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ASSESSMENT OF FLOOD PREVENTION EFFICIENCY OF THE RESERVOIR COMPLEX IN ZESŁAWICE ON THE DŁUBNIA RIVER

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ABSTRACT

The reservoir complex in Zesławice on the Dłubnia River belongs to the Cracow agglomeration. It is located near built-up areas, which reduces the available flood reserve capacity and at the same time protects these areas. The experience of the flood in 2010 confirmed that this level is not sufficient, though. The main objective of this study is to evaluate the flood protection effectiveness of the Zesławice reservoir complex by estimating the maximum flood level, which can be effectively reduced. Numerical calculations were performed on a 1-D computer model of the Dłubnia River with the MIKE 11 software (by DHI). Due to the complexity of topographical arrangement of the Zesławice reservoirs, each one was modeled as a separate 1-D object. The hydraulic connections between them were defined and the rules controlling the outflow were modeled. In addition, the evaluation of the Dłubnia riverbed capacity downstream of Zesławice was performed and a general guidelines how to increase the level of flood prevention in the impact area of the reservoirs were formulated.

Keywords: small retention reservoir, controlled retention, flood prevention, 1-D modeling

INTRODUCTION

In the case of water reservoirs with a controlled outflow regime, usually flood prevention is neither the only nor the dominant function. The available capacity of a flood reserve is limited by other tasks of the reservoir. This is a significant problem especially for small urban reservoirs – located in built-up areas, where on the one hand, the presence of buildings downstream of the reservoir imposes high level of protection, and on the other, development upstream of the reservoir limits the available flood reserve and thus the effectiveness of the reservoir's flood prevention. In addition, development of the catchment – by sealing its surface and reducing natural retention – also increases and accelerates culmination, and leads to an increase in a volume of flood waves flowing into a reservoir.

This paper focuses on a small, municipal retention basin with a controlled outflow in Zesławice on the Dłubnia River. The reservoir is located near built-up areas – limiting both the possibility to control a flood outflow and the available flood capacity of its bowl, which also is characterized by a complex spatial system and in fact consists of a complex of reservoirs with a significant range of backward effect (Michalec et al. 2016).

The main aim of this paper is to assess, how efficient is the flood prevention of a small controlled retention basin on an example of the reservoir in Zesławice on the Dłubnia. The tests and studies of the flood in 2010 (Michalec 2012) indicate that the current level of efficiency is not sufficient – in July 2010 the allotment gardens situated downstream of the reservoir in the valley of Dłubnia were flooded.

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The additional utilitarian purpose is an attempt to outline the complex geometry of the basin's bowl in a form of interconnected 1-D objects implemented in a 1-D model of the transient river flow.

DESCRIPTION OF ZESŁAWICE RESERVOIR COMPLEX

The Zesławice reservoir is located on the 8 + 740 km section of the Dłubnia River near built-up areas in Cracow (see: Fig. 1) and has a complex spatial capacity system, which in fact comprises of two parallel basins Zesławice I (ZI) and Zesławice II (Z-II) (see: Fig. 2). Zesławice I was built in 1964–1966 and commissioned in October 1966 for the purposes of supplying with industrial water to former Vladimir Lenin Steelworks and supplying the city with drinking water and preventing it from floods (Pociask-Karteczka 1994). Due to intense silting of the Zesławice I reservoir's bowl (Tarnawski and Słowik-Opoka 2002) in the 1980s the Zesławice II reservoir was built. Currently, the reservoir is used for water retention to equalize the flow downstream of the dam and flood prevention.

Fig. 1. Localization of the Zesławice reservoir against the Cracow area

Between 18th and 19th of July, 2010, allotments in the valley of Dłubnia downstream of the Zesławice reservoir (in the vicinity of Zesławicka, Ptaszyckiego and Wańkowicza Streets) were flooded. According to the instructions for water management that were in force during the flood in 2010 (Cracow Water Company Association – Krakowski Związek Spółek Wodnych 2003), flood control of the outflow from the reservoir could be administered in two ways:

