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Water management in dam reservoirs – analysis of operational risks on the example of new facilities

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Abstract: Even during normal hydrometeorological conditions, water management in dam reservoirs requires special measures and difficult operational decisions. The situation becomes even more complicated when high or even extreme surges occur. The study, which focused on four newly constructed dam reservoirs, identified key issues that may result in inappropriate operational assumptions being adopted. These include: (1) uncertainty in the values of characteristic flows – this is particularly true for the Krosnowice reservoir, where calculations were based on only one empirical method, (2) uncertainty in the capacity of the discharge devices – the capacity for bottom outlet of the Szalejów Górny reservoir was shown to be 19.5 $m^3 \cdot s^{-1}$ higher than assumed, (3) consequences of attempts to absolutely maintain permitted outflow – for the analysed reservoirs, in the matter of control flow, it ultimately results in exceeding permitted outflow by values ranging from 123.86% (Roztoki Bystrzyckie reservoir) to 2000% (Krosnowice reservoir), (4) considering the cooperation of facilities located in the same catchment – for the wave of the design flow, delaying the outflow from Szalejów Górny reservoir would allow to reduce the total wave in Kłodzko by 41.37%, (5) the need to prepare the multi-purpose reservoirs for the surge – in the event of a design flow surge it would allow to reduce the surge in Kłodzko from 242 to 101.5 $m^3 \cdot s^{-1}$, however it would require a difficult decision to anticipate emptying the facilities in the interval from 18 h before the surge for Szalejów Górny to 4 h before the surge for Boboszów.

Keywords: dam, hydrology, hydrotechnics, retention reservoir, water management

INTRODUCTION

Water management conducted on reservoirs is a complex issue and many factors need to be considered when planning the operations for a particular facility, such as, among others, maintaining an accumulation level appropriate to the economic, social or environmental needs, controlling the flow in the watercourse downstream of the reservoir, and maintaining a reasonable flood reserve (Kosierb, 2017; Chongxun *et al.*, 2021). Furthermore, when designing a new facility, it is very important to make the right hydrological and hydraulic assumptions at the planning stage of the project. The calculations for these assumptions are based on various methods for determining characteristic flows, which will ultimately (in tandem with the legal regulations of the country in question) determine the rationale for the construction of the reservoir, its size and the technology for the construction of the bottom outlet and spillway facilities (Rozporządzenie, 2007). The method of determining annual maximum flows with a specified probability depending on the nature of the catchment, the amount of hydrometeorological data available, the location of the nearest water gauge cross-section and the length of the observation line (Ozga-Zieliński *et al.*, 2022). In controlled catchments – at water gauge cross-sections, statistical methods can be used, while other locations of the controlled watercourse will also require the use of extrapolation equations or interpolation of hydrological data. The most difficult situation concerns uncontrolled catchments, where rainfall-runoff models or empirical methods – which as a rule require some approximation and have the highest error (Wałęga, Młyński and Kokoszka, 2014; Młyński *et al.*, 2019) – need to be applied. Two examples of empirical methods currently used in Poland are the Iszkowski formula, developed in the second half of the 19th century and used to calculate mean and low flows, and Stachý's precipitation formula, which makes it possible to determine flows with a certain probability for catchments of <50 km^2. The weakness of both of these methods is the need to assume values for different coefficients, i.e. outflow and retention (in Iszkowski formula), as well as wave shape, outflow, lake reduction and probability of quantiles depending on the country's region (necessary to apply Stachý's formula). Any other empirical method is based on similar coefficients and can usually only be applied in predetermined regions, i.e. with characteristics similar to the area in which it was developed (Banasik *et al.*, 2012). The results of hydrological calculations obtained (especially in uncontrolled catchments) should therefore be considered as an approximation of the actual situation.

Another element that forms the basis for assumptions about the operation of the reservoir is the capacity and form of the bottom outlet and spillway facilities. Regardless of the type and shape of these elements chosen, it is necessary to determine their hydraulic limits, on which the instructions describing, for example, the management of the gates of the individual adits will depend. As it is practically impossible to build a reservoir with identical parameters to an existing one, each dam will be a unique object and the parameters of the downstream discharge facilities will have to be determined on the basis of calculations, the correctness of which can only be confirmed at the operational stage. To this end, IT (Information Technology) or physical models are currently used on a suitably reduced scale. The latter make it possible to verify the correctness of the technical solutions adopted, such as the shape of the structure, the effectiveness of the cascade and the energy dissipation in the outfall basin (Majewski, 2019). However, since the use of computer models is faster and more versatile, basic hydraulic calculations for hydro projects are performed using them (Albo-Salih and Mays, 2021; Echeverribar *et al.*, 2021). Programs such as HEC-RAS developed for the US Army Corps of Engineers or MIKE developed by the Danish Hydraulic Institute are popularly used for this purpose. In order for the results calculated by the model to best reflect reality, it is necessary to calibrate them based on available experimental data (Gruss *et al.*, 2023). By creating an information model of non-existent objects, calibration is impossible, which again makes it necessary to take the model results as an approximation of the actual state of affairs.

The overall water management activities on a reservoir consist of many aspects that may necessitate regulating the level of dammed water or, conversely, maintaining it at a particular ordinate (Mo *et al.*, 2022; Połomski and Wiatkowski, 2023). These aspects include, among others, the preservation of the economic functions of the facility (including tourism and energy functions) the not exceeding of the permitted outflow (which does not cause losses/flooding below the facility) and the need to maintain the inviolable outflow (necessary for aquatic organisms) (Kałuża, Sroka and Lewandowska, 2017; Książek *et al.*, 2019). Environmental considerations are also important, as is for example the case for reservoirs in the Natura 2000 area, where the regulation of reservoir water levels is partly subordinated to the breeding season of wetland birds (Gwiazda *et al.*, 2014; Nikitina *et al.*, 2020; Połomski and Wiatkowski, 2024). The accumulation in the reservoir of debris carried by the river, but also of pollutants and nutrients, also defines the usability of the retained water and may require specific operational measures, such as discharging polluted water or increasing the outflow to flush out accumulated sediment (Kondolf *et al.*, 2014; Wiatkowski *et al.*, 2021). Among the key measures required for water management in the reservoir is preparing the facility for the passage of a potential flood wave (Hämmerling *et al.*, 2022). Depending on the region, based on multi-year data, it is theoretically possible to identify periods in which the chance of more intense surges is higher and during this time it would be advisable to increase the flood reserve (Delaney *et al.*, 2020). However, given current climate change, abnormal hydrometeorological situations are becoming more frequent (Dorchies *et al.*, 2016; Mohammed and Scholz, 2017; Radzka and Rymuza, 2023) with the result that reservoirs need to be ready for extreme conditions for most of the year. In order to make rational decisions and implement effective measures, it is important to constantly monitor the current and forecast hydrometeorological state in the areas of the country concerned and to ensure that reservoir staff are ready for immediate action. Although the above issues mainly concern multi-purpose reservoirs (permanently damming water), water management in dry reservoirs also requires proper planning, which particularly concerns operations during surges, including regulation of reservoir outflow in order to achieve maximum effectiveness in reducing flood damage.

In view of the circumstances described above, the purpose underlying the production of this manuscript is: (1) to analyse the hydrological and hydraulic assumptions adopted at the planning stage for the construction of four new flood control reservoirs in the catchment area of the Nysa Kłodzka River in south-western Poland, (2) to make an information model of the operation of the discharge facilities of the largest of the studied objects, to calibrate it on the basis of the recorded surge and to indicate the observations associated with it, (3) to calculate the estimated travel time of the discharge wave from individual reservoirs and to determine their interaction, (4) to consider various scenarios depending on hypothetical hydrological conditions and the function of the studied reservoirs – retention or flood control only.

