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Study of the Outflow Conditions of the Weir Skoki on the Paklica River

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1. Introduction

Relatively small water resources in Poland and their uneven time and spatial distribution necessitate an increase in the number of investments designed for appropriate management of available water. The above assumption is supported by means of different types of water structures (Bednarczyk et al. 2009). When a damming structure includes other water facilities located in its immediate vicinity, i.e. a hydroelectric power plant, a fish pass, a sailing lock, and sometimes even a water intake, the whole system constitutes a water barrage.

Exploitation of reservoirs is associated with various problems. These are, i.e., vegetation overgrowing the riverbed below and above the reservoir, or erosion and material accumulation upstream and downstream of water structures.

Vegetation overgrowth in the riverbed reduces the flow rate capacity, and by leading to an increase in the water table level it may cause the flooding of adjacent areas. Kubrak et al. (2013) presented factors transforming the water flow resistance in lowland rivers of a complex cross-section nature. In the article, the authors characterised the vegetation growing in the floodplains of the Vistula riverbed and its impact on the water flow capacity. They pointed out that it is necessary to define the rules for removing vegetation from the riverbeds of high waters. Banasik and Krzyżanowski (2015) indicated the flow resistance resulting from variability of proper channel routing and riparian vegetation in floodplain areas as the most influencing factors affecting both the capacity of the Odra River and the forecasts of its flow-state relation. The work of a small hydropower plant located on small watercourses takes place in an annual cycle covering growing and post-growing seasons – including autumn and winter with lower temperatures

(Bajkowski and Olifirowicz 2014). Each of these seasons faces different operational problems related to the work of a small hydroelectric plant (Walczak 2018).

Tarnawski and Michalec (2007), who analysed the possibility of hydraulic transmission of high water through the weir on the Uszwica river in Brzesko. Previously, during the field research consisting in the technical assessment of the weir conducted in 2005, it was found that despite visible damages, the weir met the standards necessary for correct operation.Changes in sediment transport processes are also disadvantageous due to their dynamics, particularly in the downstream of the water structure. The most hazardous factor here is local erosion, which, if it develops in an uncontrolled way, can lead to local scouring below the water structure. Urbański (2009) presented the effect of water flow conditions on the characteristics of this phenomenon. On the basis of the study he stated that an increase in the water table level below the weir extends the time needed for creating local scouring, and a double increase in the flow rate causes an eightfold increase in the depth of scouring. Dąbkowski et al. (2007) investigated through their research the process of scouring below of the tired construction with outflow over and above the gate and demonstrated that bigger depths of scour make outflow above the gate. Głowski and Parzonka (2007) analyzed the functioning and impact of the Brzeg Dolny reservoir, taking into account the provision of adequate water quantity and bleed for the proper functioning of the hydroelectric power plant and electricity production. Studies related to this issue were also conducted by Hämmerling et al. (2013) and Hämmerling et al. (2019). On the basis of laboratory and field tests, the researchers identified the parameters of the mathematical model and presented an analysis of local scouring formation using a three-dimensional SSIIM modelling program.

Water management of retention and flow reservoirs requires regulating the flow of water through damming structures. However, the use of these structures for a long time has a significant impact on their safety, durability and functional characteristics. The natural environment negatively affects their technical condition and contributes to the ageing processes they are subject to. Each structure fulfils its assumed functions at the moment when it is newly built, however, over time, these functions become more and more limited due to aging processes. The solution to this problem is repair works that allow for restoring initial properties of a damming structure. Despite undertaking such works, a decrease in its utility value will be inevitably observed. When the renovation is technically required, though, economically unjustified, the facility is temporarily shut down (Zawadzki 2005).