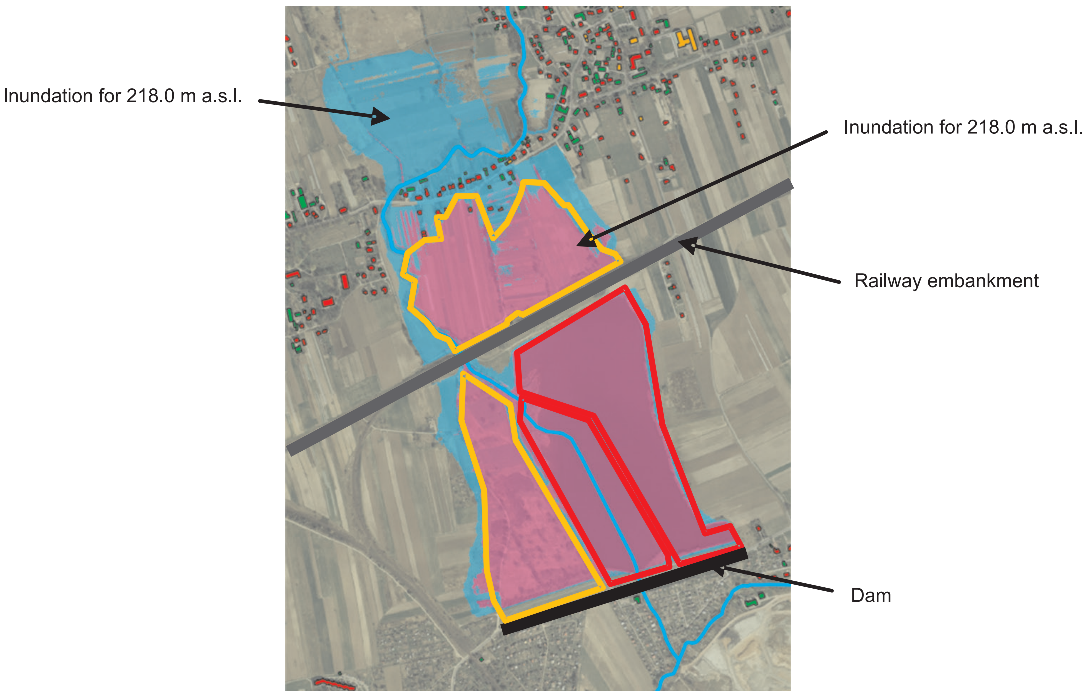

Fig. 2. Spatial arrangement of the reservoir elements

Variant I (VI) – discharges the constant safe outflow at rate of 70 $m^3 \cdot s^{-1}$, raising the basin to the maximum emergency level MaxPP (aw.) = 218.00 m a.s.l., which leads to flooding of private areas and developments in the basin's backwater.

Variant II (VII) – maintains the water table in the basin at the maximum level MaxPP = 216.50 m a.s.l., draining away all the inflow to the basin until the weir's capacity at this level is reached. In case of further increase in the inflow to the reservoir, the MaxPP is exceeded. If this variant is adopted, water is to spill from the banks of the Dłubnia on the section downstream of the dam, flooding the adjacent areas.

The inspection carried out by RZGW (Regional Water Management Board) in Cracow (Urząd Miasta Krakowa 2010) proved that water management during flooding adopted the II variant, in accordance with the instructions for the reservoir's water management. It was also concluded that (Urząd Miasta Krakowa 2010): „the alternative variant I that means achieving the maximum damming level of the basin (218.00 m a.s.l.) could not be implemented in phase B, because it would create a huge backwater on the Dłubnia upstream of the basin, expanding the reservoir's surface to 75 ha, what in result would flood the developments in municipalities of Zielonki and Michałowice, along with the railway line Cracow–Warsaw".

The statement above points to a limited flood prevention efficiency of the Zesławice reservoir, mainly due to an insufficient capacity of its bowl. Michalec and Tarnawski (2012) also mention limited flow capacity of the Dłubnia downstream of the basin.

The Zesławice reservoir was created by damming the waters from the Dłubnia River with a frontal earthen dam, class IV with a crown on an elevation of 219.20 m a.s.l. and a width of 11 m. The ordinate of the bottom is 211.50 m a.s.l. and the height of the damming at NPP is 4.5 m. The elements of the reservoir also form: a right-side barrier in a form of earth levee with a crown elevation of 216.50 m a.s.l. and a side dam between Z-I and Z-II in a form of earth levee with a crown elevation of 216.50 m a.s.l., equipped with two culverts and overflows enabling water flow between the basins. The damming levels for the reservoir and the corresponding capacities are summarized in Table 1.

Table 1. Basic parameters of the Zesławice reservoir

Damming level	Ordinate m a.s.l.	Capacity mln m^3
NPP	215,00	0,42
MaxPP	216,50	0,73
MaxPP(aw.)	218,00	1,36

It should be noted that the structure of the bowl has a complex spatial arrangement - in addition to the already mentioned Z-I and Z-II basins, at the elevation of 216.50 m a.s.l. (MaxPP), two additional floodplains are formed:

- Z-III – a floodplain on the right side of the earth levee of the Zesławice reservoir,
- Z-IV – a broad floodplain upstream of the main basin in front of a railway embankment composing with the main basin a cascade system.

The spatial arrangement of all capacities is presented in Figure 2.

The main discharge device of the reservoir is a three-span weir equipped with flat gate valves. The width of the central span is 2.8 m, while the far spans are 3.4 m wide. Also, the reservoir includes a fish ladder and a drain from Zesławice II in a form of two tubes with a diameter of Φ 0.8 m and a length of 58.5 m.

