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Comparison of the capacity of bottom outlets and surface spillways in dam constructions based on the example of two hydrotechnical dams in Poland

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ABSTRACT

The paper analyses and compares the discharge of two basic elements of spillway structures in damming structures – bottom outlets and surface spillways. The research was conducted on the example of two actual hydrotechnical structures in Poland, namely the Solina dam on the San River and the Besko dam on the Wisłok River. The comparison included the determination of flow characteristics, discharge values depending on the damming level, and the geometric parameters of the spillway devices. The analysis allowed for the assessment of the efficiency and discharge capacity of individual elements under operating conditions, as well as the identification of differences resulting from the different designs of the two dams.

Keywords: dam, bottom outlet, surface spillway.

INTRODUCTION

The construction of dams and the creation of reservoirs are an important part of society. These reservoirs enable water to be stored during periods of excess and used during periods of shortage (Beshavard et al., 2022; Lach, 2019). Dams, on the other hand, help to prevent the effects of flooding by modifying the course of the flood wave and significantly reducing its peak.

Due to the massive nature of hydrotechnical structures, they require continuous diagnostic methods and constant observation (Dong et al., 2022; Fakhfakh et al., 2012; Lach, 2021). Monitoring and diagnostics provide information on the technical condition of the structure, enabling appropriate assessments to be made, in particular assessments of the safety of the hydrotechnical structure. This is particularly important in the case of water-retaining structures, which, due to their nature, can pose a serious threat to the environment.

In order to ensure the proper operation and safety of dams, continuous monitoring is carried out to record and predict changes occurring both in the structure and in the foundation of the structure, as well as to assess its technical condition (Gamse and Oberguggenberger, 2017; Kledyński, 2011; Lach, 2018). Every dam structure should be equipped with two basic devices enabling controlled water transport from the upper to the lower station: a surface spillway and a bottom outlet (Depczyński and Szamowski, 1999). Both of these elements play a key role in ensuring the safe operation of a hydrotechnical facility and in protecting the areas located below the dam (Moghadam et al., 2025). Their proper design and selection of flow capacity parameters have a direct impact on the stability of the structure, flood safety and minimisation of the effects of possible floods (Ambrożewski, 2006; Chanson, 2024; Zhang et al., 2024).

In accordance with the applicable regulations, a surface spillway should be able to discharge water at a rate of at least 0.8 times the design flow. Q_m This requirement is set out in Chapter 8 of the Regulation of the Minister of the Environment on the technical conditions to be met by hydrotechnical structures and their location (Minister of the Environment, 2007), concerning the principles of water discharge during the operation of dams and other damming structures.

This principle results from the theoretical relationship between the water level and the discharge capacity of drainage devices. The discharge capacity of both the surface spillway and the bottom outlet depends on the water level H: for the bottom outlet calculated above the centre of the cross-section, and for the spillway above its crest. However, their hydraulic characteristics are different: the discharge of the surface spillway is proportional to $H^{3/2}$, while that of the bottom outlet is proportional to $H^{1/2}$ (Opyrchał, 2010). This means that at high H values, surface spillways are much more effective at draining excess water (Ontario Ministry of Natural Resources, 2011).

However, two key aspects are worth emphasising. Firstly, in the initial phase of water level rise, the $H^{1/2}$ function increases faster than $H^{3/2}$. Secondly, because the bottom outlet is located well below the edge of the spillway, the water level rise Q_s above its threshold is greater than Q_p above the spillway crest. As a result, the bottom outlet can begin to effectively discharge water earlier, even before the surface spillway begins to operate (Chanson, 1994).

This raises a key design question: which of the two devices – the surface spillway or the bottom outlet – provides more favourable conditions for water discharge during different phases of flooding? In practice, both elements perform complementary functions: the bottom outlet allows for a rapid reduction of the water level in the reservoir in emergency situations or during planned maintenance work (Depczyński and Szamowski, 1999), while the surface spillway is responsible for the safe drainage of large volumes of water during floods, minimising the risk of water overflowing the dam crest (Zargar et al., 2016).