Each damming structure divides a watercourse into two parts: the downstream – below the structure (downstream water) and the upstream – above the structure (upstream water). The division has a significant impact on the current river regime. The difference between upstream and downstream water is called the water surface elevation. By means of sluice devices in a damming structure, it is possible to regulate the outflow, hence the water surface elevation. When a reservoir is created, the water velocity in the upstream also changes, followed by the change in the regime of water table levels. A new phenomenon appears – waterborne bedload is deposited near the structure in the upstream, initiating the process of reservoir silting. Downstream water, which has excess energy and is sediment-free, begins to destroy intensely the riverbed below the structure (Bednarczyk et al., 2009). In order to maintain the safety of a damming structure, it is important to make appropriate hydraulic, strength and stability calculations. The calculations should take into account the entire structure and all its individual elements. Each element is designed not only to ensure the stability of the system, but also to operate reliably throughout its entire lifetime. The degree of reliability and safety of a structure corresponds to proper correction coefficients chosen for theoretical calculations and the assumed coefficients for natural parameters of materials used. Each structure designed or renovated requires special attention in relation to physical and mechanical phenomena that may have a negative impact on its safety and correct operation (Bednarczyk et al., 2009).

Table 1. Summary of major dam failures (structures higher than 15 m) that occurred between 1900-1975 acc. to International Commission on Large Dams (Kowalski 2017)

No.	Cause	Concrete dams	Earth dams	Other i.e. Steel dams	Total
1	Spillway breach	9	25	3	37
2	Erosion	3	31	–	34
3	Damage to escarpment protective elements	–	13	–	13
4	Leakage and penetration in the dam	–	37	–	37
5	Leakage and penetration in the ground	11	54	1	66
6	Landslides	7	28	–	35
7	Deflections	2	32	3	37
8	Deterioration of quality	6	5	–	11
9	Earthquakes	–	3	–	3
10	Faulty structures	2	3	–	5
11	Damage to shutters/sluices	3	4	–	7
	Total	43	235	7	285

Failures and catastrophes were the result of errors arising at various stages of construction or subsequent operation, including incorrect assessment regarding the technical condition of facilities, made by contractors who did not notice or could not foresee imminent hazards. For this reason, a person assessing a technical condition of a given facility should be responsible for own decisions and indications that have led to failure, as it is in the case of a chief designer (Parylak, 2007).

Common causes of dam failure, which are numerous, can be divided into anthropogenic and naturogenic actions. These include, among others, the following determinants: errors in design and construction, errors in concrete technology and workmanship as well as damage caused as a result of mechanical loads, physical impact or chemical aggression. Therefore, in order to ensure that a hydrotechnical structure and its elements function as long as possible in a safe and sustainable way at each stage (design, construction and operation), it is necessary to systematically and correctly conduct maintenance inspections of the investment.

1.1. Description of the research object

The research object was an uncontrolled section of the Paklica watercourse located at 6 + 400 km (Fig. 1). The water node includes a mill weir and a power plant, located in Skoki, commune Międzyrzecz, county Międzyrzecki.

The facility is directly adjacent to the county road leading from Brójec to Międzyrzecz, and more specifically to the road bridge over the Paklica River. Behind the bridge, to the south, there are: Wyszanowskie Lake and Bukowieckie Lake.

Paklica is a river about 40,0 km long, flowing through the Lubuskie Lakeland. It is a left tributary of the Obra River, where it flows into in the town of Międzyrzecz at 42 + 400 km, and flows out of Paklicko Małe Lake in the village of Wysoka. The surface of the lake is 51.0 ha, while its average depth is around 5,0 m. The total catchment area is 253,21 km^2 (Czarnecka 2005). The length of the catchment area equals the total length of the river and amounts to 40,0 km, the average width, i.e. the ratio of area to length is 7.0 km, and the average decrease is 0.74%. The river basin is located in the Łęgowski Lakeland and Bruzda Zbąszyńska, and belongs to the proglacial valley of the Warta River, which forms 22 water reservoirs. The borders of the catchment area are local elevations of land created by the accumulation of glacial sands (outwash plain surfaces). The southern border is indicated by an artificial elevation of the area, closed by an old route and embankments of the railway line between the villages of Rzepin and Zbąszyń. All towns located within the catchment area are agricultural or agricultural-forestry. The way of nearby land use is directly attributable to the nature of these localities: arable lands, approx. 65% of the total area, including 9% of green areas, 33% of forests, 2% of fishery land. The catchment is mostly located in the sub-surface zone, with formations of high permeability, what makes this area characterised by high afforestation.