ADOPTED METHOD AND SCOPE OF ASSESSMENT

The main purpose of this paper is to assess flood prevention efficiency of the water reservoir complex in Zesławice on the Dłubnia River. For this reason the following scope of works were adopted:

- Application of a 1-D model of the reservoir controlled in a 1-D model of the transient flow of the Dłubnia,
- Assessment of the river bed capacity on the section of the Dłubnia downstream of the reservoir,
- Evaluation of the efficiency to reduce flooding $Q_{1\%}$ by the reservoir,
- Assessment of flood prevention efficiency level of the Zesławice reservoir – estimation of flooding level effectively reduced by the reservoir.

In summary, some general guidelines for increasing the level of flood prevention in the area under the Zesławice reservoir influence were proposed.

The assessment utilised numerical calculations performed on a computer model of the Dłubnia constructed by the DHI MIKE 11 software. The MIKE 11 program allows calculating one-dimensional (1-D) and transient flow in open channels operating on Saint-Venant set of equations, i.e. the equations of continuity (1) and momentum (2), as presented below (DHI Denmark 2009):

$$\frac{\partial Q}{\partial x} + \frac{\partial A}{\partial t} = q \qquad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial\left(\alpha \frac{Q^2}{A}\right)}{\partial x} + gA\frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2 AR} = 0 \qquad (2)$$

where:

Q – flow rate,
A – flow area,
q – lateral inflow,
h – elevation of water table,
R – hydraulic radius,
C – Chezy coefficient,
α – Coriolis coefficient,
t – time,
g – gravitational acceleration.

The momentum equation (2) is applied assuming a subcritical flow, whereas in the case of supercritical flow a reduced formula is adopted (3):

$$\frac{\partial Q}{\partial t} + gA\frac{\partial h}{\partial x} + \frac{gQ|Q|}{C^2 AR} = 0 \qquad (3)$$

The above equations can be applied only with the assumption of homogeneity and incompressibility of water and given a small slope of riverbed (DHI Denmark 2009).

Due to the complex geometry sections (floodplains), the hydraulic radius based on the effective area and relative coefficients of resistance were applied for the calculation.

The Dłubnia River model includes engineering structures such as bridges, culverts, and potential floodplains. The Zesławice I and Zesławice II bowls and additional floodplains were mapped as separate 1-D objects by cross sections and the appropriate hydraulic connections between them in a form of overflows and culverts were defined. The mapped diagram of the reservoir's bowl in MIKE 11 software is shown in Figure 3.

The manual for controlling the outflow from the Zesławice reservoir was modeled for both variants i.e. VI and VII. The idea of controlling the outflow is based on the assumption that the manual for reservoir water management works like an algorithm and as such can be written in a form of a series of conditional instructions: IF (condition), THEN (conditionally executed code), ELSE (alternatively executed code). A string of such instructions can be represented graphically in a form of an decision tree (see: Fig. 4). MIKE 11 implements this idea through control structures – an addition to the hydrodynamic module (HD). A detailed description of the ideas and principles of modeling the control rules in MIKE 11 can be found in the author's other paper Lewicki (2004).

Hypothetical waves, based on the rainfall-runoff model developed in the Institute of Water Engineering and Management of Cracow University of Technology were used as the upper and lateral boundary conditions. The model also takes into account the side tributaries from Gołyszanka, Minóżka and Baranówka and lateral distributed inflow from differ-

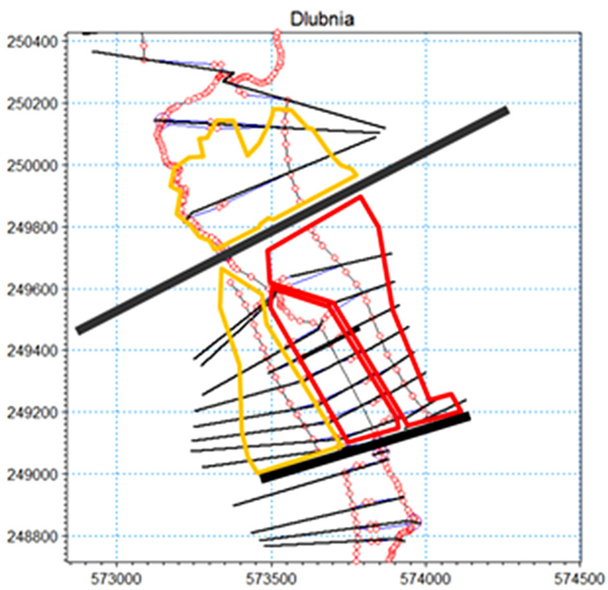

Fig. 3. Schematization of the Zesławice reservoir's bowl

ential catchments. The water level corresponding to the $Q_{1\%}$ flow rate of the Vistula River served as a downstream boundary condition. The diagram of the Dłubnia model with the arrangement of boundary conditions is shown in Figure 5, and the value of culmination flows for selected probabilities of hypothetical waves are summarized in Table 2. The section of Dłubnia in a range of damming of the Vistula levels was not taken into account in further analysis due to small impact of flows on Dłubnia on the conditions on this section.

