for a return period of 100 years). The developed models were also applied in the assessment of the efficiency of individual or interrelated flood protection measures, including the construction of the strategic Racibórz reservoir. 2D modelling is especially useful for floods with a long return period – when the water levels rise above the existing embankments. When compared to the procedure based on 1D modeling, 2D modelling more accurately indicates hazardous "hot spots" and the extent of flooding.

Modelling of the Wrocław Water Node

Wrocław Water Node (WWN) poses a particular challenge with regard to hydraulic modelling. It is a complicated system of an extensive valley and river channels, as well as water 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 water gauge section in Brzeg (km 199.1) to the water gauge section in Brzeg Dolny (km 284.7). This system also covers the towns of Brzeg and Oława, as well as the polders of Lipki-Oława, Oława and Blizanowice, with their accompanying inlet and outlet facilities.

Considering the large area of the Wrocław Water Node, five models were developed: two models for Wrocław city, two for Widawa tributary with the Odra-Widawa relief canal, and one model with an increased resolution for the City Centre Hydrosystem (CCH), which covers the central and oldest part of the city (Fig. 2). A careful calibration process was executed to ensure proper model performance (Banasiak, 2017). For this purpose, data from the flood of 2010

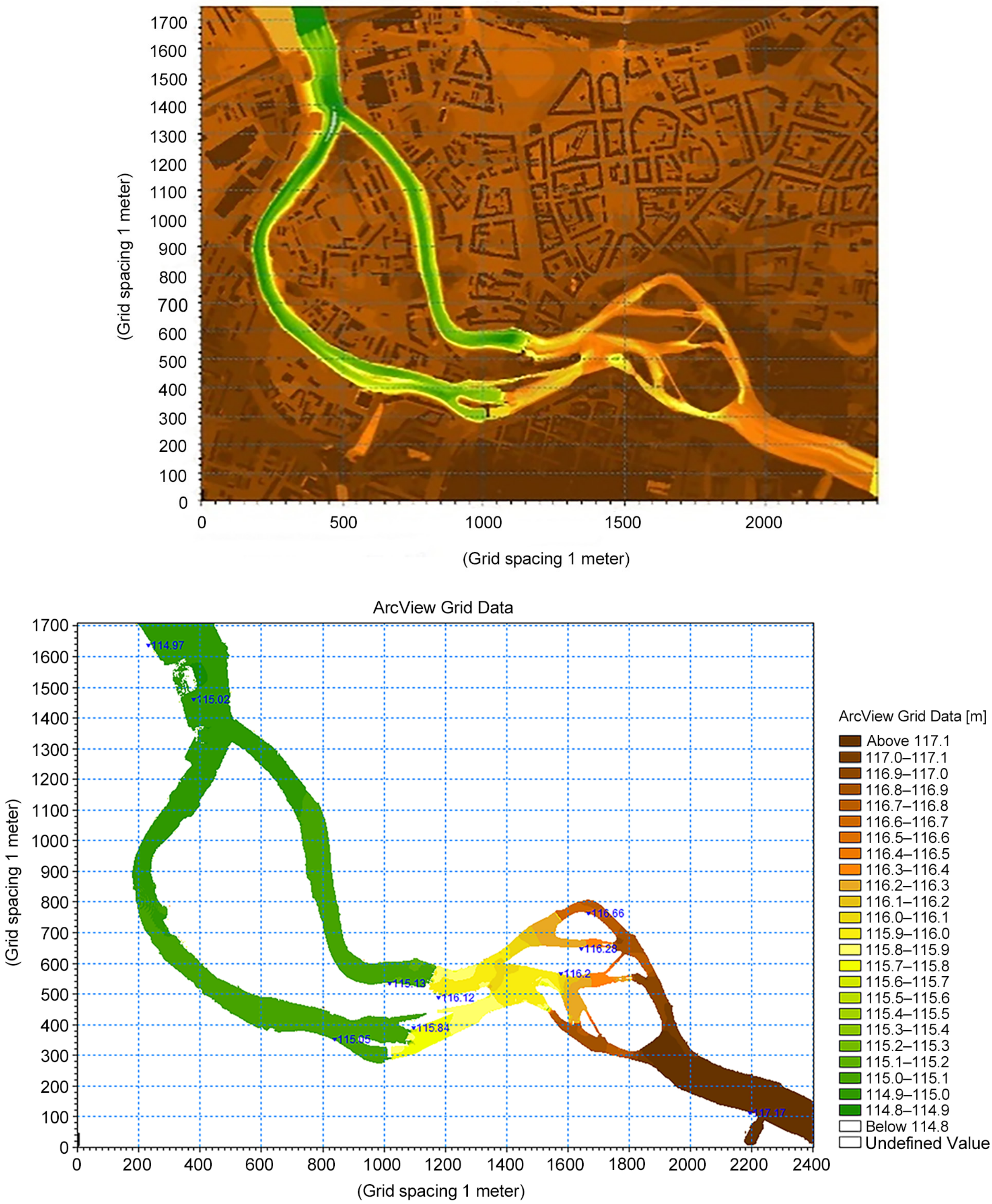

Fig. 2. 2D model of the Wrocław City Centre Hydrosystem: bathymetry of the 2D model (upper part) and the calculated water level for the 2010 flood (with the measured water levels) (source: own elaboration)