Fig. 1. The barrage in Skoki on the map (own study)

The mill weir is constructed of a channel with concrete sidewalls and a partially reinforced bottom. It was designed to accumulate water for the water mill located in Skoki Villge. The channel ends with two working sluices, which form the inlet to the hydroelectric turbines, located on both sides of the idle sluice. The idle sluice in the mill weir is a reinforced concrete structure, which together with two working sluices constitutes a complementary unit, as illustrated in Fig. 2 (Olek, 2014a).

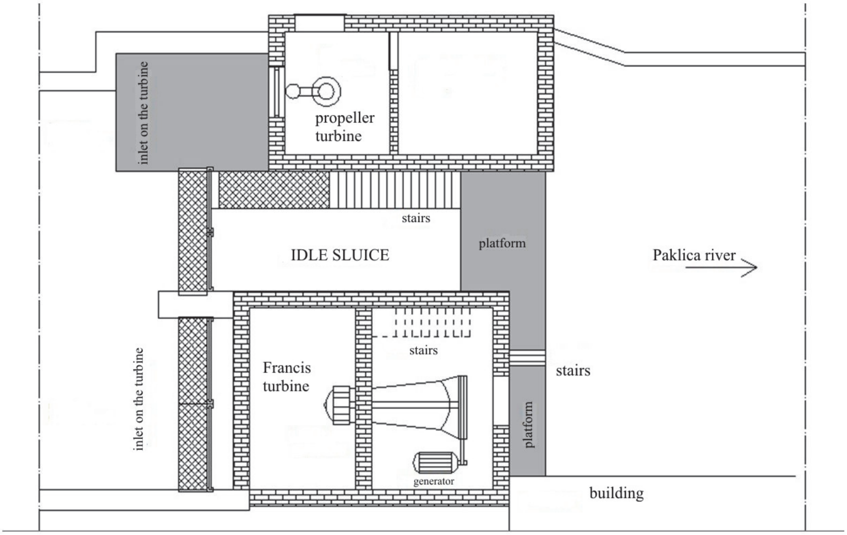

Fig. 2. Scheme of the barrage on the Paklica River

The water turbines are located in two buildings. They are part of the mill weir and can generate electricity. The first hydropower plant houses a Francis turbine with the following characteristics: water discharge $Q = 1.02$ m^3/s, rotor diameter D = 900 mm, efficiency coefficient $n < 60$ and nominal power up to 28 kW. Whereas, in the second building, there is a propeller turbine with water discharge $Q = 0.50$ m^3/s and nominal power of 14 kW. From the north, the hydroelectric power station borders with a plot of land where there is a bottom outlet with an eel basket and a fish trap placed at the artificially created outflow of water from Bukowieckie Lake. The bottom outlet consists of two inlets, with an opening of $B = 2.00 + 2.00 = 4.00$ m, connected with 30.0 m long construction pipes, ended with the fish trap and the eel basket (Olek, 2014b).

2. Methodology

Water flow velocity values were measured using Valeport Model 801 EM Flow Meter. An electromagnetic flow meter is used to accurately measure the water flow rate in open channels with an accuracy of ± 0,5%. It measures instantaneous velocity with a resolution of up to 1 mm/s, but also averages the results with a standard deviation. The water flow velocity measurements were taken for 5 cross-sections of the riverbed (Fig. 3). The selected cross-sections (3, 4, 5, 6, 8) were considered significant since they were located at the characteristic points of the studied section of the riverbed. They included: −main channel −outflow of water from the downstream, above the connection with the inflow (cross-section 3), –side channel –inflow to the main channel (cross-section 4), –main channel – below the connection of the main channel with a tributary, located behind a clump of vegetation (cross-section 5), –main channel –above the bridge (section 6), and –main channel –below the bridge, at the footbridge with an installed water gauge (section 8).