In accordance with national guidelines, each dam should have a current Water Management Manual, specifying, among other things, water management rules, the operation of spillway and discharge devices in various hydrological conditions, and emergency procedures. This document is crucial for ensuring the safety of both the structure and the areas below it (Minister of Maritime Economy and Inland Navigation, 2019).

This article attempts to answer this question. Although the considerations presented are approximate, they provide a better understanding of the relationship between the geometry and hydraulic characteristics of devices and their ability to pass flood flows. In order to give the analysis a practical dimension, it will be carried out on the example of two real structures: the Solina dam and the Besko dam, which are characterised by different structural solutions and hydrological conditions. The results of the comparison can serve as a guide for designers and operators in optimising the layout of spillway devices in existing and newly designed dam structures.

MATERIALS AND METHODS

Solina Dam

Solina Dam is the largest hydrotechnical facility in Poland, built on the San River between 1960 and 1968. Its most important functions are: energy use of retained water, flood protection by reducing flood waves below the reservoir, increasing minimum flows, water retention for municipal purposes, and increasing the tourist attractiveness of the region (Dobosz-Tempski and Dziewański, 2002; Kozicki, 2011).

Solina Dam – basic parameters

- located in Solina at km 325+400 of the San River in the Podkarpackie Province,
- heavy concrete dam with widened expansion joints 3.0 m wide, reaching from the foundation level to an elevation of 400 m a.s.l. (metres above sea level),
- has 43 sections, each with a typical length of 15 m,
- four communication and control galleries with a total length of 2073 m,
- cross-section similar in shape to a triangle,
- belongs to the first class of importance of hydrotechnical structures,
- dam length 664.8 m,
- maximum height 81.8 m,
- dam crest width 8.8 m,
- slope of the downstream face 1:0.05,
- slope of the upstream face 1:0.75,
- elevation of the dam crest 423.00 m a.s.l.,
- elevation of the spillway threshold 413.50 m a.s.l.,
- elevation of the upper edge of the segmental closures 420.50 m a.s.l.,

- elevation of the bottom outlets 366.10 m a.s.l.,
- it forms the Solina water reservoir with a total capacity, including backwater, of $503.97 \cdot 10^6 m^3$ (Kozicki, 2011).

Bottom outlets and spillways on the Solina dam

The dam has three spillway sections located in its central part with a width of 17.52 m, closed by welded steel segments (Figure 1). The upper edge of the segment in the closed position exceeds the normal damming level by 0.5 m. The spillways capacity at normal impoundment is 1278 $m^3 \cdot s^{-1}$ (3 × 426 $m^3 \cdot s^{-1}$). The extreme spillway sections have bottom outlets with a rounded rectangular cross-section. They are closed with rectangular steel gates, opened by hydraulic jacks located in the gate chamber (Figure 2). Their maximum discharge is 320 $m^3 \cdot s^{-1}$ (2 × 160 $m^3 \cdot s^{-1}$). To simplify the calculations, it was assumed that the cross-section of the spillway is a circle with a diameter of 2.80 m. The cross-sections of the spillway and bottom outlet of the Solina dam are shown in Figure 3. The figure also shows the elevation of the crest and the elevations of the spillway sill and outlet axis.

Besko dam

The Besko Dam was commissioned in 1978. Its purpose and that of the reservoir it creates is to protect the Wisłok River valley below the dam from flooding, to provide water for municipal needs, to equalise flows on the Wisłok River below the structure, to provide water for energy purposes and for fish breeding and farming.

Besko dam – basic parameters

- located in Sieniawa on the Wisłok River in the Podkarpackie Province,
- heavy concrete dam with 14 concrete expansion joints,
- belongs to class II of hydrotechnical structures,
- two inspection and drainage galleries,
- dam length 174 m,
- maximum height 38 m,
- dam crest width 8.5 m,
- slope of the downstream embankment 1:0.03,
- slope of the air release slope 1:0.7,
- forms the Besko water reservoir with a maximum capacity of $13.71 \cdot 10^6$ m^3 (Wiejaczka and Wesoły, 2017).

