Modelling of the Impact of the Retention Reservoir on the Flood Protection of the City – A Case Study for the City of Kalisz (Central Poland)

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Abstract Floods are natural phenomena related to the circulation of water in nature and they cannot be avoided. Despite the methods of predicting floods, technological development and civilization progress, the flood risk has been still increasing. The relevant hydrotechnical advancement, rational spatial development and optimal water management have a significant impact on reducing the consequences of flooding. Particularly retention reservoirs are decisive to rising flood safety and living conditions of urban residents who are at risk of flooding. The construction of a retention reservoir is a serious engineering, economic and eco-scale challenge. It must be preceded by numerous studies and analyses necessary to carry out the entire construction process and subsequent operation in an optimal way. At present, a number of engineering and environmental analyses are supported by the use of forecasting and computational tools based on the mathematical description of a given physical phenomenon. With their use, it is possible to determine, at the design level, the impact of a technical facility on various elements of the natural or the human environment. The paper presents the impact analyses of a planned retention reservoir located on the Prosná river in the flood protection system in Kalisz (Poland). The flood protection system is insufficient in Kalisz and its weakness was demonstrated, among others, by flood in May, 2010. Analyses were based on data received from the unsteady flow numerical modelling system and optimisation methods to support the management process of retention reservoir resources for extreme periods. The formulated task of dynamic optimisation due to its non-linearity was simplified to a static task by discretisation of an independent variable.

1. Introduction
Floods have always accompanied people and cannot be avoided because they are natural phenomena related to the circulation of water in nature. Despite significant technological development and civilization progress as well as elaboration of increasingly sophisticated methods of predicting the arrival of high water or flooding, the flood risk follows an upward trend and poses a threat to the human environment [1-3]. Although the role of flooding is sometimes favourable in terms of ensuring natural conditions for habitats in river valleys, it is insignificant in relation to its damaging consequences [4].

The relevant hydrotechnical advancement, rational spatial development and optimal water management have a significant impact on reducing the consequences of flooding. Particularly retention reservoirs are important for rising flood safety and living conditions of urban residents who are at risk of this phenomenon. Retention reservoirs allow for managing water resources by storing water during floods and supplying rivers during low flow periods. Often, they perform complex functions ranging...
from flood protection, through meeting economic, energy, and navigation needs, ending with environmental and recreational purposes [5-6]. Retention of water and reduction in maximum water flows do not eliminate the flood risk entirely, however, they are an important element of flood protection systems [5]. The total volume of reservoirs in Poland is estimated at approx. 3.3 billion m³ of water. In order to ensure full flood safety, it is assessed that this amount should be increased threefold [7].

The construction of a retention reservoir is a serious engineering, economic and eco-scale challenge [1, 4]. It must be preceded by numerous studies and analyses necessary to carry out the entire construction process and subsequent operation in an optimal way [5]. At present, a number of engineering and environmental analyses are supported by the use of forecasting and computational tools based on the mathematical description of a given physical phenomenon [8-11]. With their use, it is possible to determine, at the design level, the impact of a technical facility on various elements of the natural or the human environment. An important element of increasing flood protection is the development of various types of hydrotechnical constructions and devices adapted to work in flood risk conditions [12, 13].

It is worth recalling that Poland is considered to be one of the European countries where inland water resources are the poorest. The amount of water per capita in Poland is approx. 1,600 m³ and locates the country only on the 26th position in Europe (the average in Europe is approx. 4,900 m³) [14]. Precipitation in the world is unevenly distributed and depends primarily on latitude. The equatorial region and latitude 60° are characterised by rainfall significantly higher than that occurring in arctic regions and latitude 30°. Location above the sea level also has a significant impact on the amount of precipitation – rainfall in mountainous areas is usually higher than in lowlands. In Poland, Wielkopolska (Greater Poland) is a region with very few water resources characterised by the lowest precipitation level ranging from 450 to 550 mm, in dry years even less than 350 mm [14].

The Prosna River basin and the basin of the middle Warta are located in an area where water resources and precipitation are exceptionally low. In dry periods, in the Prosna River above Kalisz, there are flow rates less than 1.0 m³/s, which do not ensure the biological flow rate [7]. At the same time, due to heavy rains, primarily in spring and summer, the Prosna river is characterised by a significant increase in the water level. This phenomenon is exemplified with floods in Kalisz in 1985, 1995, 1997, 2010, as well as heavy flooding caused by rapid melting of snow in 1979 and 1980 [14].