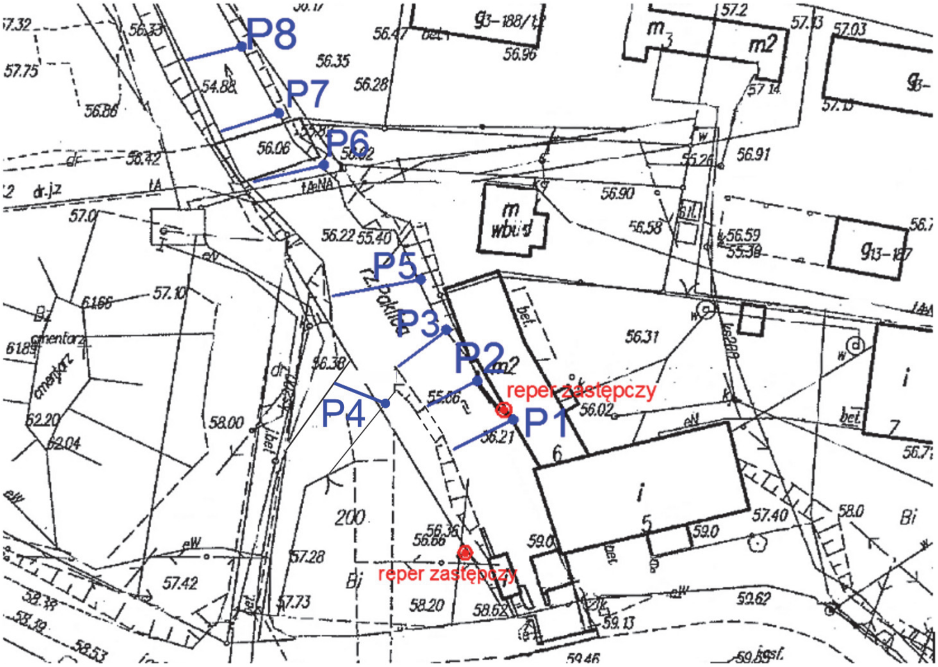

Fig. 3. Diagram of the Paklica River section with marked cross-sections

The velocity measurements in the determined cross-sections (Fig. 3) was carried out over the entire width of the riverbed, where the hydrometric verticals were spaced approximately 1.0 m apart, at points located at a distance of 0.05 m from each other. The obtained results were used to prepare the velocity distribution in individual cross-sections of the riverbed as well as throughout the entire section of the river below the Skoki barrage.

For the purpose of the present article there was also carried out an analysis of spillway capacity using the empirical relationship (Kisielev 1972, Franzini & Finnemore 1972, Sobota 1994, Lewandowski 2006) for flow rate Q regarding a free outflow broad-crested weir (Fig. 4):

$$Q = mb\sqrt{2g}H_0^{\frac{3}{2}}$$

where:
m – discharge coefficient,
b – length of the crest [m],
$H_0 = H + \frac{\alpha v_0^2}{2g}$ (weir head+velocity head) [m].

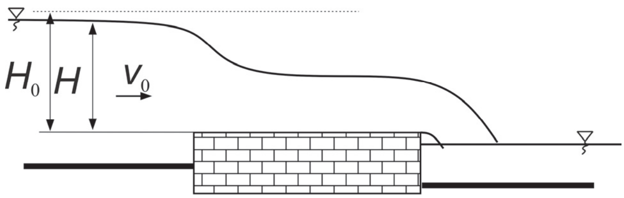

Fig. 4. Diagram of the free outflow broad-crested weir

The values of the expenditure factor m of a broad-crested rectangular weir range from 0.295 to 0.365 (Kisielev 1972, Kubrak 1989). This is influenced by, among others the shape of the edge of the threshold at the inlet (rounded, cut off, or sharp) and the roughness of the surface of the rectangular weir range.