Bottom outlets and spillways on the Besko dam

Creager-type surface spillway – two openings with a cross-section of 11.20 × 2.60 m. The closures are 2.60 m high flaps controlled by hydraulic drives (Figure 4). The maximum spillway discharge Q_{max} for a dam level of 337.50 m a.s.l. is 332 $m^3 \cdot s^{-1}$. Rectangular bottom outlets are located in the dam body below the surface spillways – two openings measuring 1.50 · 1.80 m, closed by flat steel gates with hydraulic drives, two on each conduit (Figure 5). The maximum discharge of the bottom outlets is Q_{max} = 110 $m^3 \cdot s^{-1}$. A cross-section of the Besko dam is shown in Figure 6.

Research methodology

The spillways used in dam structures are rectangular spillways, whose discharge Q is a power

Figure 1. Spillways sections of the Solina dam

Figure 2. Bottom outlets of the Solina dam

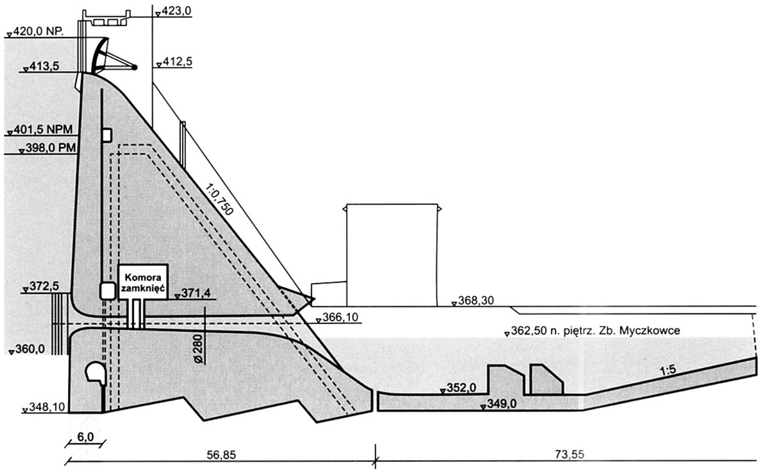

Figure 3. Cross-section of the Solina dam (spillways and bottom outlets) (Kozicki, 2011)

function of the water level H above the spillway edge (Kubrak and Kubrak, 2004):

$$Q = \sigma_k \cdot \sigma_z \cdot \varepsilon \cdot m \cdot \sqrt{2 \cdot g} \cdot B \cdot H_0^{3/2}$$
$$H_0 = H_P + \frac{\alpha \cdot v^2}{2 \cdot g} \quad (1)$$

where: Q – spillway discharge [m^3·s^{-1}], σ_k – threshold shape coefficient [-], σ_z – spillway submergence coefficient [-], ε – lateral throttling coefficient (lateral contraction) [-], m – discharge coefficient [-], H_0 – height of the energy line above the spillway crest [m], H_p – height of the upper water surface above the spillway crest [m], g – acceleration due to gravity [m·s^{-2}], B – spillway width [m], α – Coriolis coefficient [-], v – water velocity [m·s^{-1}],

The formula (1) covers both sharp-edged and practical-shaped transfers. The symbols for the individual variables included in the above formula are shown in Figure 7.

Bottom outlets are pressure discharge openings, which can be approximated as small openings whose discharge is expressed by the following formula (Kubrak, 1998):

$$Q_S = \alpha_k \cdot \phi \cdot A_0 \cdot \sqrt{2 \cdot g \cdot H_S} = \mu \cdot A_0 \cdot \sqrt{2 \cdot g \cdot H_S} \quad (2)$$

where: Q_s – botom outlet discharge [m^3·s^{-1}], μ – discharge coefficient, calculated as $m = a_k \cdot f$ [-], α_k – contraction coefficient [-], ϕ – velocity coefficient [-], A_0 – cross-sectional area of the hole [m^2], H_s – elevation of the upper water above the centre of the drain [m].

The discharge of the bottom outlet Q_s (formula 2) is therefore proportional to the square root of the value of the water level H_s above the outlet threshold.