MATERIALS AND METHODS

Four newly created dry reservoirs in the Nysa Kłodzka catchment area, in south-western Poland – Szalejów Górny, Krosnowice, Roztoki Bystrzyckie and Boboszów – were selected for analysis. The basic characteristics of these sites are summarised in Table 1 and their location is illustrated in Figure 1.

The methods for calculating the characteristic and probable maximum flows for individual sites are summarised in Table 2.

The output of the discharge devices for the water management instructions for the reservoirs described was calculated using computer models. In the following part of the article, assumptions were made about the operation of the bottom outlet of the Szalejów Górny reservoir (for the others, there is currently no data available for model calibration), the construction of which is shown in Figure 2.

The structure of the bottom outlet consists of two rivulets, 2.65×3.0 m and 1.65×2.5 m, with a gradient of 1.0%. The water enters the two lines through gate valves measuring 1.65×1.65 m,

Table 1. Characteristics of the Szalejów Górny, Krosnowice, Roztoki Bystrzyckie and Boboszów reservoirs

Characteristic	Szalejów Górny	Krosno-wice	Roztoki Bystrzyckie	Bobo-szów
Capacity (mln m^3)	10.67	1.9	2.75	1.41
Capacity below spill-way level (mln m^3)	9.2	1.5	1.7	1.1
Area (ha)	118.7	44.12	48.7	21.12
Design flow rate ($m^3 \cdot s^{-1}$)	183	68	110	64
Control flow ($m^3 \cdot s^{-1}$)	269	105	154	89
Permitted outflow ($m^3 \cdot s^{-1}$)	42	5	28	14
Maximum discharge of bottom outlet[1)] ($m^3 \cdot s^{-1}$)	80	48	34.4	17.8
Compartmented watercourse	Bystrzyca Dusz-nicka	Duna	Goworówka	Nysa Kłodzka
Length of watercourse from reservoir to out-let (km)	8.5	1.0	0.7	–
Year of commissioning	2023	2023	2021	2023

[1)] For the ordinate below the level of accumulation at which the spillway begins to operate.
Source: own elaboration based on Hydroprojekt (2016a; 2016b); Sweco Engineering (2015), Sweco Hydroprojekt Polska (2015); Połomski and Wiatkowski (2022).

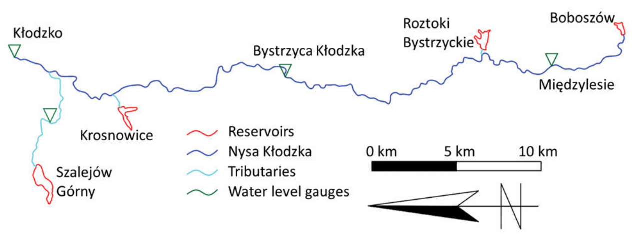

Fig. 1. Location of Szalejów Górny, Krosnowice, Roztoki Bystrzyckie and Boboszów reservoirs in the Nysa Kłodzka River catchment area; source: own elaboration

Table 2. Methods of calculating values of flows for Szalejów Górny, Krosnowice, Roztoki Bystrzyckie and Boboszów reservoirs

Reservoir	Calculation method for characteristic and probable maximum flows
Szalejów Górny	transfer (extrapolation) of multi-year data
Krosnowice	the Iszkowski formula and the Stachý precipita-tion formula
Roztoki Bystrzyckie	the Iszkowski formula, the Stachý precipitation formula, the Wołoszyn regional formula and transfer (extrapolation) of multi-year data
Boboszów	transfer (extrapolation) of multi-year data and Wołoszyn regional formula

Source: own elaboration.

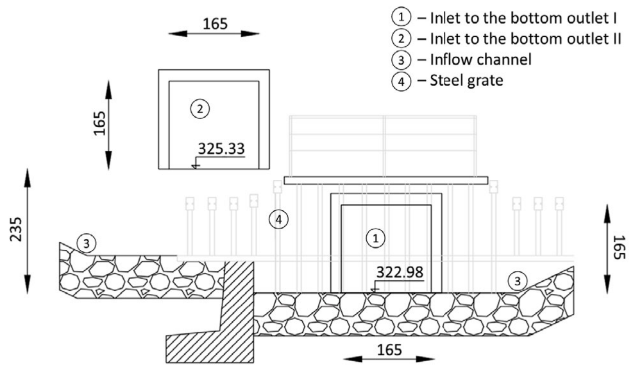

Fig. 2. Cross-section of the inlet to the bottom outlet of the Szalejów Górny reservoir; source: own elaboration

located at different levels (the height between the lower edges of the inlets is 2.35 m). In order to determine the discharge capacity depending on the water level in the Górny Szalejów reservoir, a model was created in the HEC-RAS programme, which was calibrated based on the December 2023 surge that led to the first damming of the facility's bowl.

In order to determine the estimated (approximate) velocity of wave travel down the Nysa Kłodzka River to the water gauge cross-section in the town of Kłodzko, four versions of the computer model were created in the HEC-RAS programme, i.e. in the sections between individual reservoirs and to the town mentioned above. Using the Numerical Terrain Model (Geoportal, no date), dozens of river bed cross-sections were delineated at each section, in which the water velocity was determined for a fixed flow rate. A simplified longitudinal profile of the analysed section of the Nysa Kłodzka River, 46.48 km long, is presented in Figure 3.

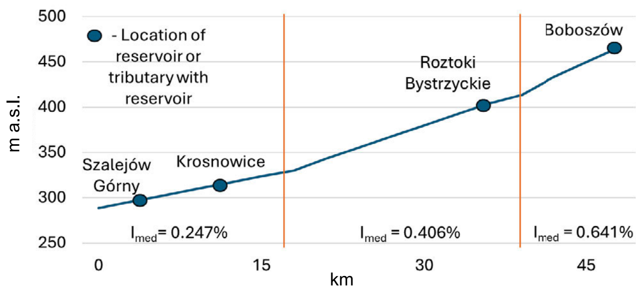

Fig. 3. Simplified longitudinal profile of the Nysa Kłodzka River from Boboszów reservoir to the town of Kłodzko; source: own elaboration

In order to illustrate the water management issues in dam reservoirs, three different scenarios were adopted assuming different hydrological conditions or reservoir function. The first two scenarios concern the simultaneous occurrence of control or design flow waves in the case of dry reservoirs, i.e. assuming their current function. Knowing the variability and unpredictability of hydrometeorological conditions, the occurrence of exactly such a correlation of events is not a highly probable phenomenon. However, it should be emphasised that the use of flows established for the purpose of reservoir design is intended to demonstrate operational risks during intense (design flows) and extreme (control flows) flood events, the occurrence of which in the region is not excluded. The third scenario assumes the operation of the reservoirs as multifunctional facilities during gauge flows. The choice of this scenario is justified by the need to expand the picture of reservoir management to include the use of facilities that permanently dam up water for effective flood control, as well as by the concepts that emerged at the planning stage to extend the function of the analysed reservoirs to include retention, and the possibility of implementing these concepts in the future.

In order to consider various scenarios, the Reitz-Kreps method was used to determine the shape of wave hydrographs with a given probability of exceeding (Gądek and Środula, 2014). The wave volume was calculated using Auto-CAD as the area under the hydrograph. The hydrograph is described by Equations (1) and (2):

– ascending part (arrival wave)

$$Q_{t_w} = Q_{\max_p}\sin^2\left(\frac{\pi}{2}\frac{t}{t_w}\right) \tag{1}$$

– descending part (falling waves)

$$Q_{t_0} = Q_{\max_p}e^{-\alpha(t-t_w)} \tag{2}$$

where: Q_{t_w} = flow at time t in the arrival phase ($m^3 \cdot s^{-1}$); Q_{t_0} = flow at time t in the falling phase ($m^3 \cdot s^{-1}$); $Q_{\max_p}$ = culminating flow with assumed probability of exceedance ($m^3 \cdot s^{-1}$); t_w = rise time of surge (h) (due to the character and location of the basin, for Szalejów Górny reservoir assumed 15 h, for Krosnowice assumed 10 h, and for Roztoki Bystrzyckie and Boboszów assumed 5 h); t = time from the beginning of flood up to the moment under consideration (h); α = recession coefficient determined on the basis of the analysis of known hydrographs (–).