Geodetic measurements sections from 2013 were used to map the flow area geometry. Due to the lack of sufficient data for calibration and verification of the model, an expert assessment of water flow conditions in the entire flow range was made. The coefficient values of roughness in cross-sections were defined on the basis of information on a type of land cover at individual measuring points, included in the geodesic documentation.

This served as a model for assessment of the bed capacity on the section downstream of the Zesławice reservoir and for analysis of the impact of the available discharge from the reservoir on the areas located along this section.

Subsequently, simulations of the reservoir operation were performed for $Q_{1\%}$ flood rate, which corresponds to culmination of the wave reaching the reservoir at the level of approx. 130 $m^3 \cdot s^{-1}$. Simulations for both variants VI and VII were conducted according to the instructions for water management from 2003.

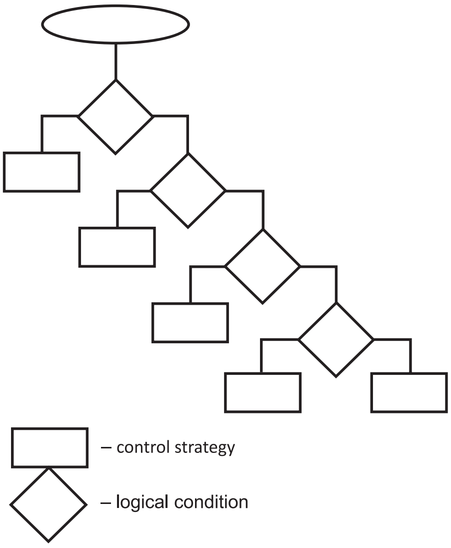

Fig. 4. Schematic structure of issue tree representing control structure functioning

To assess flood prevention efficiency of the reservoir, identifying the highest level of flood that can be effectively reduced by the reservoir was required, with – at the same time – avoiding threats downstream and upstream of the reservoir.

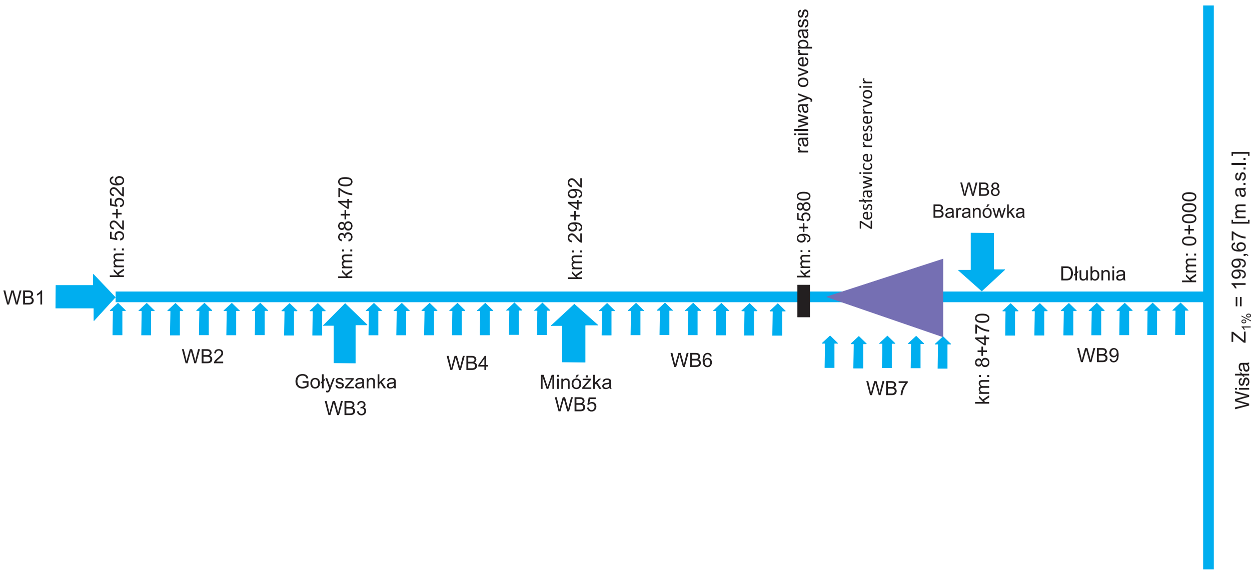

Fig. 5. Scheme of boundary conditions of the Dłubnia River model

Table 2. Culmination flow rates for chosen probabilities of hypothetical flood waves