For the purposes of the analysis, a discharge coefficient μ of 0.5 was assumed for the bottom

Figure 4. Spillway sections of the Besko dam

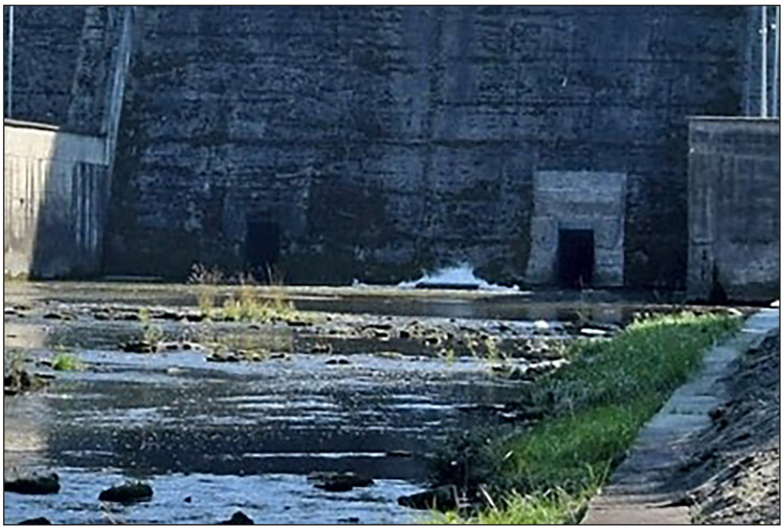

Figure 5. Bottom outlets of the Besko dam

outlets of both dams, while the overflow discharge coefficient *m* was taken from the literature (Kisiel, 2006). The remaining coefficients were assumed to be equal to 1. The calculations were performed for a 1 m width of the outlet and spillway.

RESULTS AND DISCUSSION

Figures 8–11 present the results of a comparative analysis of hydraulic expenditures for the Besko and Solina dams, covering both bottom outlet and spillway. The study was conducted in two calculation variants:

- Variant I – without taking into account discharge coefficients,
- Variant II – taking into account discharge coefficients appropriate for spillway and bottom outlet.

The aim of the analysis was to determine the ordinate of the upper water level at which the discharge values of the spillway and bottom outlet are equal. The results obtained enable the assessment of the relationship between the damming level and the flow characteristics through individual elements of the hydrotechnical structure.

In the case of the Besko dam, the elevation of the upper water surface at which the bottom outlet discharge reaches a value equal to the spillway discharge is 340.72 m a.s.l. A comparison of this value with the actual elevation of the dam crest, which is 338.20 m a.s.l., shows that

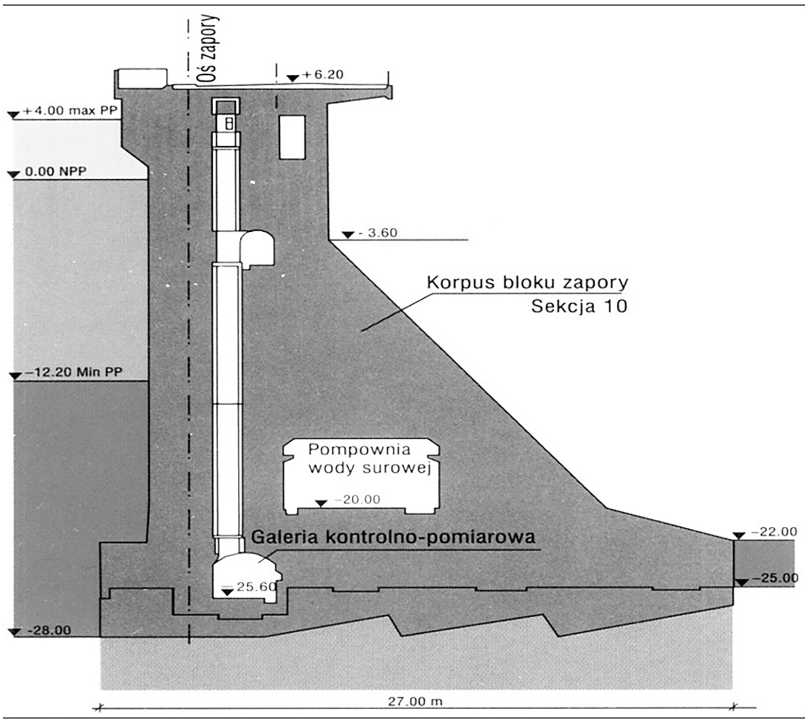

Figure 6. Cross-section of the Besko dam (Regional Water Management Authority in Krakow)