The Prosna River has often been the subject of studies related to the construction of a retention reservoir within its catchment area that would combine flood protection and drought prevention functionalities. It was considered that the reservoir would be located in Wielowieś Klasztorna and in the area of Wieruszów. Taking into account the significant development of the river and the valley near Wieruszów, far from advantageous topographical conditions and worse, in comparison with the area of Wielowieś Klasztorna, retention possibilities, it was decided to locate the retention reservoir near the already mentioned locality, Wielowieś Klasztorna [7].

The main reason behind the intention to build the reservoir in Wielowieś Klasztorna was the flood risk for the city of Kalisz. The areas most exposed to flooding are the districts of Zawodzie – located in the left-hand part of Kalisz and Rajsków housing estate – in the right-hand part of the city [15]. Formerly, these areas were part of the natural Prosna river floodplains, yet, single-family housing estates has been established there. High water in 1997 and 2010 threatened the right-bank part of the city with extensive flooding due to the resulting backwater in the Śwędrnia River flowing from the estuary to the Bernardyński Canal. The events confirmed the fact that the previous flood protection system was not sufficient [15].
2. Location and characteristics of the Wielowieś Klasztorna reservoir

The planned reservoir will be located entirely in the Warta water region [7], Greater Poland, including the area of 3 districts and 5 communes (Figure 1):

The Prosna River, where the planned Wielowieś Klasztorna reservoir will be located, is a left-bank tributary to the Warta River. Its sources are located on Woźnicko - Wieluńska Upland near Wolencin, approx. 250 m a.s.l. The river is 216.8 km long, with the catchment area of 4924.7 km². The Prosna River, in the section below the designed main dam of the planned Wielowieś Klasztorna reservoir, flows in a natural channel where no regulatory works have been carried out so far. The riverbanks are intensely overgrown with shrubs and trees (Figure 2). On the one hand, the vegetation stabilises the
banks and prevents major changes in the watercourse level system, and on the other hand it significantly affects water flow conditions, particularly within the high water zone. The left side of the river in the section near the frontal dam features a high bank.

![Figure 2. Natural riverbed of the Prosna river (Małgorzata Majchrzak-Majchrzak, 2018)](image)

The designed dam is located at km 93 + 000 of the Prosna River, i.e. approx. 24 km above Kalisz, between two villages: Wielowieś Klasztorna, Sieroszewice commune on the left side and Kakawa Nowa, Godzieszewo commune on the right side. The cross-section of the designed frontal dam closes the catchment area with 2350.0 km². The valley in the place of the dam is relatively narrow, which has a significant impact on the volume of the dam and the cost of earthworks [7].

The designed reservoir will significantly change the conditions in the riverbed. The changes will concern water flows, which will depend on water management of the reservoir as well as riverbed processes such as deep and longitudinal erosion. Construction work in the reservoir and regulatory work related to its operation may completely change the current appearance of the studied section, primarily lead to changes in the development of the river banks.

3. Conceptual assumptions of the Wielowieś Klasztorna reservoir
The first concepts assumed the construction of a reservoir with a very large capacity of up to 155 million m³. Over time, after detailed risk analyses and assessments of the impact the project would have on the natural environment, it was found that there were no such significant water needs in the Prosna River basin. Thus, it was considered that the construction of a reservoir with such a large capacity was not necessary. As a result of the above, in 1992, Regionalny Zarząd Gospodarki Wodnej in Poznań
(RZGW in Poznań) [the Regional Water Management Board] commissioned to develop a concept of a reservoir with three times smaller volume, approx. 50 million m³ [8].

Primarily, the reservoir was to take into account a number of conditions, including i.e. reduction in maximum flood flow rates and flood protection in Kalisz. These also covered: possibility of economic growth by enhancing tourist values, water increase in low flow rates in the river below the dam, securing the biological flow rate, use of retained water for agriculture, energy use through the construction of a small hydropower plant, possible provision of water for communal purposes as well fishing industry [8]. The first concept taking into account the RZGW guidelines was developed by Biuro Projektów Hydroprojekt based in Poznań. Its parameters are presented in Table 1.

| Specification          | Reservoir level [m a.s.l.] | Total capacity [mln m³] | Flood zone [ha] | Average depth [m] |
|------------------------|-----------------------------|-------------------------|-----------------|-------------------|
| Maximum water level    | 124.00                      | 48.79                   | 1,660.00        | 2.84              |
| Minimum water level    | 120.00                      | 8.86                    | 558.00          | 1.01              |

The concept took into account the construction of a partition located in the middle of the reservoir, which, while maintaining the water level also in the upper part of the reservoir, would prevent it from being exposed. As a consequence, the flood zone with the minimum pool level would increase by 360 ha.