In presenting the results in the individual scenarios and their variants, attention was first of all paid to exceeding the permitted outflow from individual reservoirs, exceeding the mean annual flow (MAF) in the town of Kłodzko, the scale of this phenomenon and its cause. For this purpose, in addition to percentage values, a statistical index was used, the basis of which is the value of permitted outflow (or MAF), and the numerator is the maximum value of flow in a given period: $i_{t/s} = \frac{Q_{\max}}{Q_{\text{permitted}}}$. Using chain-base index (i_g), the medium-term rate *(r)* of change of flow was also calculated using the Equations (3) and (4):

$$i_g = \sqrt[n-1]{i_{n/n-1}\ i_{n-1/n-2} \cdots\ i_{n2/n1}} \tag{3}$$

$$r = i_g - 1 \tag{4}$$

where: n = number of periods (–); $i_{n/n-1}$ = last chain-base index (–); $i_{n2/n1}$ = first chain-base index (–); r = rate of change (–).

RESULTS AND DISCUSSION

CHARACTERISTIC AND PROBABLE MAXIMUM FLOWS

For each of the selected reservoirs, a different approach was used to determine the values of characteristic and probable maximum flows. The relatively simplest circumstances concerned the Szalejów Górny reservoir, where the water gauge station collecting data since 1951 is located about 5 km downstream of the dam cross-section, counting along the Bystrzyca Dusznicka stream. The catchment area of the reservoir (*Ax*) has an area of 128.6 km^2, which, when compared with the catchment area of the water gauge section (*Ay* = 173.7 km^2), fulfils the relation *Ay* > *Ax* > 0.4*Ay* (Ozga-Zieliński *et al.*, 2022), so the use of data transfer (extrapolation) is fully justified. A different situation concerns the uncontrolled catchment of the Krosnowice reservoir (33.60 km^2). For this location, it was not possible to use multi-year data, so it was decided to use the Iszkowski formula (for characteristic flows) and the Stachý precipitation formula (for probable maximum flows). As already mentioned in the introduction of this article – both of these methods require the adoption of numerous coefficients, and the results obtained with their help do not accurately reflect the actual river regime (Młyński *et al.*, 2019). Due to the crucial importance of hydrological calculations in the context of reservoir size and construction technology (followed by costs and construction safety), the determination of characteristic and probable maximum flows based on only one empirical method seems an unjustified approach. In the absence of multi-year data, it would be reasonable to enrich the calculations with the results obtained using a rainfall-runoff computer model or other empirical methods. The latter was used in the case of establishing hydrological data at the Roztoki Bystrzyckie reservoir cross-section (catchment area of 34.55 km^2), where a total of three methods of determining probable maximum flows were applied – two empirical and one transferring data from a water gauge cross-section (closing a catchment area of 50.13 km^2) on the Nysa Kłodzka River in Międzylesie, i.e. about 6.3 km above the dam. Although the catchment sizes fulfil the aforementioned relationship *Ay* > *Ax* > 0.4*Ay*, the extrapolation method should not be used for two different watercourses (Ozga-Zieliński *et al.*, 2022). However, as the cross-sections being compared are in close proximity to each other, comparing the extrapolation results with the other two methods used (to draw an arithmetic mean) is a reasonable exercise. For the last of the analysed reservoirs (Boboszów, catchment area of 18.3 km^2), one empirical method was used and data were transferred from a water gauge cross-section (closing a catchment area of 50.13 km^2) on the Nysa Kłodzka River in the town of Międzylesie, i.e. about 6 km downstream of the dam. In this case, although the compared cross-sections are located on the same river, the relation *Ay* > *Ax* > 0.4*Ay* is not fulfilled, and there are tributaries of other watercourses between them, which also constitutes a certain limitation of the possibility to apply extrapolation (Ozga-Zieliński *et al.*, 2022). However, comparing the water levels near the reservoir cross-section with the cross-section in Międzylesie read during the 1995–2011 floods, their linear correlation was noted. Therefore, the results of extrapolation are a valuable element contributing to the picture of hydrological data at the Boboszów reservoir location. However, this picture would be more complete if more than one empirical method were used. In summary, results most closely corresponding to actual hydrological conditions can be expected for the Szalejów Górny reservoir, followed by the Roztoki Bystrzyckie, Boboszów and Krosnowice reservoirs.

SZALEJÓW GÓRNY RESERVOIR DISCHARGE FACILITY

The reservoirs described in this article are dry facilities with a flood control function only. Therefore, under normal hydrometeorological conditions, the waters of the dammed rivers flow freely through their bottom outlets. Due to the low water levels in the rivers, forced trial damming was not implemented after construction. This not only poses a certain risk as to the uncertainty of the safe operation of the facility under extreme conditions, but also does not allow the capacity of the bottom outlet to be accurately determined.

At the end of December 2023, a surge occurred that led to damming in the Szalejów Górny and Krosnowice reservoirs. For the former, data was collected on the formation of the upper (in the reservoir) and lower (after the bottom outlet) water levels, which made it possible to calibrate a model of the operation of the bottom outlet with fully raised gates. The shape and position of the bottom outlet inlets, consistent with the actual construction of the bottom outlet and the measured upper water level, were used as boundary conditions for the model in HEC-RAS. The results of the model calibration are shown in Figure 4.

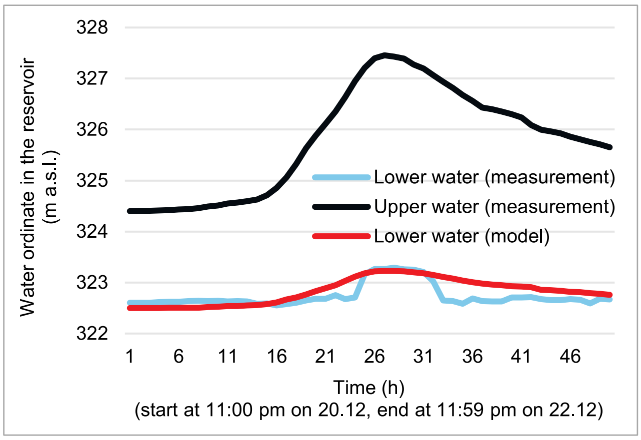

Fig. 4. Calibration of the bottom outlet model for the Szalejów Górny reservoir based on readings from surge time; source: own study

Using the calibrated model, a discharge curve of the bottom outlet (fully open) was created depending on the water level in the reservoir, as illustrated in Figure 5.