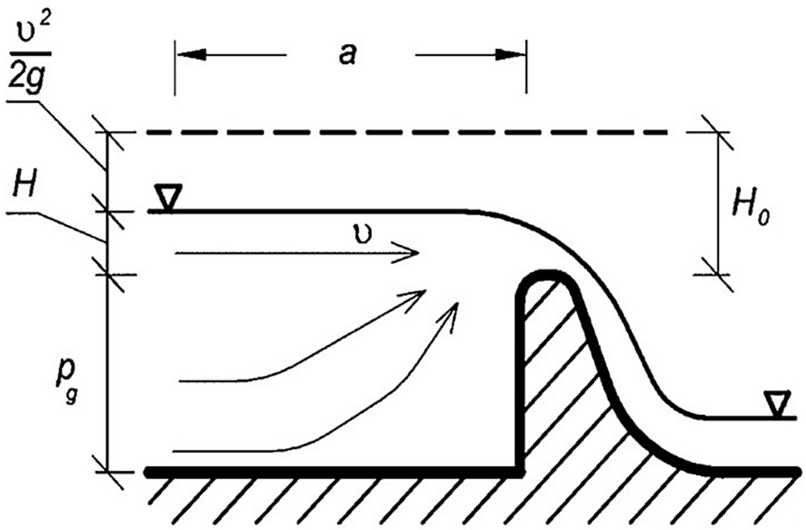

Figure 7. Practical-shaped spillway markings (Opyrchał et al., 2017)

the discharge equalisation level is 2.52 m above the dam crest. Similarly, for the Solina dam, the calculated upper water elevation at which the bottom outlet discharge is equal to the spillway discharge is 426.25 m a.s.l. Comparing this value with the elevation of the structure's crest (423.00 m a.s.l.) allows us to conclude that the flow equilibrium level is located 3.25 m above the dam crest. The results obtained indicate that in both analysed cases, the elevation corresponding to the equalisation of discharges exceeds the actual elevation of the crest of the structure, which is important for the assessment of the hydraulic safety of structures (Table 1)

Significant simplifications were applied to the calculations, which means that the results obtained should not be fully and uncritically applied to the actual conditions prevailing in hydrotechnical structures such as the Solina and Besko dams. In particular, the method of calculating the discharge per 1 m of spillway and bottom outlet raises some doubts. It is known that, among other

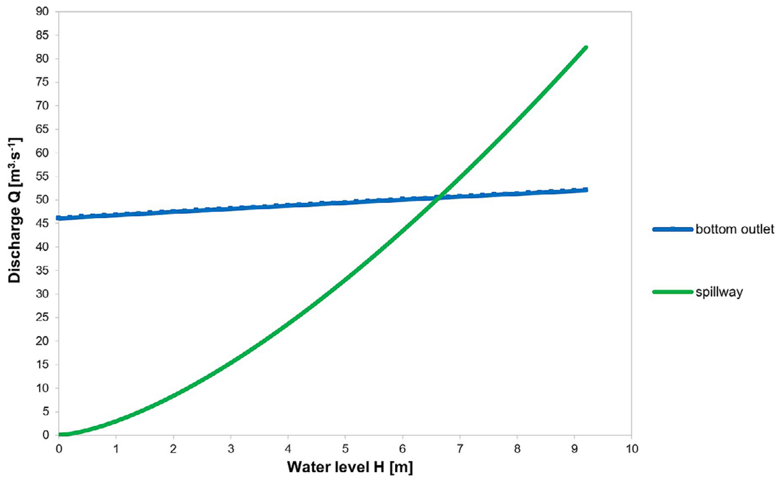

Figure 8. Comparison of spillway and bottom outlet discharge for the Besko dam without taking discharge coefficients into account