(with a flow rate of 2200 $m^3 \cdot s^{-1}$, and a return period estimated at ca. 100 years) were used. At that time, extensive hydrometric measurements were carried out, which provided data regarding the flow rate and water levels at critical points of the system during the peak of the wave. This allowed for a reliable extrapolation of the results to even higher flows (500- and 1000-year water), for which the WWN was redesigned after the flood. Moreover, using these hydrodynamic models, calculations were carried out to verify the maximum flow of the largest flood on the Odra River, which occurred in 1997. In Wrocław, it amounted to approx. 3950 $m^3 \cdot s^{-1}$, with 3640 $m^3 \cdot s^{-1}$ being the figure that was previously established (Banasiak, 2018a).

In the years 2013–2016, the main part of the modernization of the WWN was conducted. It was a major investment effort, which – in combination with the construction of the Racibórz reservoir on the Upper Odra – aimed to prevent the dramatic effects of the flood that Wrocław suffered in 1997. A number of water structures were rebuilt, 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 model, and new flood hazard maps were developed. At the same time, the effect of these investments (partially presented in Figure 3) on the capacity of the WWN was assessed (Banasiak, 2018b). It was established that the current capacity of the system is higher than the designed assumptions, which had been determined on the basis of the 1D model – and this conclusion can be considered encouraging. However, some negative aspects of the WWN's modernization were also revealed, i.e. limited effectiveness of some solutions, for instance the adoption of the City Channel (Kanał Miejski) for flood passage. This highlights the importance and necessity of detailed hydrological and hydraulic analyses when planning such investments.

Dam break modelling

As already mentioned, the embankment break scenarios were part of the flood risk assessment; this is a complex methodological issue. Taking into consideration the hundreds of kilometres of embankment, a large number of potential threats in various locations can be assumed, as well as different sizes and rates of breaching are to be expected. In the first planning cycle for