3. Results

The water flow velocity measurements were taken using a flow metre in the studied section of the Paklica River for 5 cross-sections of the riverbed. The analysed section of the watercourse was characterised by highly varied water velocity. The reasons for these disturbances were, among others: variable water depths in each cross-section, overgrown riverbed embankments, dense grassy vegetation and a poor technical condition of the water barrage. During the measurements, the sluices of the hydraulic structure were closed, however, due to the poor technical condition of the entire facility, numerous water leakages could be observed. As a result, there was a small amount of flowing water, and consequently – low flow velocity values in cross-sections below the barrage (cross-section 3), a significantly larger amount of water, and higher flow velocity values in the inlet channel, below the fish trap (cross-section 4). Cross-section 5 was the section below the connection of the main channel to the inflow channel, behind a clump of plants (axis of the river bed). This cross-section was characterised by large flow velocity fluctuations in relation to its depth due to the occurrence of rich river vegetation. Cross-sections 6 and 8 demonstrated a gradual stabilisation of water flow velocities, because they were in a proper distance from the barrage and there were no elements in the area that could disturb the water flow rate (i.e. aquatic vegetation).

The graphical representation of the results of water velocity measurements in the riverbed includes only selected characteristic points. All the presented velocity distributions concerned the hydrometric verticals located in the central part of the measurement cross-section.

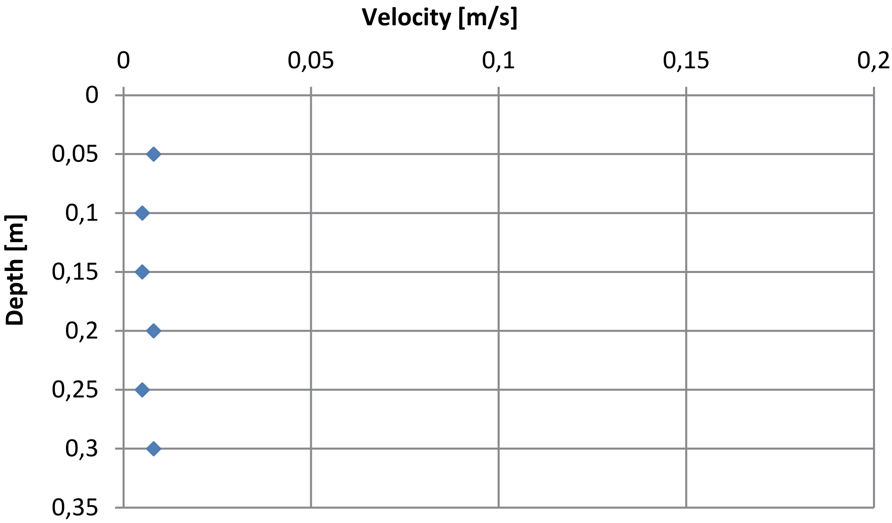

Fig. 5. Vertical velocities distribution in axis of cross-section 3 on the Paklica River

Velocity distributions in the central part of the cross-section (Fig. 5) were characterised by a low value of water flow rate resulting from a small depth of the riverbed and a specific location. Velocity values in the hydrometric vertical did not exceed 0.1 m/s.

However, an increase in velocity by almost 100% was observed in cross-section 4 (Fig. 6), which was located in the inflow channel where there is a fish trap. The lowest average velocity was measured at a depth of 0.35 m, and the highest 0.1 m from the bottom.

The average water velocity (approx. 0.1 m/s) was also measured in cross-section 5 (Fig. 7), although the velocities for individual depths varied significantly by up to 0.03 m/s. Variability in velocity values with a simultaneous increase in depth was caused by the location of the cross-section including the connection of the main channel to the inflow channel and the resultant local water accumulation as a direct effect of a large clump of grassy vegetation (Fig. 8).