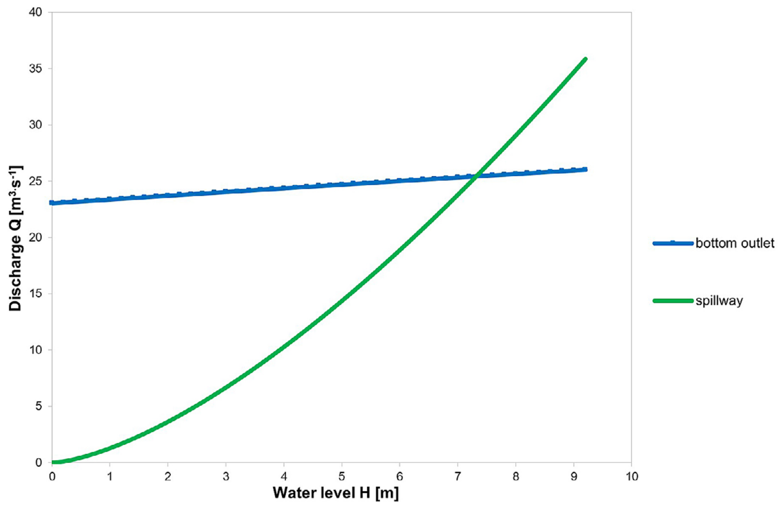

Figure 9. Comparison of spillway and bottom outlet discharge for the Besko dam taking discharge coefficients into account

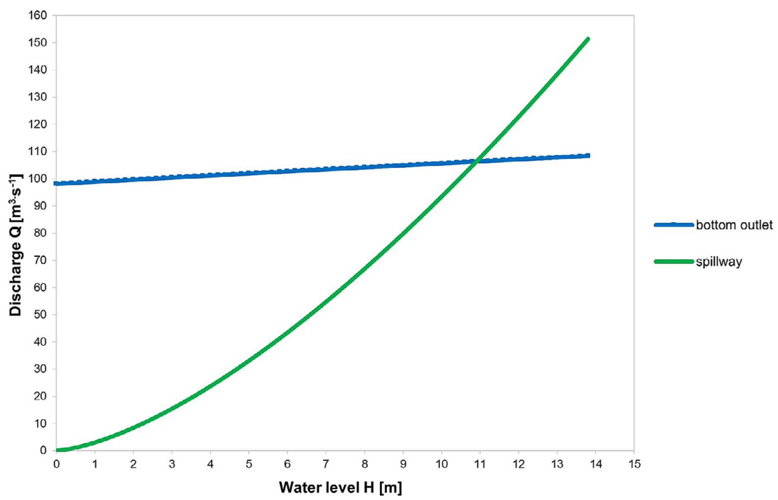

Figure 10. Comparison of spillway and bottom outlet discharge for the Solina dam without taking discharge coefficients into account