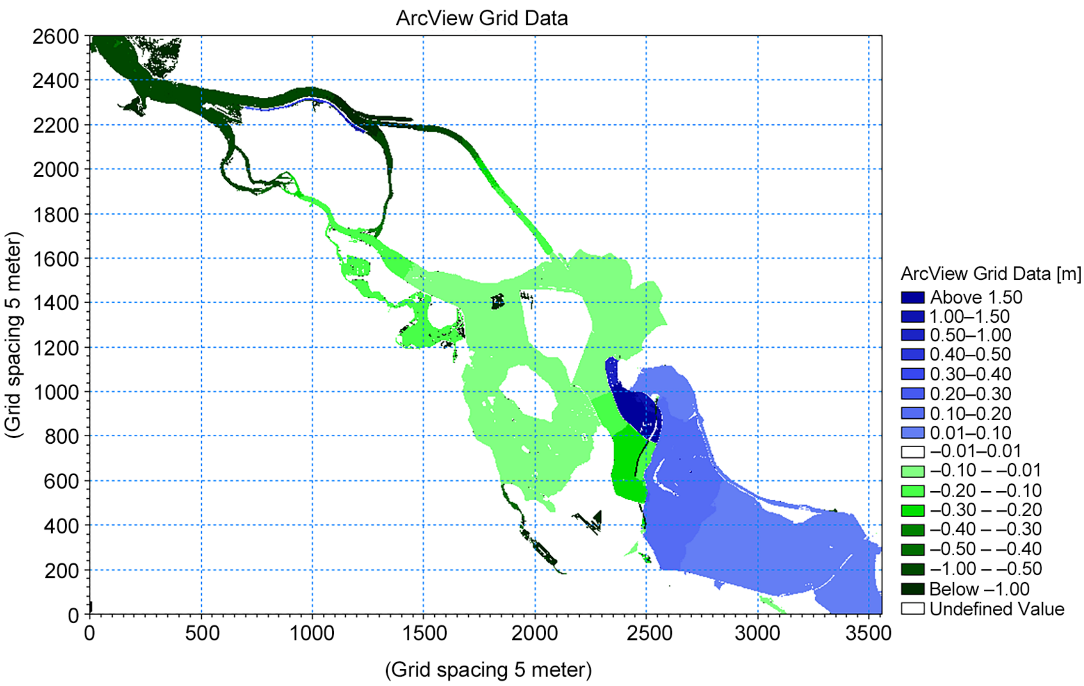

Fig. 3. Change of the water level due to the modernization of the Wroclaw Water Node (for the design discharge) (source: own elaboration)

the Odra River, 30 cases of breaches in embankment were considered, with all of them being analysed using 2D models for a flood occurrence probability of p = 1%. An example is illustrated in Figure 4. In the conducted simulations, the time of outflow through the breach was from 1 to 3 days, depending on the shape of the flood wave and the topography of the terrain. The simulations involved the removal of a part of the embankment to its base (in the computational bathymetry), and the creation of breaches 80–100 m wide (typical according to historical events) in selected locations that have the greatest risk of flooding. It is worth noting that the MIKE21 software gives the possibility of using dynamic bathymetry, i.e. defining the change in bathymetry from state A to state B according to linear interpolation within a given time. Thanks to this tool, it is possible to better simulate the outflow dynamics and the washout of the breach. This procedure, however, significantly extends the computer simulation time and size of output files.

Ice jam flood modelling

Another special type of application of 2D models consists in simulations of flood risk due to ice jams that can occur on the Odra River. The formation of ice jams and their hydraulic capacity are complex, relatively poorly understood phenomena, and there are not many numerical tools to approach such a problem. The undertaking of this issue resulted from the implementation of a feasibility study in 2015 for the modernization of the regulating structures for the free-flowing Odra River. The study is part of the World Bank project and is currently in progress. The main assumption of the project was to restore groynes that are over 100 years old, and also to improve unfavorable navigation conditions, including the ensuring of effective icebreaking and the prevention of ice jams.

MIKE21 software does not offer a direct tool for simulating ice jams. Therefore, an ice jam is simulated by inserting an impermeable barrier in a vulnerable cross-section, and by using a “sink and source”