In order to confirm the validity of constructing the reservoir, in 1996 there were carried out model tests to verify its flood protection functionality [8]. Model tests using the systems i.a. Mike Basin, Mike 11, Reservoir and Mike Shi indicated then that based on data from long-term daily hydrological observations (1950-1983), safe water discharge from the reservoir, ensuring safety for Kalisz, was 85 m³/s, which equalled to the water flow rate of 120 m³/s in the Prosna river in the city. Tests also included the efficiency of the reservoir at 1% water, i.e. occurring once every 100 years, showing that at the flow rate shaped at this level the reservoir would not be able to limit the flow rate at the previously indicated safe discharge of 85 m³/s. The flow rate that would occur in this situation in Kalisz, about 300 m³/s, could be reduced by half, which would save the city from the state of flood disaster. Expertise demonstrated that, besides the construction of the reservoir, ensuring the safety for Kalisz required the expansion of the water node, increasing its capacity up to 150-180 m³/s [8].

3.1 Description of the planned reservoir
At the normal pool level (NRL)= 124.00 m a.s.l. the reservoir retain 48.8 million m³, with the flood zone of 1704.0 ha, whereas at the maximum pool level Max RL = 125.00 m a.s.l. the reservoir will retain 67.5 million m³, taking the area of 2047.0 ha. Table 2 specifies a detailed list of the reservoir's parameters.

The planned Wielowieś Klasztorna reservoir will be a multi-purpose water reservoir, the functions of which, according to the Update of Feasibility Study [7], will be as follows:

1. Protect the areas downstream the reservoir against flood by reducing flow rates in the area of Kalisz. The overarching objective of the planned reservoir will be to reduce the flood wave to a size that is safer for the city of Kalisz and areas below the frontal dam, i.e. Q=116 m³/s at max. discharge from the reservoir equal to 85 m³/s.
2. Protect agricultural areas of the Prosnia River valley against the effects of flooding.
3. Retain water in order to enable controlled water management.
4. Increase the minimal flow rates in the Prosnia river to secure the minimum acceptable flow in the watercourse.
5. Protect against the effects of drought and meet water demand for agricultural irrigation.

| No. | Specification                                      | Reservoir level [m a.s.l.] | Total capacity [mln m³] | Flood zone [ha] | Average depth [m] |
|-----|---------------------------------------------------|---------------------------|-------------------------|----------------|------------------|
| 1.  | Maximum reservoir level [Max RL]                  | 125.00                    | 67.50                   | 2,047.00       | 2.86             |
| 2.  | Normal reservoir level [NRL]                       | 124.00                    | 48.80                   | 1,704.00       |                  |
| 3.  | Minimum reservoir level [Min RL] - lower part     | 120.00                    | 5.95                    | 384.60         | 2.86             |
| 4.  | Minimum pool level [Min RL] - upper part          | 121.50                    | 4.80                    | 533.00         |                  |

The necessity to build the reservoir is also dictated by the incidence of hydrological droughts that occur in this area.

4. Research tools

Proper design of the retention reservoir as well as its impact on the transformation of flow rate below the frontal dam is not currently possible without the use of numerical flow models in open channel networks [11].

The analysis of flood reserve of the planned Wielowieś Klasztorna reservoir on the transformation of 2010 flood wave used a mathematical model based on the reservoir retention equation developed by I. Laks for the operational assessment of the Jeziorsko reservoir. A broader description of the model and the assumptions made therein can be found in the study [16] by Kaluža and Laks.