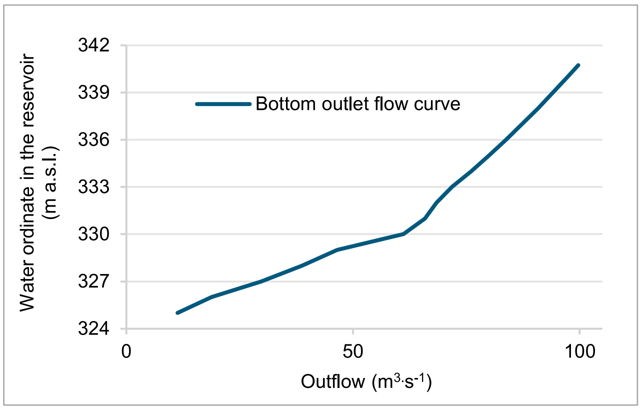

Fig. 5. Bottom outlet flow curve calculated from the model in HEC-RAS; source: own study

On the basis of the model results, it can be concluded that when the reservoir is filled to the 340.75 ordinate (the level at which the spillway begins to operate), the bottom outlet flow rate reaches a value of 99.50 $m^3 \cdot s^{-1}$. This is 19.50 $m^3 \cdot s^{-1}$ higher than the value calculated at the design documentation stage for the Szalejów Górny Reservoir. This circumstance suggests that calculations based on IT models that are impossible to calibrate are fraught with the risk of being inaccurate, and the reservoir operation instructions developed on their basis under flood conditions may result in consequences different from those expected. This is of particular concern in the case of reservoirs where the area below the dam is prone to flooding and requires the maintenance of limited permitted outflow. Based on inaccurate assumptions, opening the bottom outlet gate to a level theoretically intended to allow moderate runoff to be maintained may actually result in insufficient wave reduction and localised flooding below the reservoir. Basic measures to obtain accurate data on the performance of the bottom outlet and to avoid inefficient use of the reservoir include: (1) artificial filling of the reservoir (above the normal level of damming) and its controlled emptying, which would be accompanied by observations and hydraulic measurements allowing the precise determination of the output of the bottom outlet depending on the position of the gates and the water level in the facility's bowl, (2) during surges, ensuring that the reservoir staff makes decisions on increasing or reducing the damming on the basis of current observations, readings from water gauge patches (especially those below the dam) and hydrometeorological forecasts. However, both of these measures have implementation difficulties. In order to fill the reservoir to a high ordinate, it is required to undertake this activity during periods of higher water levels, the timing of which is difficult to predict. Attempting to fill the reservoir (especially a dry reservoir – with a flood control function only) during low flows would result in a very long duration of the measure and a detrimental reduction of the flow in the watercourse below the reservoir. Furthermore, as a result of inducing artificially high damming, the facility user would be exposed to additional costs resulting from the need to undertake clean-up and maintenance measures after the entire project is completed. Ensuring that the reservoir is operated with flexible decision-making depending on current observations may also be difficult, as staff will be unwilling to take responsibility for any errors and will require clear operating instructions which, as mentioned earlier – may be fraught with the risk of being inaccurate when their provisions are not supported by adequate studies.

SCENARIO 1 – DRY RESERVOIRS, CONTROL FLOW

The occurrence of a control flow in the watercourses of all four reservoirs was assumed as scenario 1. The consequences of attempting to maintain the permitted outflow were considered, and a "suggested outflow" was determined, i.e. the outflow that would be most favourable to maintain throughout the passage of the wave in order to prevent the spillway from occurring and at the same time to reduce the exceedance of the permitted outflow as much as possible. The velocity of the waves was then determined and their overlap was visualised in the cross-section of the town of Kłodzko.

Figure 6 shows the wave transformation successively for the Szalejów Górny, Krosnowice, Roztoki Bystrzyckie and Boboszów reservoirs.

In the instance of the Szalejów Górny reservoir, an attempt to maintain the permitted outflow (42 $m^3 \cdot s^{-1}$) throughout the wave transition would result in reaching the spillway ordinate 19 h after the start of the wave and a sudden increase in the reservoir outflow to a value of 117.5 $m^3 \cdot s^{-1}$. This would represent an exceedance of the permitted outflow by 179.76%. Maintaining

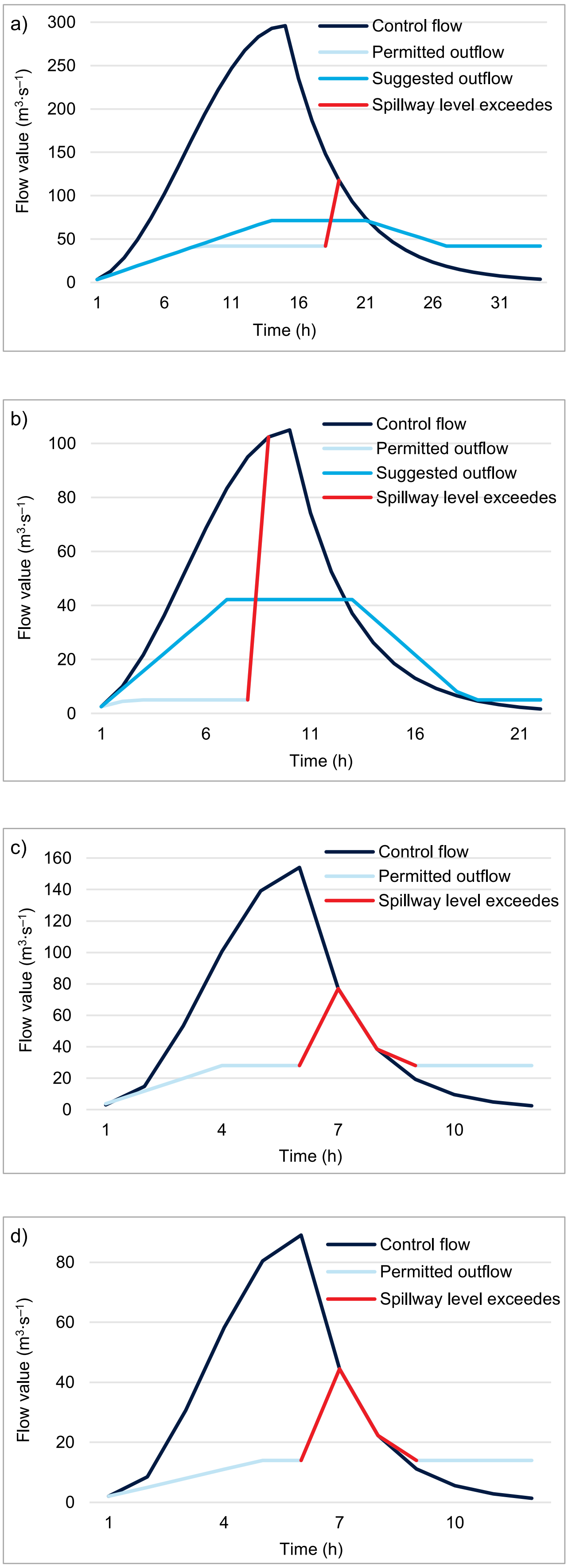

Fig. 6. Transformation of the control flow wave for the reservoirs: a) Szalejów Górny b) Krosnowice, c) Roztoki Bystrzyckie, d) Boboszów; source: own study

the suggested outflow at 71.31 $m^3 \cdot s^{-1}$ would avoid filling the reservoir above the spillway level and ultimately result in exceeding the permitted outflow by only 69.78%. The single-basis statistical index describing the outflow in the 19th hour relative to the permitted outflow is 2.80 for the 117.5 $m^3 \cdot s^{-1}$ value and 1.70 for the 71.31 $m^3 \cdot s^{-1}$ value. Using chain-base index, the average rate of increase in flow values between the hour of exceeding the permitted outflow and the hour of reaching the suggested outflow is 10.06% from hour to hour.