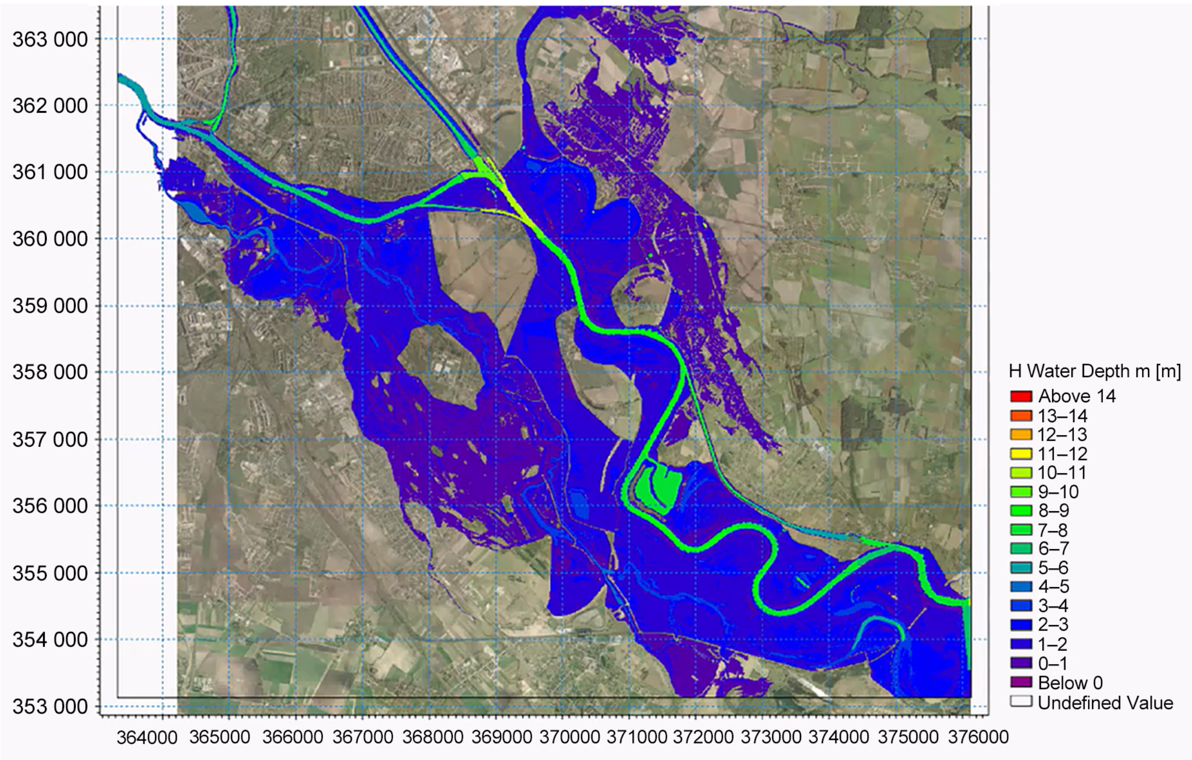

Fig. 4. Dam break simulation at Łany near Wrocław city for a flood with exceedance probability p = 1% (source: own elaboration)

tool. Therefore, a flow of 400 $m^3 \cdot s^{-1}$ is simulated (yearly average flow is ca. 200 $m^3 \cdot s^{-1}$), with 25, 50 or 75 percent of it being let though the artificial barrier using the "source" function. 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 the dynamics and scale of the ice jam hazard, as well as the risk related to this phenomenon. Such simulations can be combined with the analysis of a dam's break in order to obtain a complete picture of the potential depth and extent of flooding. Figure 5 presents such simulations for the city of Głogów. In this case, the inundation zone beyond the embankments on the right river bank is large (with a length of more than ten kilometers),whereas 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 sufficiently long time. Fortunately, most of the city and its industrial zone are located on the left river bank. Similar modelling was executed for the cities of Nowa Sól and Słubice, with the obtained results being used for a cost-benefit analysis of the project (IMGW, 2015).

Flood routing

Flood routing was applied for the subsequent sections of the Odra River: the channelized sections, and the free flowing river sections. The analyses were carried out for historical flood waves of 2010 and 1997, and also for hypothetical flood waves with a low probability of occurrence (once every 500–1000 years). These studies provided interesting and significant results, which became the foundation for the verification of the flood peak discharges and "gauge stage-discharge" relationships, as well as the verification of the design discharges (described in the following Sections).