In this model, the retention increase (over time) in the reservoir can be written in the form of an equation [16]

\[
\frac{dV^k}{dt} = \sum_{j=1}^{m_p} Q_{dop}^j(t) - Q_{odp}^j(t)
\]

Hence the retention equation for this reservoir will take the form:

\[
V^k(t) = \int_{t_p}^{t_e} \left( \sum_{j=1}^{m_p} (Q_{dop}^j(t) - Q_{odp}^j(t))dt + V^k(t_p) \right)
\]

where \(Q_{dop}\) means inflow to the reservoir, \(Q_{odp}\) means outflow from the reservoir, and \(t_p\) and \(t_e\) are the starting and ending simulation times, respectively. The sub-function is fixed at the time step, and the equation (2) is a numerical integration [16].
Determination of the water table ordinate for the reservoir requires defining the parameters of the water table level curve $V_k(H_z)$. The curve is provided as an adequate equation, or it is described in the form of a polygonal chain with $n_w$ vertices.

Having data on the inflow hydrograph to the reservoir, we can determine the outflow hydrograph through a properly formulated optimisation task.

This task was formulated for the reservoir as follows [16]:

- the goal function is the minimum value of the area between inflow and outflow hydrographs,
- the reservoir can be filled (emptied) to specific ordinates determining the volume of the flood reserve or the maintenance volume for low-season periods,
- 24h increases or decreases in water table levels cannot exceed values specified in operating instructions.

With the target function and constraint conditions formulated in this way, there was obtained the optimal outflow hydrograph (from the point of view of the adopted criteria). The optimisation task is strongly non-linear, thus it was required to use numerical methods [16].

In the first stage, an inflow hydrograph was determined in the cross-section of the frontal dam of the designed reservoir. It was assumed to determine the hydrograph on the basis of the flow hydrograph in the river gauge station in Piwonice (district of the city of Kalisz). The flow rate values in this hydrograph were corrected with the reduction factor calculated on the basis of formula:

$$R_Q = \left(\frac{A_{WK}}{A_{pn}}\right)^n$$  \hspace{1cm} (3)

where:

- $A_{WK}$ – catchment area in the calculation profile of the Wielowieś Klasztorna reservoir frontal dam [km$^2$],
- $A_{pn}$ – catchment area in the calculation profile of Piwonice (river gauge),
- $n$ – power factor for the analogy method equal to 0.75 for the discussed Prosna section [16].

Table 3 presents the values of catchment area and characteristic flow rates.

| Calculation profile               | River kilometrage | Catchment area [km$^2$] |
|-----------------------------------|-------------------|-------------------------|
| Mirków (river gauge station)      | 140+100           | 1,255.00                |
| Grabów on Prosna                  | 110+000           | 1,931.60                |
| Dam - Wielowieś Klasztorna        | 93+000            | 2,350.00                |
| Piwonice (river gauge station)    | 69+800            | 2,938.20                |

The flow reduction coefficient $R_Q$ calculated according to Formula (3) is 0.85. Figure 3 presents the calculated flow rate hydrograph for the frontal dam calculation profile. The water table level curve of the reservoir for the water reserve from 124 m a.s.l. to 125 m a.s.l. was aligned with the second degree polynomial:
\[ H_z = -0.000638V^2 + 0.1288V + 119.26 \]  \hspace{1cm} (4)

where:
\( V \) - volume in million m\(^3\).

\textbf{Figure 3.} Flow rate hydrographs Q in the Piwonice gauge station and in the main dam cross-section of the designed Wielowieś Klasztorna reservoir for 2010 flood wave.

Knowing the inflow hydrograph and the equation of water table level curve, it is possible to determine the outflow hydrograph by using the above mentioned model based on the retention equation (1).

Unfortunately, for the purpose of the work, information on the reservoir's operational assumptions for the flood wave passage was not attainable. Therefore, the following calculation assumptions have been arbitrarily adopted:

1. the reservoir begins to retain the flood wave with an equal supply of 70 m\(^3\)/s,
2. the reservoir begins to discharge the retained volume at the inflow of 75 m\(^3\)/s,
3. there is no anticipatory discharge,
4. the discharge from the reservoir is designed to last 12 days,
5. the maximum increase in water table cannot exceed 0.30 m/24h.