Boundary condition	Catchement	p%		
		1	5	10
WB1	From springs to km: 52+526	3,86	2,95	2,41
WB2	from km: 52+526 to Gołyszanka	50,85	36,00	28,74
WB3	Gołyszanka	12,55	9,30	7,48
WB4	from Gołyszanka to Minóżka	20,64	15,60	12,76
WB5	Minóżka	33,46	22,00	17,10
WB6	from Minóżka to railway overpass	54,18	38,30	29,55
WB7	from railway overpass to Baranówka	2,72	2,25	1,93
WB8	Baranówka	37,77	28,00	22,73
WB9	from Baranówka to estuary	19,68	14,50	11,62

RESULTS OF MODEL CALCULATIONS

Riverbed capacity assessment

Capacity analysis of the Dłubnia's bed on the section downstream of the reservoir (see: Table 3) showed a significant variation in the length of permissible flows (with admission to flood undeveloped areas), which generally exceed 65 $m^3 \cdot s^{-1}$ – an approximate to the permissible flow rate specified in the manual, which is 70 $m^3 \cdot s^{-1}$. Only between the Morcinka street and the left tributary of Baranówka the flow fitting in the riverbed is lower and amounts to 30–40 $m^3 \cdot s^{-1}$, and its surpassing leads to flooding of nearby allotment gardens which happened during the flooding in 2010.

For the purpose of further analyses, it was assumed that the allowed outflow from the reservoir can reach 70 $m^3 \cdot s^{-1}$, because such riverbed capacity can be provided with relatively little effort. It should be noted, however, that an inflow from the Baranówka watercourse ($Q_{1\%}$ = 35 $m^3 \cdot s^{-1}$) can significantly increase flows in the Dłubnia riverbed, which means that to maintain the permitted flow downstream of the mouth of the Baranówka the effectively available discharge from the reservoir should be smaller in the case of waves' overlapping.

The estuary section of the Dłubnia within the influence of high levels on the Vistula was not analysed in detail due to the presence of backwater levees significantly raising the riverbed capacity of the Dłubnia.

Evaluation of the $Q_{1\%}$ wave reduction level

The results of flood transformation for $Q_{1\%}$ are given in Figure 6. The analysis of the results for the variant VI of outflow control proves that due to the landform in the area of the reservoir's bowl, raising the acceptable damming level from MaxPP = 216.5 m a.s.l. to MaxPP (aw.) = 218.00 m a.s.l. significantly increased the total capacity of flood reserves, almost doubling it (from 0.73 million m^3 to 1.36 million m^3). However, as the simulation has shown, it proved to be insufficient to maintain the permitted outflow and has been substantially exceeded. At its culmination, the outflow was 122 $m^3 \cdot s^{-1}$. In the case of variant VII the culmination outflow amounted to 125 $m^3 \cdot s^{-1}$.

The reduction level of culmination of the wave flowing into the reservoir turned out to be small for both variants 96–97%. In both cases, the adopted maximum damming level has not been exceeded, however accumulating water to the elevation of MaxPP(aw.) = 218.00 m a.s.l. has a negative impact on sites upstream of the reservoir, causing extensive backwaters. In this situation, it is preferable to apply the variant VII.

To maintain the permitted outflow at the level Q_{doz} = 70 $m^3 \cdot s^{-1}$ and the maximum damming level at 216.5 m a.s.l. the flood reserves for the $Q_{1\%}$ wave were short of about 1.6 million m^3 and at the level of 218.00 m a.s.l. about 0.9 million m^3 – meaning that the reservoir's capacity available under present conditions is insufficient to ensure adequate flood prevention.

Table 3. Capacity of the Dłubnia riverbed downstream of of the Zesławice reservoir

Section	Section of Dłubnia		$Q_{1\%}$VI	Q_{bed}	Notes
	from	to	m³ · s⁻¹		
I	8+740 dam axis Zesławice res.	8+705 Morcinka St	122	122	–
II	8+705 Morcinka St	8+470 left tributary – Baranówka	122	30–40	flooded allotment gardens
III	8+470 left tributary – Baranówka	7+970 railway embankment	133	85–133	flooded wasteland
IV	7+970 railway embankment	7+040 Okulickiego St	133	90	flooded wasteland
V	7+040 Okulickiego St	5+360 Kocmyrzowska St	133	65–133	flooded allotment gardens
VI	5+360 Kocmyrzowska St	3+780 Solidarności Avenue	133	100–133	flooded wasteland
VII	3+780 Solidarności Avenue	2+340 Ptaszyckiego St (DK 79)	133	26–133	flooded wasteland
VIII	2+340 Ptaszyckiego St (DK 79)	0+000 estuary to the Vistula	133	> 133	backwater to the Vistula

Evaluation of flood level effectively reduced by the reservoir

Then, a series of tests identified the maximum flood wave, which would be effectively reduced by the reservoir, i.e. in such a way to avoid a danger of flooding both downstream and upstream of the reservoir. This means that when such a flood passes through, the permitted discharge and normal damming level (NPP) should not be exceeded. The flooding closest to meeting the above criteria was $Q_{5\%}$. The results of $Q_{5\%}$ flood transformation, corresponding to the wave reaching the reservoir with culmination at 89 $m^3 \cdot s^{-1}$ are shown in Figure 7.