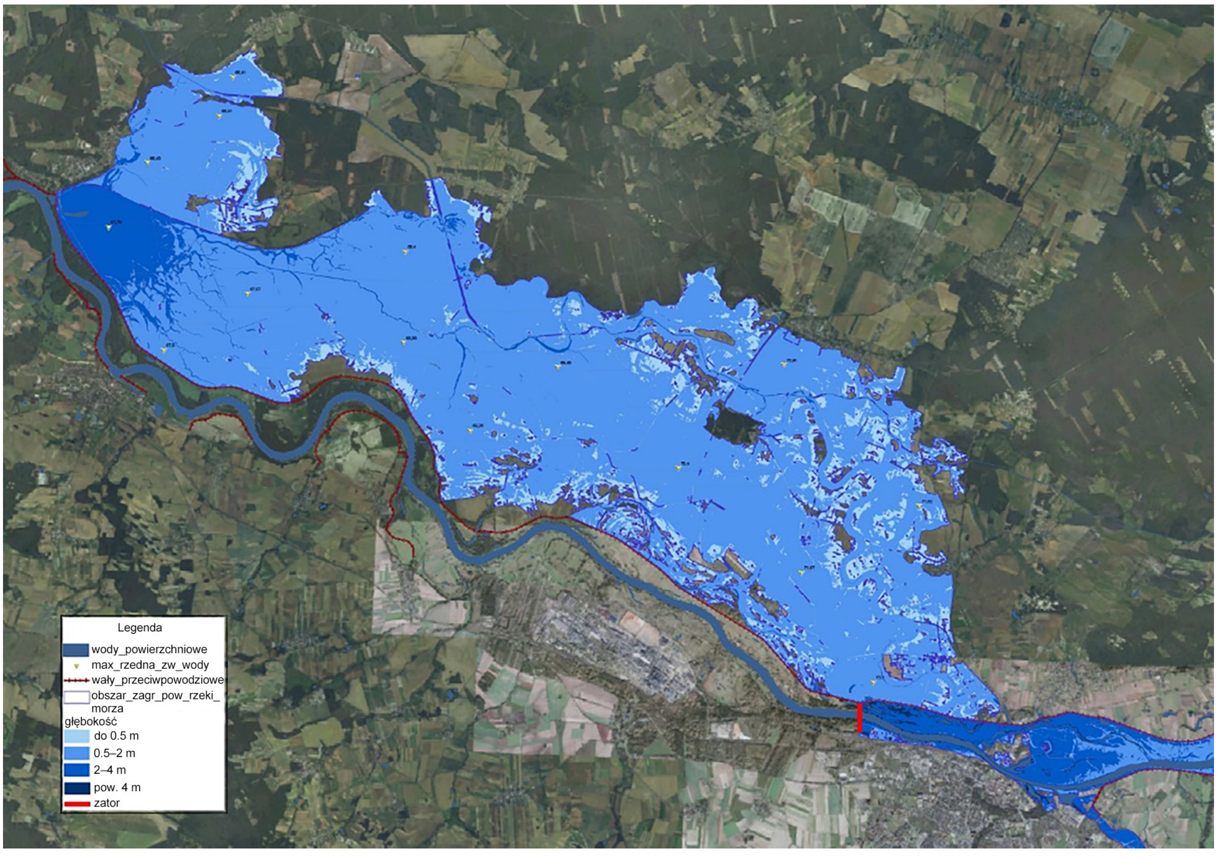

Fig. 5. Modelling of flooding caused by ice jams near the city of Głogów (source: own elaboration)

Verification of the flood peak discharges and gauge stage-discharge relationships

Determining the gauge H-Q relationships (rating curves), in the case of a lack of or limited hydrometric data, can be uncertain or even speculative. Therefore, on that basis alone, it may be impossible to determine the maximum flood flows, which is a very important task. 2D modelling is a tool that supports the reconstruction of the passage of historical floods, and also the verification of their data.