In the instance of Krosnowice reservoir, an attempt to maintain the permitted outflow (5 $m^3 \cdot s^{-1}$) throughout the wave transition would result in the spillway ordinate being reached 10 h after the start of the wave and the reservoir outflow suddenly increasing to a value of 105 $m^3 \cdot s^{-1}$. This would represent a 2000% exceedance of the permitted outflow. Maintaining the suggested outflow at 42.20 $m^3 \cdot s^{-1}$ would avoid filling the reservoir above the spillway ordinate and ultimately result in exceeding the permitted outflow by only 744%, which is still a significant value and indicates the high risk of flooding below the reservoir in the event of improper operation, even under conditions less extreme than the control flow. The single-basis statistical index describing the outflow in the 10th hour relative to the permitted outflow is 21.0 for a value of 105 $m^3 \cdot s^{-1}$ and 8.44 for a value of 42.20 $m^3 \cdot s^{-1}$. Using chain-base index, the average rate of increase in the flow value between the hour of exceeding the permitted outflow and the hour of reaching the suggested outflow is 59.46% from hour to hour.

In the instance of the Roztoki Bystrzyckie reservoir, the permitted outflow (28 $m^3 \cdot s^{-1}$) is very close to the maximum discharge of bottom outlet (34.4 $m^3 \cdot s^{-1}$) and there is no possibility of a controlled increase in outflow to effectively avoid exceeding the spillway ordinate. This would occur 7 h after the start of the surge and result in a sudden increase in reservoir outflow to a value of 77.01 $m^3 \cdot s^{-1}$. This would represent an exceedance of the permitted outflow of 175.03%, which could only be mitigated if the reservoir was equipped with higher capacity bottom outlets. The single-basis statistical index describing the outflow in the 7th hour relative to the permitted outflow is 2.75.

In the instance of Boboszów reservoir, the permitted outflow (14 $m^3 \cdot s^{-1}$) is very close to the maximum discharge of bottom outlet (17.8 $m^3 \cdot s^{-1}$) and there is no possibility of a controlled increase in outflow to effectively avoid exceeding the spillway ordinate. This would occur 6 h after the start of the surge and would result in a sudden increase in the reservoir outflow to a value of 44.50 $m^3 \cdot s^{-1}$. This would represent a 217.85% exceedance of the permitted outflow, which could only be mitigated if the reservoir was equipped with higher capacity bottom outlet. The single-basis statistical index describing the outflow in the 7th hour relative to the permitted outflow is 3.17.

On the basis of the data summarised in Table 3, it was possible to calculate how outflow waves from individual reservoirs would overlap in the Kłodzko cross-section in two instances – with an absolute attempt to maintain permitted outflow (Fig. 7) and with the outflow suggested for Szalejów Górny and Krosnowice reservoirs (Fig. 8). It should be emphasised that for the purpose of the scenarios analysed (intended only to illustrate the problem of water management in dam reservoirs), no account was included in the calculations of flow other than that resulting from operation of the reservoirs,

Table 3. Summarises the average outflow wave velocities at the individual reservoirs in the sections indicated, together with the time taken to travel through them

Flow and distance	Average speed ($m \cdot s^{-1}$)	Distance (km)	Time (h)
44.5 $m^3 \cdot s^{-1}$ from Boboszów to Roztoki	7.53	11.05	1.47
77 $m^3 \cdot s^{-1}$ from Roztoki to Krosnowice	5.68	28.5	5.01
44.5 $m^3 \cdot s^{-1}$ from Roztoki to Krosnowice	5.58	28.5	5.10
105 $m^3 \cdot s^{-1}$ from Krosnowice to Kłodzko	5.46	7.08	1.30
77 $m^3 \cdot s^{-1}$ from Krosnowice to Kłodzko	5.28	7.08	1.34
44.5 $m^3 \cdot s^{-1}$ from Krosnowice to Kłodzko	4.98	7.08	1.42
117.5 $m^3 \cdot s^{-1}$ from Szalejów Górny to Kłodzko	6.19	10.1	1.63

Source: own study.

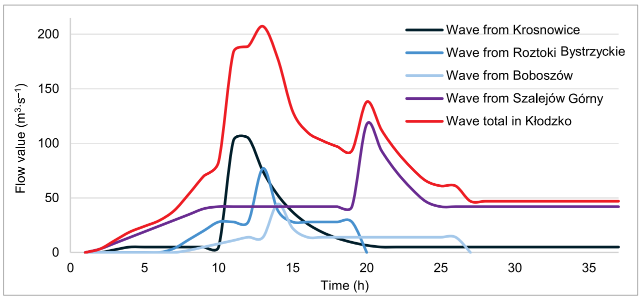

Fig. 7. Impact of reservoir outflow waves on the town of Kłodzko – maintained permitted outflow; source: own study

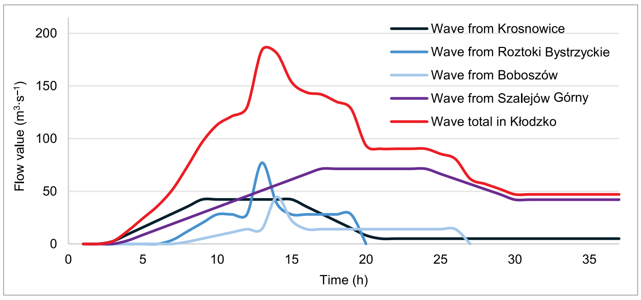

Fig. 8. Impact of the outflow wave from the reservoirs on the town of Kłodzko – application of the suggested outflow; source: own study

i.e. flows that might occur in the river due to its natural drainage of the region were disregarded.

The passage of the control flow wave through the reservoirs, where an attempt was made to maintain the permitted outflow, would result in the occurrence of a flood wave in the town of Kłodzko. Its culmination would reach the level of 207.26 $m^3 \cdot s^{-1}$, which would consist of waves caused by exceeding the spillway ordinate of the Krosnowice, Roztoki Bystrzyckie and Boboszów reservoirs and the permitted outflow of the Szalejów Górny reservoir. This value exceeds by more than sixteen times the average value of average annual flows equal to 12.5 $m^3 \cdot s^{-1}$ for this location (IMGW-PIB, no date). The next wave peak in Kłodzko occurs about 8 h after the first one and has a value of 138.04 $m^3 \cdot s^{-1}$, which is mainly influenced by exceeding the spillway level of Szalejów Górny reservoir. The single-basis statistical index describing flows of 207.26 and 138.04 $m^3 \cdot s^{-1}$ relative to the mean annual flow (12.5 $m^3 \cdot s^{-1}$) is 16.58 and 11.04, respectively. Using chain-base index, the average rate of increase in flow values from the beginning of the surge to the hour at which the flow of 207.26 $m^3 \cdot s^{-1}$ is reached is 39.63% from hour to hour.

The passage of the control flow wave through the reservoirs and the application of the suggested flow for Szalejów Górny and Krosnowice results in the occurrence of a flood wave in the town of Kłodzko, the culmination of which would reach the level of 183.86 $m^3 \cdot s^{-1}$, consisting of waves caused by exceeding the spillway ordinate of Roztoki Bystrzyckie and Boboszów reservoirs and the suggested outflow of Szalejów Górny and Krosnowice reservoirs. The decrease of the culminating flow value in relation to the previous variant is 11.29%. This is relatively little; however, the occurrence of the second wave peak has been reduced, reaching a value of 90.31 $m^3 \cdot s^{-1}$, i.e. by 34.57% less. The single-basis statistical index describing flows of 183.86 $m^3 \cdot s^{-1}$ and 90.31 $m^3 \cdot s^{-1}$ relative to the mean annual flow (12.5 $m^3 \cdot s^{-1}$) is 14.7 and 7.22, respectively. Using chain-base index, the average rate of increase in flow values from the beginning of the surge to the hour of reaching the flow of 183.86 $m^3 \cdot s^{-1}$ is 53.28% from hour to hour. The higher average rate than in the previous variant is due to the initially intensified outflows from Szalejów and Krosnowice reservoirs established to prevent the functioning of spillways. Table 4 summarises the individual parameters calculated under the two different operating options for scenario 1 – the occurrence of control flows in the dry reservoirs.