The outflow from the reservoir in the variant VI was maintained at the permitted level only with a small and brief exceedance of the assumed MaxPP (max. by 4 cm in about 7 hours). However, in the variant VII damming was maintained at the assumed level also with small and brief exceedance of permitted outflow by a maximum of 6 $m^3 \cdot s^{-1}$ during about 6 hours.

SUMMARY AND CONCLUSIONS

The complex of reservoirs on the Dłubnia in Zesławice is characterized by a small total capacity and considering its location – near built-up areas – it has a very limited effectiveness for preventing Cracow from floods.

The results of the simulations with a preliminary assessment of flood prevention efficiency of the complex in Zesławice allow to formulate the following conclusions:

- The effectiveness level of reservoirs' flood prevention should be considered insufficient.
- The area under influence of the reservoir covers terrains located downstream in Cracow as well as, due to it complex spatial structure, sites directly upstream in the locality of Raciborowice.
- It does not provide adequate protection against flooding with probability p = 1% of the areas within Cracow as well as it may pose a threat to sites upstream of the reservoir with water accumulation up to the level of MaxPP (aw.).
- An effective reduction is possible only for floods that do not exceed the level of $Q_{5\%}$.

To increase the degree of flood prevention in the area under the Zesławice reservoir influence some guidelines and considerations were prepared with regard to the following measures:

- Increasing the available capacity of flood reserves.
- Raising the permitted outflow from the reservoir.