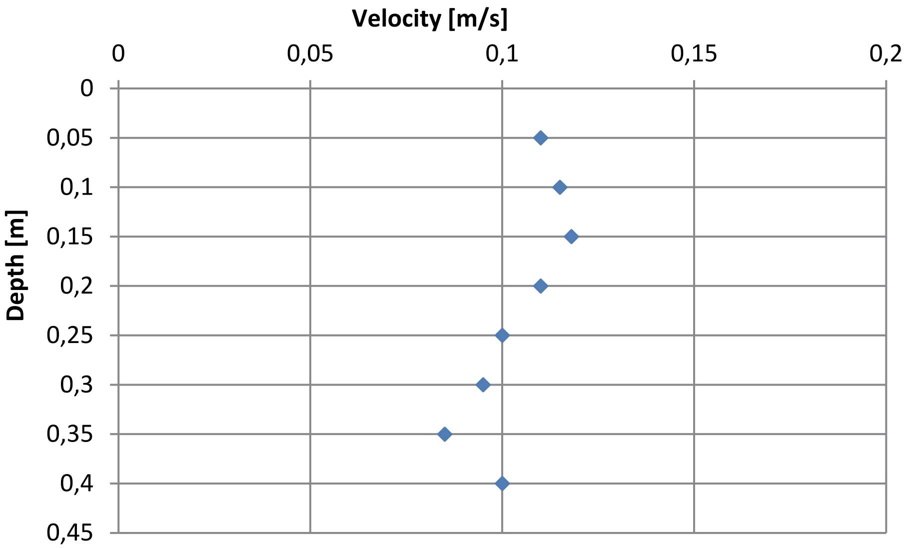

Fig. 6. Vertical velocities distribution in axis of cross-section 4 on the Paklica River

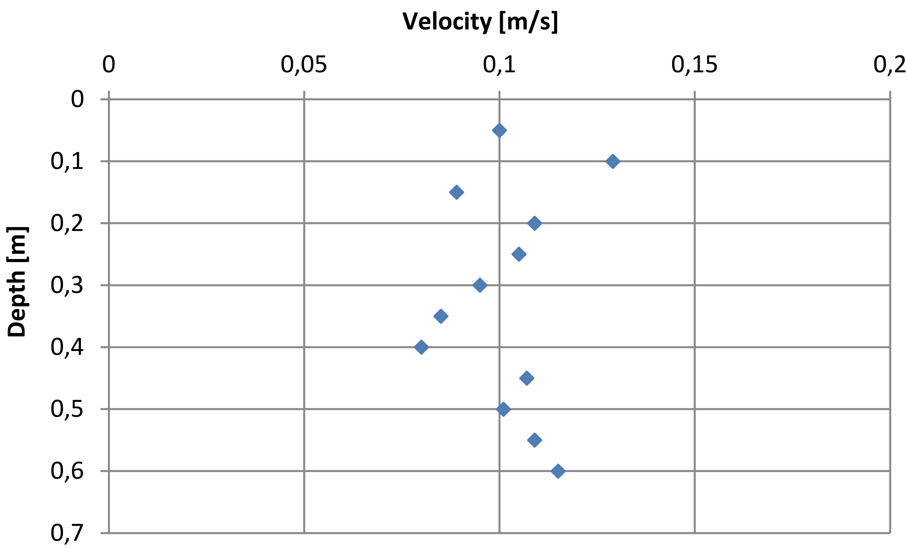

Fig. 7. Vertical velocities distribution 2 m from BL in cross-section 5 on the Paklica River