SCENARIO 2 – DRY RESERVOIRS, DESIGN FLOW

In the event of a design flow and wave shape analogous to those in the preceding subsection, in the Szalejów Górny, Roztoki Bystrzyckie and Boboszów reservoirs, it is possible to maintain permitted outflow for the entire duration of the surge. For the Krosnowice reservoir, in order to prevent the triggering of a spillway, it is necessary to increase the outflow to a level of at least 17.5 $m^3 \cdot s^{-1}$. In such a situation (in order to intercept the wave and empty the reservoir), the indicated outflows would be maintained for successively: 56.8 h from Szalejów Górny reservoir, 31.0 h from Krosnowice reservoir, 16.3 h from Roztoki Bystrzyckie reservoir and 19.2 h from Boboszów reservoir. Table 5 summarises the wave travel velocity of the permitted outflows allowed in the individual river sections. Again, no account was included in the calculations of flows other than those resulting from the operation of the reservoirs, i.e. flows that could occur in the river due to its natural drainage of the region were ignored.

Assuming the onset of the design flow wave at the same moment on all four reservoirs, the time at which the individual flows would overlap in the given cross-sections was calculated, in particular in the cross-section of the town of Kłodzko, located below all the facilities. In addition, two variants were considered – the independent operation of each facility, and considering the deliberate delay of water outflow from Szalejów Górny reservoir. The calculations are illustrated in Figures 9 and 10.

Table 4. Summary of scenario 1 – control flow, dry reservoirs

Location	Maximum outflow ($m^3 \cdot s^{-1}$)	Exceedance of permitted outflow or mean annual flow		Average growth rate to Q_{max} from hour to hour (%)
		(%)	statistical index	
Option 1 (attempting to maintain permitted outflow)				
Szalejów Górny	117.50	179.76	2.80	–
Krosnowice	105.00	2000.00	21.00	–
Roztoki Bystrzyckie	77.01	175.03	2.75	–
Boboszów	44.50	217.85	3.17	–
Kłodzko	207.26	1558.08	16.58	39.63
Option 2 (use of suggested outflow)				
Szalejów Górny	71.31	69.78	1.70	10.06
Krosnowice	42.20	744.00	8.44	59.46
Roztoki Bystrzyckie	no possibility to avoid exceeding the spillway level			
Boboszów	no possibility to avoid exceeding the spillway level			
Kłodzko	183.86	1370.88	14.70	53.28

Source: own study.

Table 5. Wave velocities of the permitted outflow from the reservoirs

Flow and distance	Average speed ($m \cdot s^{-1}$)	Distance (km)	Time (h)
14 $m^3 \cdot s^{-1}$ from Boboszów to Roztoki Bystrzyckie	6.36	11.05	1.74
28 $m^3 \cdot s^{-1}$ from Roztoki Bystrzyckie to Krosnowice	5.30	28.5	5.37
42 $m^3 \cdot s^{-1}$ from Roztoki Bystrzyckie to Krosnowice	5.61	28.5	5.08
14 $m^3 \cdot s^{-1}$ from Roztoki Bystrzyckie to Krosnowice	4.40	28.5	6.47
17.5 $m^3 \cdot s^{-1}$ from Krosnowice to Kłodzko	3.84	7.08	1.84
45 $m^3 \cdot s^{-1}$ from Krosnowice to Kłodzko	5.00	7.08	1.42
59.5 $m^3 \cdot s^{-1}$ from Krosnowice to Kłodzko	5.02	7.08	1.41
42 $m^3 \cdot s^{-1}$ from Krosnowice to Kłodzko	4.92	7.08	1.44
31.5 $m^3 \cdot s^{-1}$ from Krosnowice to Kłodzko	4.59	7.08	1.54
14 $m^3 \cdot s^{-1}$ from Krosnowice to Kłodzko	3.58	7.08	1.98
42 $m^3 \cdot s^{-1}$ from Szalejów Górny to Kłodzko	5.34	10.10	1.89

Source: own study.

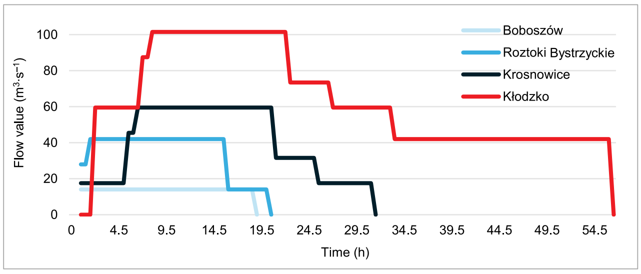

Fig. 9. Overlap of permitted outflows in individual cross-sections – self-contained reservoir operation; source: own study

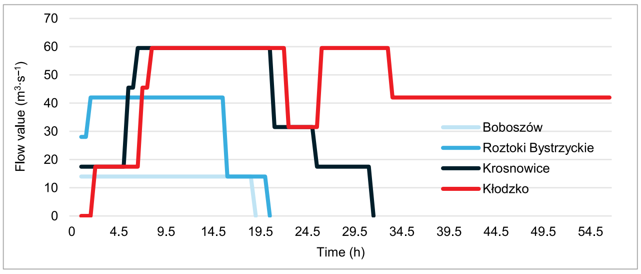

Fig. 10. Superimposition of permitted outflow in individual cross-sections – delayed outflow from Szalejów Górny; source: own study

As the Szalejów Górny reservoir has a relatively large capacity (10.67 mln m^3) there is a possibility of increasing the retention of water from the design flow and delaying the outflow for about 24 h, which would allow to reduce the total surge in Kłodzko by 41.37% – from 101.5 to 59.5 m^3·s^{-1}.

SCENARIO 3 – MULTI-FUNCTIONAL RESERVOIRS, DESIGN FLOW

The occurrence of a design flow in the watercourses of all four reservoirs was assumed as scenario 3, under the variant of multi-functional (continuously damming) facilities. The Normal Damming Level was assumed to be 70% of the dam crest height. The consequences of a wave passing through the unprepared reservoirs were considered, and it was calculated how far in advance it would be necessary to start draining the reservoirs in order to fully capture the wave while not exceeding the permitted outflow. The velocity of the waves was then determined and their overlap was visualised in the cross-section of the town of Kłodzko. Figure 11 shows the wave transformation for the Szalejów Górny, Krosnowice, Roztoki Bystrzyckie and Boboszów reservoirs, respectively.

If the Szalejów Górny reservoir were to operate as a multi-purpose reservoir, in order for it to effectively capture the design flow wave (without causing the permitted outflow = 42 m^3·s^{-1} to be exceeded) it would be necessary for it to be emptied in advance, commencing approximately 18 h before the wave arrives. If this was not done, and an attempt was made to maintain the permitted outflow, the filling of the reservoir would exceed the spillway level approximately 15 h after the wave commences, causing the permitted outflow to be exceeded by 335.71%. The single-basis statistical index describing the outflow in the 15th hour from the start of the wave relative to the permitted outflow is 4.35.

If the Krosnowice reservoir were to operate as a multi-purpose reservoir, in order for it to effectively capture the design flow wave (without causing the suggested outflow = 17.5 m^3·s^{-1} to be exceeded), it would be necessary for it to be pre-emptively and almost completely emptied beginning approximately 12 h before the wave arrives. If this action were not taken, and an attempt were made to maintain the suggested outflow, the filling of the reservoir would exceed the spillway ordinate approximately 12 h after the wave onset, causing the permitted outflow (5 m^3·s^{-1}) to be exceeded by 860%. The single-basis statistical index describing the outflow in the 12th hour from the start of the wave relative to the permitted outflow is 9.60.