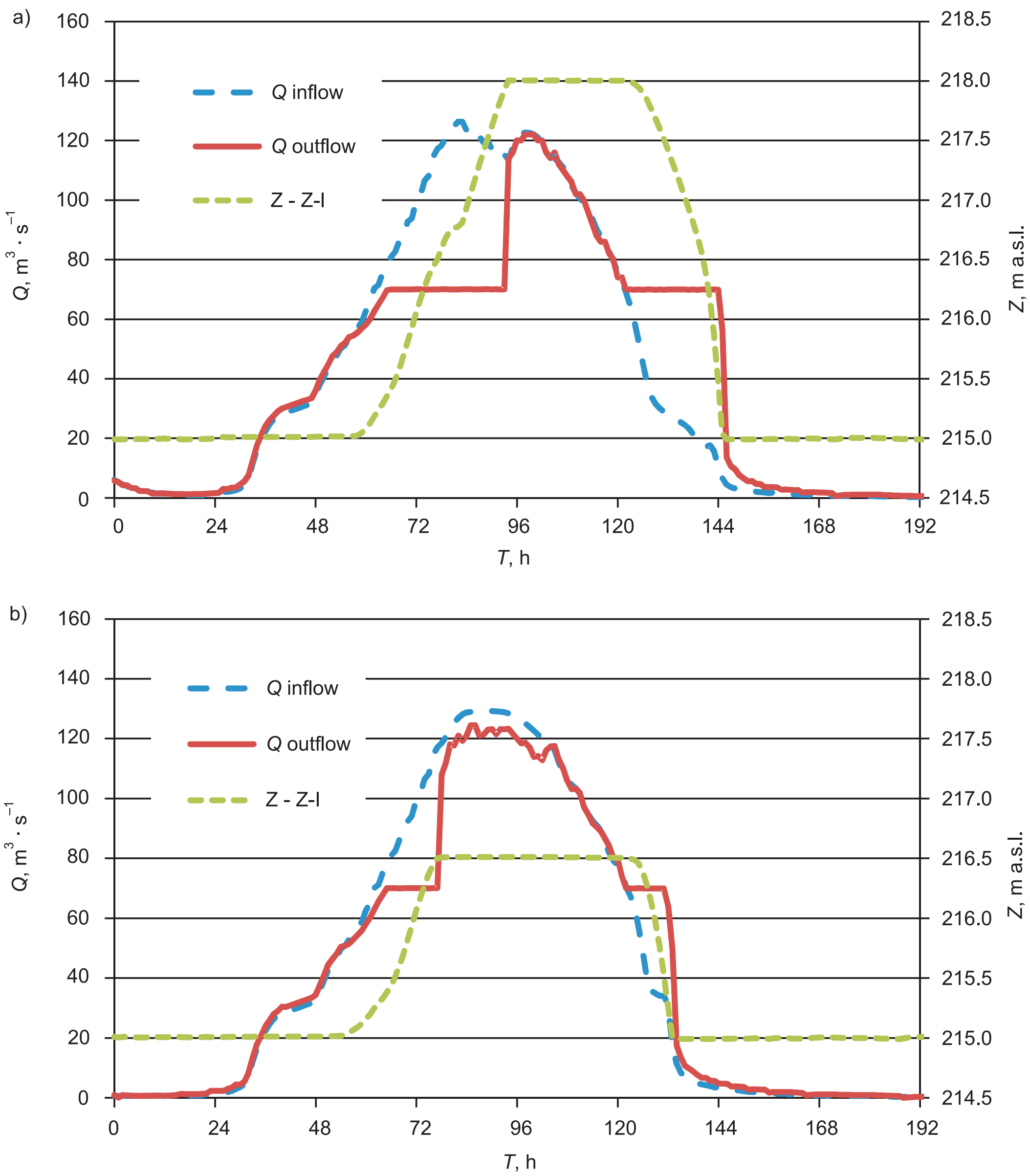

Fig. 6. The results of $Q_{1\%}$ flood wave simulation through the Zesławice reservoir according to: a) variant VI, b) variant VII

- Reducing the probability of high floods.

The possibility of increasing the available capacity of the flood reserves is restricted for safety reasons to the maximum elevation of the emergency damming level MaxPP (aw.) = 218.00 m a.s.l., and as numerical simulations have shown with respect to $Q_{1\%}$ flooding this does not significantly raise the level of wave reduction, on the contrary – causing danger of flooding in the reservoir's backwater. Therefore, raising the maximum damming level in the reservoir would require at the same time taking protective measures in this area or changing the way it is used. An additional volume of flood reserves could bring a reduction of NPP and a clearing of the reservoir's bowl, but the obtained capacity would fall short of the needs.

The permitted outflow from the reservoir, at which the total reduction of wave $Q_{1\%}$ would occur, was es-