The above assumptions reflect the unfavourable scenario of the reservoir's operation, where hydrological forecasts do not allow the operator to respond to flood risk in advance. The reservoir also does not retain the flood volume until the occurrence of medium flows, it discharges water no sooner than in high flow periods. Such an assumption originates from the time limit in which the reservoir's hydro-technical devices operate under extreme conditions. Figure 4 presents the calculated hydrograph of the discharge from the reservoir for the modelled period.
5. The impact of the reservoir on flow rates and water table levels in Kalisz (Piwonice river gauge station)

The Wielowieś Klasztorna reservoir will have the most significant impact on transformation of the Prosna river flow rate in the section from the frontal dam to its confluence with the Warta river. One of the objectives that provided a basis to build this reservoir is to strengthen the flood protection system in Kalisz. The reduction in flood wave should decrease flow rates and water levels within the Kalisz Water Way System. The quantitative impact of the reservoir on flow rates in the Piwonice river gauge cross-section was estimated in a simplified manner using the flow curve for this river gauge. Based on data on water levels and flow rates for 2010 flood wave in the Piwonice cross-section, the authors determined a flow rate equation for the range 19 to 150 m$^3$/s. This curve (third degree polynomial) along with the equation and the correlation coefficient are indicated in Figure 5.

The actual flow hydrograph in the cross-section of Piwonice was modified by simulation results obtained from the transformation model. For each flow rate occurring from 21/05/2010 to 9/06/2010, the difference between the inflow and the outflow from the reservoir was subtracted (during the flood wave retention phase) or added (during the discharge phase of accumulated volume). It was assumed that in the section from the frontal dam to Piwonice there would be no significant transformation of the outflow hydrograph from the reservoir.

The actual and calculated flow rate hydrographs of 2010 flood wave in the Piwonice cross-section is presented in Figure 6. The maximum flow rate in the Piwonice river gauge station would be reduced by 31% fluctuating from 149 to 104 m$^3$/s. The flow curve equation from Figure 5 was used to determine the hydrograph of water levels for the transformed wave - which is shown in Figure 7. The maximum water level would be reduced by 0.21 m and would not exceed 104.81 m a.s.l. However, the reservoir would extend the duration of water levels above alarm values (103.98 m a.s.l.) by 7 days, which would result in increased hydraulic pressure on embankments and other hydrotechnical equipment.
Figure 5. Flow rate curve for Piwonice river gauge determined on the basis of IMGW data on 2010 water levels and flow rates.

Although the presented analysis is evidently very simplified, it allows for quantitative determination of the impact of the proposed reservoir on the flood protection system in Kalisz.

Figure 6. Flow rate hydrographs in the Piwonice river gauge cross-section for 2010 flood wave
Figure 7. Water level hydrographs in the Piwonice river gauge cross-section for 2010 flood wave

6. Conclusions
The obtained computational results and their analyses allow for formulating the following conclusions:

- The designed Wielowieś Klasztorna reservoir will change the natural hydrological regime of the Prosna river in the entire analysed section. The reservoir will significantly affect flood flow rates in the section of the Prosna river directly below the frontal dam and it also applies to the city of Kalisz.
- The Wielowieś Klasztorna reservoir would enable a safer passage for 2010 flood wave through Kalisz. The calculations confirmed the initial assumptions contained in the Hydroprojekt study (1992) on reducing the flow rate to less than 85 m$^3$/s in the frontal dam cross-section and less than 120 m$^3$/s in the Piwonice cross-section. In this hypothetical variant, the reservoir would reduce the flow rate in the considered cross-sections to 80 m$^3$/s and 104 m$^3$/s, respectively. The maximum reduction in water levels in the Piwonice cross-section would be 0.21 m.
- The reduction in maximum flow rates caused by the reservoir lengthens the wave and increases the pressure of high water on the river embankments. The analysed variant assumed that the duration of water levels exceeding the alarm level in the Piwonice river gauge cross-section would be extended by 7 days. The construction of the reservoir should be combined with modernisation and reinforcement of the flood embankment system protecting the city of Kalisz.
- Proper reservoir management requires reliable and accurate long-term inflow forecasts to the reservoir. It is necessary to develop a monitoring and forecasting system of water inflow to the Wielowieś Klasztorna reservoir, since the data is considered indispensable to obtain optimal discharge hydrographs.

The results obtained in this work along with their interpretation are a good example of numerical models being powerful tools to support flood risk assessment. They enable to perform quick variant analyses, which may be helpful in the decision-making process regarding water management on the Prosna river, or the management of the Wielowieś Klasztorna reservoir either during its standard operation or in extreme situations.

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