If the Roztoki Bystrzyckie reservoir were to operate as a multipurpose reservoir, in order for it to effectively capture the design flow wave (without causing the permitted outflow = 28 m^3·s^{-1} to be exceeded) it would be necessary for it to be emptied in advance, commencing approximately 6 h before the wave arrives. If this was not done, and an attempt was made to

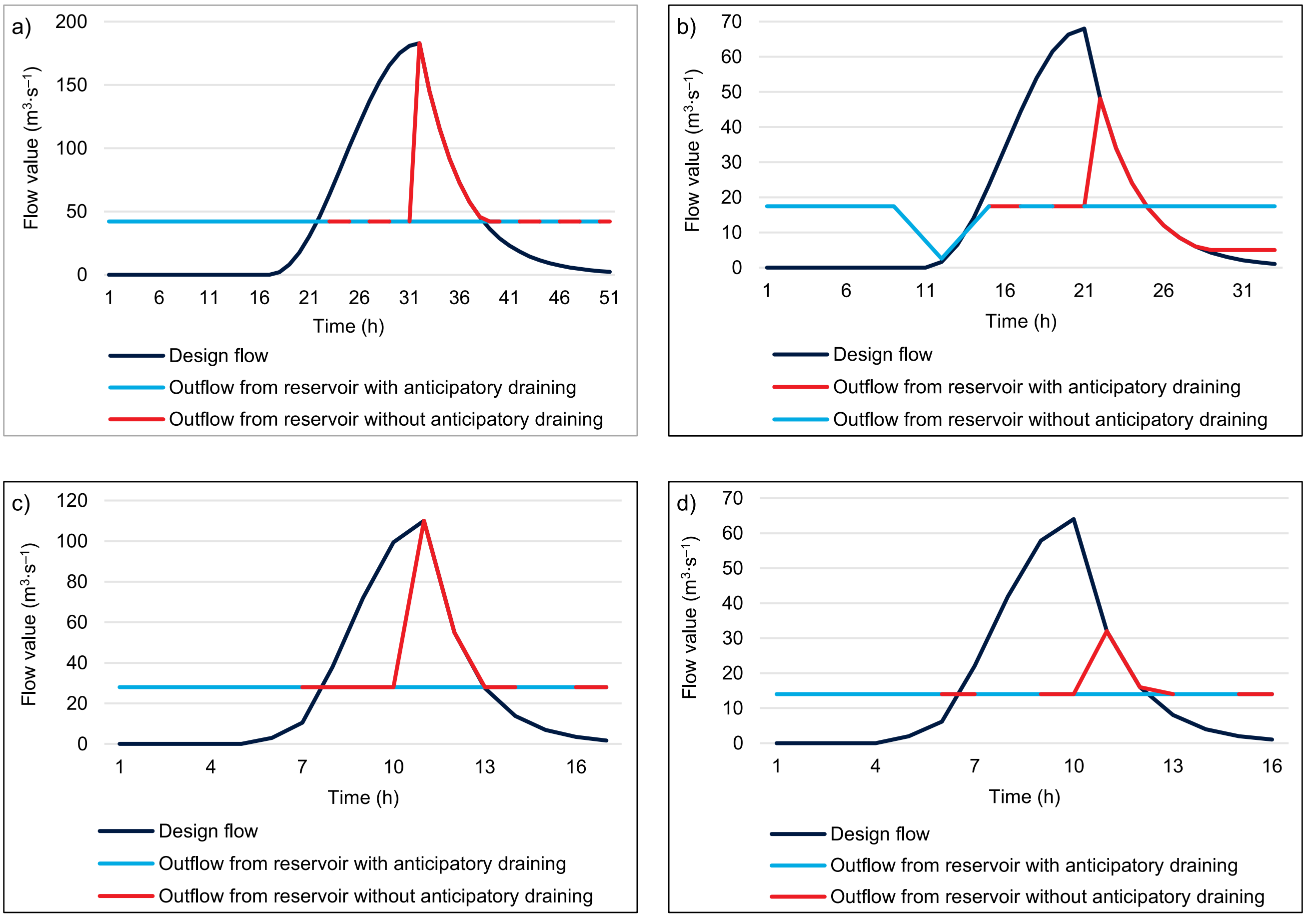

Fig. 11. Transformation of the design flow wave for the reservoirs (as multipurpose): a) Szalejów Górny b) Krosnowice, c) Roztoki Bystrzyckie, d) Boboszów; source: own study

maintain the permitted outflow, the filling of the reservoir would exceed the spillway level approximately 5 h after the wave commences, causing the permitted outflow to be exceeded by 292.85%. The single-basis statistical index describing the outflow in the 5th hour from the start of the wave relative to the permitted outflow is 3.92.

If Boboszów reservoir were to operate as a multipurpose reservoir, in order for it to effectively capture the design flow wave (without causing the permitted outflow = 14 $m^3 \cdot s^{-1}$ to be exceeded), it would be necessary for it to be emptied in advance, commencing approximately 4 h before the wave arrives. If this was not done, and an attempt was made to maintain the permitted outflow, the filling of the reservoir would exceed the spillway ordinate approximately 6 h after the wave onset, causing the permitted outflow to be exceeded by 128.57%. The single-basis statistical index describing the outflow in the 6th hour from the start of the wave relative to the permitted outflow is 2.28.

On the basis of the data collected above, it was calculated how outflow waves from individual reservoirs would overlap in the Kłodzko cross-section in two instances – wave passage through unprepared reservoirs (Fig. 12) and assuming advance emptying of the reservoirs (Fig. 13). It should be emphasised that for the purpose of the scenarios under consideration (intended only to illustrate the problem of water management in dam reservoirs), no account was taken of flows other than those resulting from the operation of the reservoirs, i.e. no account was taken of flows that might occur in the river due to its natural drainage of the region.

The passage of the design flow wave through the reservoirs in the multifunctional variant, where no prior draining has been conducted, results in the occurrence of a flood wave in the town of Kłodzko. The wave has three peaks of flow values: 183.5 $m^3 \cdot s^{-1}$ as a result of the overlap of the permitted outflows of the Szalejów Górny and Boboszów reservoirs, the suggested outflow of the Krosnowice reservoir and overtopping the spillway ordinate of the Roztoki Bystrzyckie reservoir; 150.08 $m^3 \cdot s^{-1}$ as a result of overlapping the permitted outflows of the Szalejów Górny and Roztoki Bystrzyckie reservoirs and exceeding the spillway ordinate of the Krosnowice and Boboszów reservoirs; 242 $m^3 \cdot s^{-1}$ as a result of overlapping the permitted outflows of the Krosnowice, Roztoki Bystrzyckie and Boboszów reservoirs and exceeding the spillway ordinate of the Szalejów Górny reservoir. The single-basis statistical index describing flows of 183.5, 150.08 and 242 $m^3 \cdot s^{-1}$ relative to the mean annual flow (12.5 $m^3 \cdot s^{-1}$) is 14.68, 12.00 and 19.36, respectively. Using chain-base index, the average rate of increase in flow values from the start of the surge to the hour the flow reached 183.5, 150.08 and 242 $m^3 \cdot s^{-1}$ is 41.71, 18.58 and 18.19% from hour to hour, respectively.