Fig. 8. Measurement of water flow velocities on the Paklica River

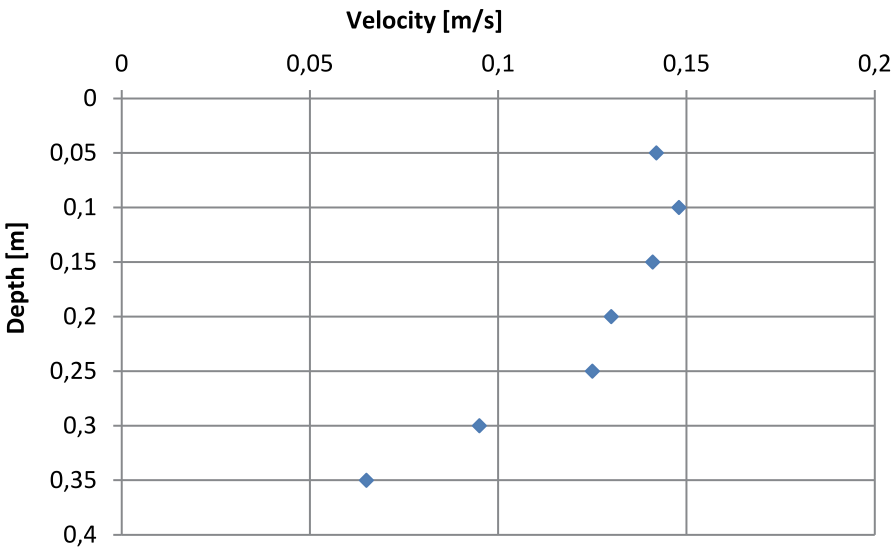

Fig. 9. Vertical velocities distribution in axis of cross-section 8 on the Paklica River

A significant effect of grassy vegetation on velocity values was observed in analyzed cross section (Fig. 8), located in the area with intensive biological development represented by reed on both sides of the cross-section. Riparian vegetation additionally affected the narrowing of the cross-section, particularly at the level of water table. The bottom zone had the velocity values higher by half than the average. (Local vegetation has the shape of cylindrical elements, through which water flows without much resistance).

The highest average velocity values were measured in the axis of cross-section number P8, which is shown in Figure 9. The location of the measurement cross-section (equal to 10 m) was important here. The area lacks riparian vegetation, and the hydro-technical structure itself is in such a distance that it does not affect flow conditions.

In order to properly assess the weir's capacity, it was assumed that the length of the crest is 2.76 m, and the values for water height above the crest fall within 5 cm to 100 cm. Calculations of the flow capacity of a broad-crested rectangular weir at the barren drop of the barrage were made taking into account two values of the flow rate coeficient: m = 0.292 (current state, damaged concrete surfaces of the overflow) and m = 0.365 (after modernization). The results are calculated in the Fig. 10.

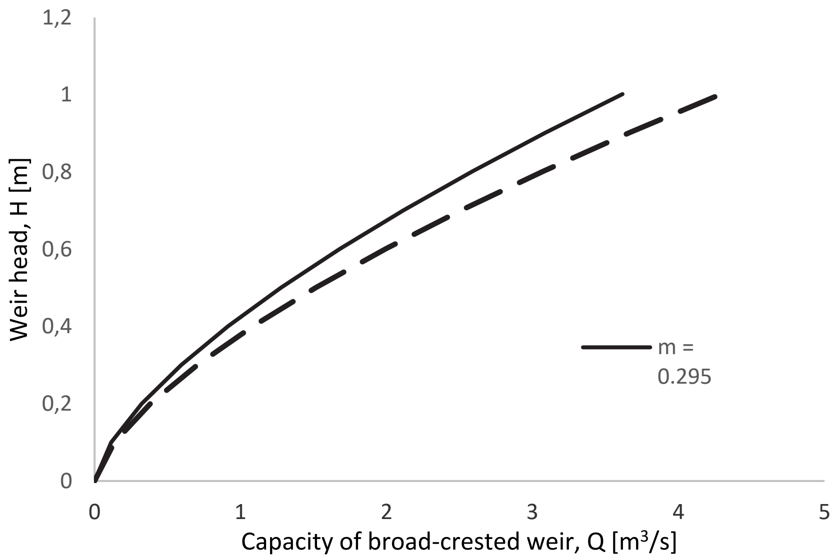

Fig. 10. Capacity of broad-crested part of the Skoki weir

The expenditure of a broad-crested rectangular weir at the idle drop of a water step at NPP = 58.40 m above sea level (H = 0.8 m) is 2.57 m^3/s and together with other overflow devices it allows safe passage of large waters. The modernization of this broad-crested rectangular weir (rounding the inlet edge, smoothing the broad-crested rectangular weir) would increase its capacity by approx. 19%. It would also be necessary to equip the overflow with a modern steel movable closure, e.g. a flat gate valve (Novak et al. 2001).