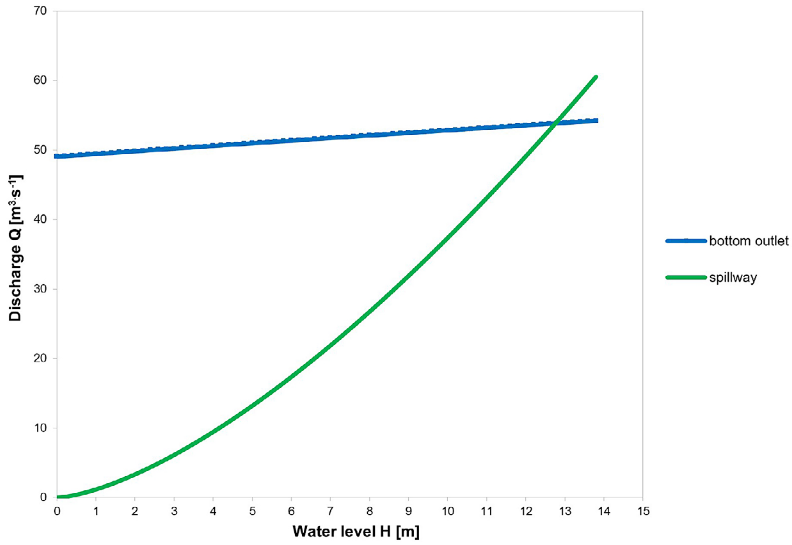

Figure 11. Comparison of spillway and bottom outlet discharge for the Solina dam taking discharge coefficients into account

Table 1. Comparison of the results of the analysis with the actual elevation of the dam crest in Besko and the dam in Solina

Pramater	Besko dam	Solina dam
Elevation of the dam crest [m a.s.l.]	338.20	423.00
Elevation of the upper water level for which the discharge equals the overflow (obtained from the analysis) [m a.s.l.]	340.72	426.25
Difference in elevations [m]	2.52	3.25

things, the width of the spillway and outlet has a significant impact on the values of calculation coefficients, such as the lateral contraction coefficient σ_k. However, in the presented analysis, their values were assumed to be constant, which introduces additional interpretative limitations.

It should be emphasised, however, that the aim of the analysis was not to perform detailed calculations for specific damming structures, but to verify the general design principle that, in order to ensure hydrotechnical safety, the spillway discharge should be at least 80% of the reference flow Q_m. Due to the fact that the discharge capacity of a spillway depends directly on the cross-sectional area of the flow, with different spillway and discharge areas, it is reasonable to convert the flow rate to 1 m of device length, which allows for an objective comparison.

Assuming the validity of this comparative method, the results of the calculations indicate that the current legal provision contained in the Regulation of the Minister of the Environment of 20 April 2007 on the technical conditions to be met by hydrotechnical structures and their location (Minister of the Environment, 2007) currently in force has no clear hydraulic justification. An analysis carried out on the example of the Solina and Besko dams showed that bottom outlets are more hydraulically efficient than surface spillways.

However, it should be noted that the choice of damming device cannot be based solely on hydraulic criteria. The construction of bottom outlets involves higher investment costs than the construction of spillways. At the same time, large bottom outlets have a significant operational advantage – they allow for more effective passage of debris and sediments, which reduces the silting up of the retention reservoir. Studies show that the greater the capacity of bottom outlets, the greater the ability to transport sediments outside the reservoir, and thus the longer its effective use (Majewski and Walczykiewicz, 2012).

In view of the above, it seems reasonable for legal regulations to give designers greater freedom in the selection of discharge devices, allowing for the optimisation of design solutions depending on local hydrological and operational conditions. The simultaneous construction of both large bottom outlets and surface overflows may not be economically justified.

Consequently, the choice between a bottom outlet and a surface spillway should be treated as an optimisation problem, in which the following factors should be taken into account:

- ensuring the hydrotechnical safety of the facility,
- construction and operating costs,
- the effects of loss of retention functions as a result of silting and eutrophication of the reservoir,
- the possibility of effective transport of debris.

CONCLUSIONS

In the case of both analysed hydrotechnical structures – the Solina and Besko dams – the equalisation of unit costs (per 1 m) of the bottom outlet and surface spillway occurs at a level significantly exceeding the crown elevation of the structure. This result indicates that, under operating conditions, the bottom outlet is a more hydraulically efficient device, not only in terms of floodwater discharge, but also in terms of its ability to transport debris and sediments from the upper to the lower position.

In light of the results obtained, it seems reasonable to reconsider the validity of the restrictive provision requiring the capacity of the surface spillway to be at least 0.8 Q_m. The selection of the parameters of the discharge devices and their capacity should be based on an optimisation process, taking into account:

- ensuring the required level of hydrotechnical safety of the facility,
- investment and operating costs,
- potential losses resulting from the degradation of the reservoir or the limitation of its retention functions.

This approach allows for the rational design of spillway parameters, adapted to the specific local conditions and functions of a given hydrotechnical facility.

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