The passage of the design flow wave through the reservoirs in the multifunctional variant with advance emptying results in the occurrence of a reduced flood wave in the town of Kłodzko, the culmination of which would reach the level of 101.5 $m^3 \cdot s^{-1}$, consisting of the permitted outflow from the Szalejów Górny, Roztoki Bystrzyckie and Boboszów reservoirs and the suggested outflow from the Krosnowice reservoir. The decrease of the culminating flow value in relation to the previous variant is 58.05%, which should be considered a significant limitation. The single-basis statistical index describing the flow of 101.5 $m^3 \cdot s^{-1}$ relative to the mean annual flow (12.5 $m^3 \cdot s^{-1}$) is 8.12. Using chain-base index, the average rate of increase in flow values from the beginning of the surge to the hour of reaching the flow of

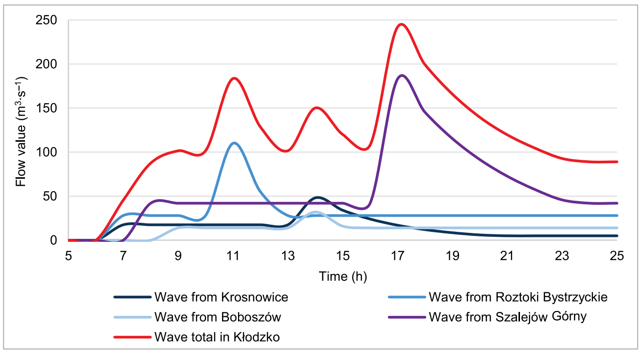

Fig. 12. Impact of reservoir outflow waves on the town of Kłodzko – unprepared multifunctional reservoirs; source: own study

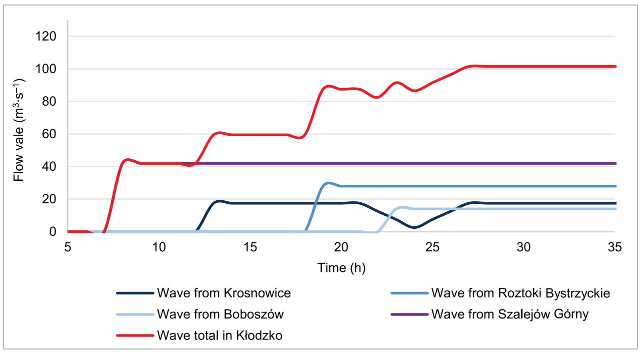

Fig. 13. Impact of reservoir outflow waves on the town of Kłodzko – pre emptied multifunctional reservoirs; source: own study

Table 6. Summary of scenario 3 – design flow, multi-functional reservoirs

Location	Maximum outflow ($m^3 \cdot s^{-1}$)	Exceedance of permitted outflow or mean annual flow		Reservoir emptying time before the surge (h)
		(%)	statistical index	
Option 1 (unprepared multifunctional reservoirs)				
Szalejów Górny	183.00	335.71	4.35	–
Krosnowice	48.08	860.00	9.60	–
Roztoki Bystrzyckie	110.00	292.85	3.92	–
Boboszów	32.00	128.57	2.28	–
Kłodzko	242.00	1836.00	19.36	–

cont. Tab. 6

Location	Maximum outflow ($m^3 \cdot s^{-1}$)	Exceedance of permitted outflow or mean annual flow		Reservoir emptying time before the surge (h)
		(%)	statistical index	
Option 2 (pre emptied multifunctional reservoirs)				
Szalejów Górny	42.00	0	1.00	18
Krosnowice	17.50	250.00	3.50	12
Roztoki Bystrzyckie	28.00	0	1.00	6
Boboszów	14.00	0	1.00	4
Kłodzko	101.50	712.00	8.12	–

Source: own study.

101.5 $m^3 \cdot s^{-1}$ is 4.75% from hour to hour. Forced emptying of the reservoir may be associated with significant socio-economic or environmental consequences, therefore the decision to undertake such a measure would have to result from precise hydrometeorological forecasts, which may be difficult to obtain early enough for a sub-mountainous catchment (Carvalho-Santos *et al.*, 2017). Table 6 summarises the individual parameters calculated under the two different action options for scenario 3, i.e. the occurrence of design flows in the multi-functional reservoirs.

CONCLUSIONS

The analyses conducted have revealed the main problems associated with water management on dam reservoirs. These include:

1. Uncertainty in the values of characteristic and probable maximum flows. In the reservoirs described, only in the instance of the Szalejów Górny reservoir was the calculation of values of characteristic flows and probable maximum flows reasonably based on the method of transfer (extrapolation) of data from many years. For the other reservoirs, empirical methods (with significant uncertainty) or their combination with transfer methods applied despite theoretically incorrect boundary conditions were adopted. The results for the Duna stream (Krosnowice reservoir) were based on only one empirical method, so the largest uncertainty should be assumed for this site.
2. Uncertainty in the capacity of the air release devices calculated at the investment planning stage. The capacity of the bottom outlets of the designed reservoirs is determined using computer models that cannot be properly calibrated at the investment planning stage. The HEC-RAS model of the Szalejów Górny reservoir bottom outlet, calibrated on the basis of the surge from the year in which the facility was put into operation, shows that the actual capacity of the facility is higher than assumed (by 19.50 $m^3 \cdot s^{-1}$ for the ordinate at which the spillway starts to operate). Thus, in order to establish the actual outflow rate curve from the reservoir at different damming levels and with different gate opening variants – it would be necessary to artificially induce high damming and controlled draining together with precise hydraulic surveys.
3. Negative consequences of trying to absolutely maintain the permitted outflow. In the instance of waves with higher flow rates, attempts to absolutely maintain the permitted outflow from the reservoirs could result in the facility filling up, triggering a spillway and ultimately creating a wave that poses a major threat to the areas downstream of the dam. For the analysed reservoirs in the dry variant, such a circumstance would occur for the control flow, where an attempt to absolutely maintain the permitted outflow would result in it being exceeded by values ranging from 175.03% for Roztoki Bystrzyckie reservoir to 2000% for Krosnowice reservoir. Applying a constant "suggested outflow" at a level moderately higher than the permitted outflow for Szalejów Górny and Krosnowice reservoirs would allow to avoid complete filling of the reservoir and thus to reduce the scale of exceeding the permitted outflow from 179.76 to 69.78% (Szalejów Górny) and from 2000 to 744% (Krosnowice). There would also be a reduction in the wave peak in the downstream town of Kłodzko, from 207.26 to 183.86 $m^3 \cdot s^{-1}$ and from 138.04 to 90.31 $m^3 \cdot s^{-1}$. In the event of the Roztoki Bystrzyckie and Boboszów reservoirs, the theoretical capacity of the bottom outlet does not allow for a pre-emptive increase in outflow, and for the control flow a spillway will necessarily be triggered.
4. Consideration of the cooperation of other facilities in the same catchment area. Failure to coordinate discharges from reservoirs in the same catchment may result in flooding in the region downstream of all facilities. Assuming the passage of the design flow wave through all the analysed reservoirs in the dry variant results in the overlapping of the four permitted outflows in the town of Kłodzko below, creating a wave with a flow of 101.5 $m^3 \cdot s^{-1}$. Delaying the outflow from the Szalejów Górny reservoir would reduce the total wave in the town of Kłodzko by 41.37%, to 59.5 $m^3 \cdot s^{-1}$. Deliberate and forcible retention of water in reservoirs is, however, a risky activity and requires precise and continuous hydrometeorological observations during the surge, together with a balancing of potential risks and benefits.
5. Need to prepare multifunctional reservoirs for wave passage. Assuming the four analysed reservoirs as operating in the multifunctional variant, the flood capacity (above the normal level of damming) is not sufficient to catch the wave of the design flow while maintaining the permitted outflow. Without advance draining in each facility, a spillway would be triggered and eventually a wave would form in the downstream town of Kłodzko with peak flows of 183.5, 150.08 and 242 $m^3 \cdot s^{-1}$,

respectively. Preparing the reservoirs in advance allows this wave to be reduced to 101.5 $m^3 \cdot s^{-1}$. However, it would require a difficult decision to start emptying the reservoirs (with permitted outflow) well in advance, i.e. between 18 h before the wave arrives for Szalejów Górny and 4 h before the wave arrives for Boboszów.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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