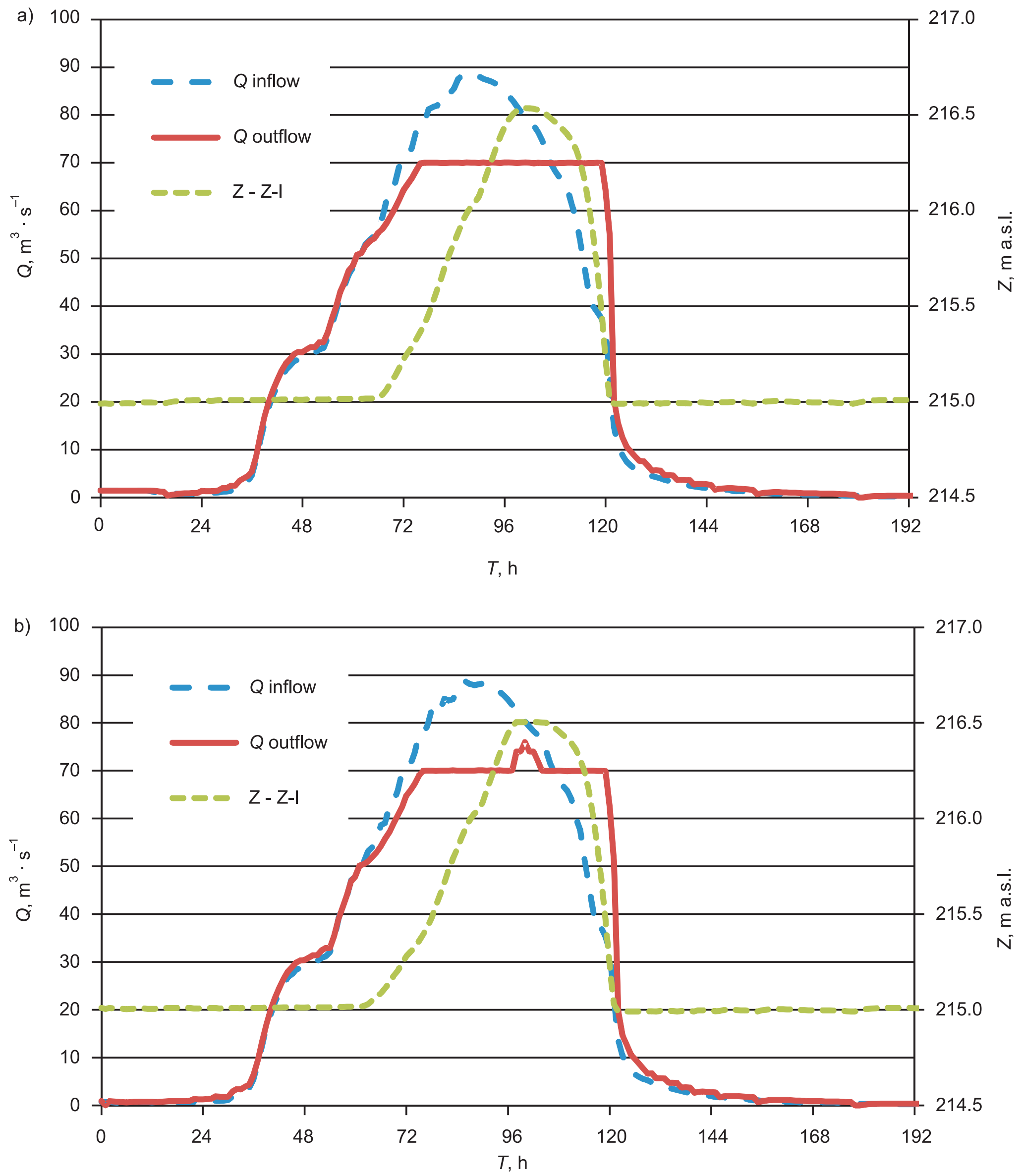

Fig. 7. The results of $Q_{5\%}$ flood wave simulation through the Zesławice reservoir according to: a) variant VI, b) variant VII

timated at approx. 90 $m^3 \cdot s^{-1}$ at the damming up to elevation MaxPP(aw.). This rate exceeds the Dłubnia riverbed's capacity in many sections downstream of the reservoir, therefore such an increase in the permitted outflow should be accompanied by protective measures for the threatened areas (for example, levees and/or flood walls) and increasing the riverbed's capacity. At the same time, because of the damming of the reservoir to MaxPP(aw.) it would be necessary to introduce protective measures for areas within backwater range.

Reducing the probabilities of high floods would require changes in the outflow regime and retention conditions in the reservoir's catchment, and thus implementing changes at the regional level. Such measures should be aimed at reducing size of floods with a specified probability and could include changes of catchment management and, in particular searching for a possibility to increase retention, for example, in the form of dry flood reservoirs.

In view of limited opportunities of increasing the capacity of the analysed reservoir complex, its structure and impact on adjacent areas and the required high level of flood prevention for urban areas, it seems that the most effective approach to reduce flood risk in this area is a comprehensive approach, involving simultaneously several types of operations and covering both the reservoir and the riverbed together with the adjacent areas as well as the reservoir's catchment. Such an approach requires effective instruments that take into account all the important factors, influencing both the functioning of the reservoir and its impact on the flow conditions of the riverbed. The choice of MIKE 11 software and application of 1-D model of the reservoir controlled in the 1-D model of the river allows to conclude that the adopted efficiency assessment method results in:

- Mapping of the complex geometry of the reservoir's bowl and the interactions between its components.
- Mapping the rules for the reservoir management.
- Assessment of the riverbed's capacity downstream of the reservoir.
- Evaluation of the reservoir's impact on the conditions of flood routing downstream and upstream of the reservoir.

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OCENA EFEKTYWNOŚCI PRZECIWPOWODZIOWEJ KOMPLEKSU ZBIORNIKÓW WODNYCH W ZESŁAWICACH NA RZECE DŁUBNI

ABSTRAKT

Kompleks zbiorników Zesławice na rzece Dłubni zlokalizowany jest na terenie miasta Krakowa w pobliżu obszarów zabudowanych, co z jednej strony ogranicza dostępną pojemność rezerwy powodziowej, z drugiej zaś, narzuca wysoki poziom ochrony tych obszarów. Doświadczenia powodzi z roku 2010 potwierdziły, że poziom ten nie jest wystarczający. Głównym celem niniejszej pracy jest ocena efektywności przeciwpowodziowej kompleksu Zesławice poprzez oszacowanie poziomu maksymalnego wezbrania, które może być efektywnie redukowane. Obliczenia numeryczne przeprowadzono na komputerowym modelu 1-D rzeki Dłubni zbudowanym w oparciu o program MIKE 11 firmy DHI. Ze względu na złożony układ topograficzny kompleksu poszczególne zbiorniki odwzorowano jako odrębne obiekty 1-D, zdefiniowano połączenia hydrauliczne między nimi i zamodelowano reguły sterowania odpływem. Ponadto, dokonano oceny przepustowości koryta Dłubni poniżej Zesławic oraz sformułowano ogólne wytyczne dla zwiększenia poziomu ochrony przeciwpowodziowej w obszarze oddziaływania zbiorników.

Słowa kluczowe: mały zbiornik retencyjny, retencja sterowana, ochrona przed powodzią, modelowanie 1-D