In the case of the Odra River, numerous extrapolations of the rating curves for a number of water gauge stations, as well as for uncontrolled cross-sections (between water gauge stations), were verified and corrected. In some cases, it was found that the results of hydrometric measurements, which were carried out in difficult conditions of high water, contained faults or did not take into account the flow in the uncontrolled part of the valley, e.g. the Krapkowice and Nowa Sól sections. In these locations, during the flood in 2010, a significant amount of water flowed over the measurement section i.e. above the road embankment, or through a breach in the embankment. Moreover, the measurements were rarely made during the peak of the flood wave. In turn, the calculations using the 2D model provide a reliable basis for extrapolating flows to higher water levels, and also improve existing databases (Banasiak, 2019b). Exemplary verification results are given in Table 2. For all locations, a sensitivity analysis was made to check the potential effect of a change in the main channel and floodplain roughness on the calculated rating curve. For instance, for the Głogów cross-section, the calculated peak discharge of the 1997 flood varied within the limits of 2100 and 2450 $m^{1/3}s^{-1}$. Here, the recorded maximum discharge of the 2010 flood is very supportive, for which the best fit was obtained in the case of M = 38,4 $m^{1/3}s^{-1}$ for the main channel, and M = 20,4 $m^{1/3}s^{-1}$ for the grass flood plains (a 10 per cent rise to the initial values). Hence the maximum 1997 flood discharge was estimated to 2300 $m^{1/3}s^{-1}$, as presented in Figure 6.

Table 2. Peak discharges for the 1997 flood ($m^3 \cdot s^{-1}$) (source: own elaboration)

	Chałupki	Brzeg	Wrocław	Ścinawa	Głogów	Połęcko
Before	2160	3530	3640	3000	3040	3200
Based on 2D model	2950	4200	3900	3000	2300	2250

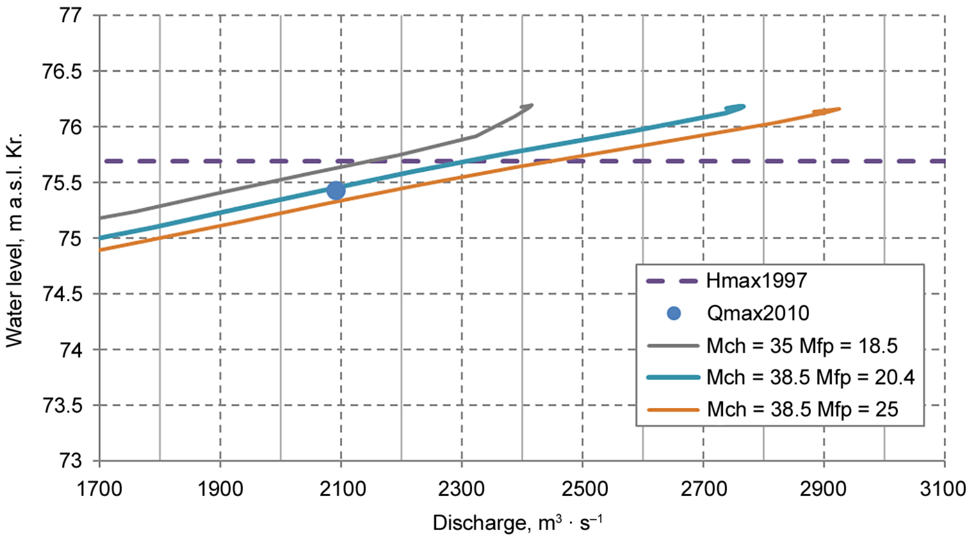

Fig. 6. Calculated upper part of the rating curve for the Głogów cross-section (roughness factor for the main channel – M_{ch}, for floodplain – M_{fp}, observed maximum water level in 1997 – H_{max}, recorded maximum discharge during the flood in 2010 – Q_{max}) (source: own elaboration)

Verification of the design discharges

Recently, the Odra River has not only been the subject of anti-flood measures, but also technical and spatial studies that aim to develop the Odra River Waterway. These studies also verified the potential adaptation of the river to the international navigable class, and included plans to build subsequent barrages. Design discharges constitute an important planning parameter. Their determination is usually based on the statistical approximation and extrapolation of various distributions of the probability of discharges being exceeded. This is conducted in accordance with the applicable hydrological methodologies.