4. Discussion

The effect of flow resistance of vegetation on the riverbed capacity was the subject matter considered among others by Walczak et al. (2015), who studied the influence of seasonal changes in vegetation on river flow velocity values. Kozioł et al. (2016) stated that the method of Shiono and Knight allows for predicting the lateral velocity profile averaged in depth in compound channels with high vegetation in floodplains compliant with laboratory hydraulic measurements. Walczak et al. (2018) analysed the development of vegetation over a 12-year period and confirmed that reduction in the flow rate can reach 45% for scenarios in which the only considered factor is an increase in the diameter (at constant density), and up to 70% in the case of an increase in the vegetation density. Fig. 7 and 9 show the logarithmic distribution of water velocities that occurs in the areas without elements blocking free flow rate.

On the basis of on-site verification and empirical calculations, it can be noticed that direct proximity of shrubby vegetation on Bukowiec Lake does not affect the weir's capacity. Only elastic vegetation, represented by leaves and branches of grasses, can be found at the inlet trash racks of the weir. The poor technical condition of the weir's concrete elements subject to aging processes does not allow for impounding water. Lack of measuring and control devices as well as fish passes, plus the insufficient capacity necessitate modernisation of the weir.

5. Summary

For the purpose of this work, there were analysed: spillway capacity and water flow conditions below the damming structure on the Paklica River. As the technical condition of individual elements of the damming structure confirmed, it was found that the system could not perform its functions effectively. A small amount of water (due to leakage through the flat gates) flowed through the weir channel and HP, hence the occurrence of low water flow rates within the section from the weir to the connection with the fish trap channel. It was stated that the flow rates were much higher in the channel discharging water from the fish trap than in the channel discharging water from the hydroelectric power plant and the weir, which was caused by a poor technical condition of the fish trap and numerous leaks. Local changes and disturbances of water velocity in cross-sections were strongly shaped by vegetation overgrowing the riverbed. It can be observed that the cross-sections located in the areas of grassy vegetation were characterised by high variability of velocity values, which directly affected the flow rate. Field studies were conducted during the period of full vegetation, therefore the analyzed speed distributions take into account its occurrence in cross-section.

Modernization of the broad-crested rectangular weir located on the Paklica River by rounding the inlet edge and smoothing the broad-crested rectangular weir would increase its capacity by approx. 19%. Equipping the broad-crested rectangular weir with a modern steel movable closure would allow more accurate flow control on the barrage.

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Abstract

The paper presents an assessment analysis of the flow capacity of the barrage on the Paklica river. The analysed barrage consists of a mill weir and bottom outlets, and is supplied with water from Bukowiecki Lake. The reasons for addressing this subject matter were: from the need to determine the technical condition as well as the ecological condition of the lower position. The environmental status of the area below the system was considered as equally important. Field research included photographic documentation of the technical condition of the weir, taking into account the state below and above the structure, its abutments and the threshold. Additionally, there were made velocity distribution measurements in the downstream during the growing season, assuming this period as the least favourable with respect to hydraulic conditions.

Keywords:
broad-crested rectangular weir, velocity, flow rate coeficient

Badanie warunków odpływu z jazu Skoki na rzece Paklica

Streszczenie

W artykule oceniona została przepustowość stopnia wodnego na rzece Paklica. Analizowany stopień składa się z jazu młyńskiego i upustów dennych i jest zasilana wodą z jeziora Bukowieckiego. Przyczyny podjęcia tego tematu były następujące: potrzeba ustalenia stanu technicznego, a także stan ekologiczny analizowanego obiektu. Równie ważny był stan środowiskowy obszaru poniżej stopnia wodnego. W czasie badań terenowych wykonano dokumentację fotograficzną stanu technicznego jazu z uwzględnieniem stanu górnego i dolnego stanowiska, przyczółków oraz progu. Dodatkowo wykonano pomiary rozkładu prędkości w dolnym stanowisku w czasie wegetacji przyjmując ten okres za najmniej korzystny ze względów hydraulicznych.

Słowa kluczowe:
przelew o szerokiej koronie, prędkości, współczynnik wydatku