The modelling efforts showed, however, that the statistical approach could be misleading when extrapolating a probability curve towards low probability ranges. This is due to the fact that flood propagation drastically changes under certain conditions, e.g. when crossing the level of the embankment's crest and when activating additional storage areas. Therefore, the determination of design discharges, to limit the uncertainty, should involve genetic studies of the formation and propagation of a flood, and the modelling of extended areas of a river. The sample results of such an approach and the conducted calculations are given in Table 3. This table presents a comparison of the design discharges obtained using only the statistical approach (Pearson III, LN or GEV distributions of the yearly peak flows), which is the recommended method according to governing methodology, complemented with statistical results obtained using probability distributions suggested by the 2D flood routing. In other words, 2D results clearly indicate limits for the design discharge along the river under the given conditions. On the freely flowing Odra River, the differences between the results obtained using the two approaches can be significant, and they increase with a decrease in the probability of flooding (IMGW, 2021).

Table 3. Design discharges for probability p = 0.2% ($m^3 \cdot s^{-1}$) (source: own elaboration)

	Ścinawa	Głogów	Nowa Sól	Cigacice	Połecko
Statistical approach	2801	2875	2820	2580	2780
Statistical approach supported by the 2D model	2760	2510	2533	2325	2494

CONCLUSIONS

Hydrodynamic numerical modelling has become an inherent part of scientific and engineering practice. It is an important factor that supports planning and decision making in the water sector. In particular, 2D modelling has become a more viable and efficient tool, which has been demonstrated and illustrated with several examples. The experience gained during the 2D modelling of a nearly 600 km long section of the Odra River, within the concept called ODRA2D, confirms that such modelling helps to bring hydrological and hydraulic products to a higher standard.

The implementation of this concept facilitated conducting many important analyses, and it also provided new answers to previously formulated questions, e.g. how well the inhabited areas located along the Odra River are protected against flooding. It also enabled very important maximum discharges of historical floods to be verified, as well as statistical assumptions and estimates of discharges (with a low probability of occurrence) along the river to be checked.

The ODRA2D concept is deployed in flood modelling context. Thus, subsequent efforts should focus on in-channel processes, and use more flexible modelling to better mimic complex flow patterns in groyne-regulated channel in different spacial scales. This could further support water quality, sediment transport and inland navigation analyses. It is worth considering the use and development of free or open source tools/platforms that could be more easily disseminated to other users.

Updated hydrodynamic software and an increase in the processing power of computers will contribute to the even more effective use of 2D modelling in subsequent flood, drought, and water quality management planning not only in the case of the Odra River but for many other rivers.

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ODRA2D – KASKADOWY MODEL 2D POWODZI NA ODRZE – OPRACOWANIE I ZASTOSOWANIA

ABSTRAKT

Cel pracy

Opracowanie nowych hydrodynamicznych narzędzi numerycznych do symulacji przepływu w dolinie Odry na potrzeby oceny ryzyka oraz zarządzania zagrożeniem powodziowym.

Materiał i metody

Wykorzystanie programu MIKE21 do budowy modeli. Przetwarzanie i analiza geoprzestrzennych danych topograficznych (ArcGis) w celu uzyskania danych wejściowych i wyjściowych do modelowania. Wszechstronne wykorzystanie danych teledetekcyjnych (cyfrowy model terenu i ortofotomapy) w połączeniu z tradycyjnymi źródłami danych.

Wyniki i wnioski

Opracowano kaskadę dwudziestu pięciu modeli MIKE21, która objęła niemal 600-kilometrowy odcinek Odry. Modele wykorzystano do przebadania wielu zagadnień, takich jak: ocena zagrożenia powodziowego w odniesieniu do różnych scenariuszy, ocena powodzi na skutek zatorów lodowych i pęknięć w wałach, ocena efektywności prac łagodzących skutki powodzi w złożonym systemie wodnym Wrocławia, weryfikacja historycznych danych powodziowych i zależności etapowo-wyładowczych, a także weryfikacja zrzutów miarodajnych.

Słowa kluczowe: rzeka Odra, modelowanie hydrodynamiczne 2D, ocena zagrożenia powodziowego