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ORIGINAL ARTICLE

Engineering–geological investigation of the river bottom near a dam's stabilization threshold based on two different evaluation methodologies

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Abstract

The article concerns engineering and geological studies of the river bed near the threshold stabilizing the water flow of the Włocławek hydroelectric power plant in Poland. We paid attention to the differences in river erosion behind the dam, as one section of the study area was dominated by erosion of potholes and the other by sedimentation of river material. A protective threshold (partly concrete, partly gabion) was built to stabilize the water flow and optimize the hydrological regime near the dam. As a result of the erosion process (behind part of the hydroelectric power plant) and sedimentation (behind part of the weir), this threshold is constantly being destroyed. This threatens uncontrolled changes in water level, instability of water masses and, consequently, constitutes a threat to the stability of the hydrotechnical structure. The principal aim of the study is to propose a new methodology to perform a risk assessment and to indicate how to protect the threshold structure. Initially, geodetic and bathymetric measurements were performed of the river bed, potholes and the threshold. Then the results were analysed, the risks were estimated and two independent risk assessment procedures were proposed. One suggestion concerning the area of potholes was to backfill them to protect the threshold made of concrete slabs. In the second section, there is a sedimentation of the river material around the gabion threshold, which is damaged, especially during flooding. To protect this gabion threshold, a different approach has been taken of modelling the water flow based on digital bottom models (DBMs). An engineering–geological investigation of one river bottom benefited from two types of protection features (a concrete threshold and gabion threshold) using two different methodologies to evaluate hazard and design subsequent protection of the thresholds. The results of our study support the structure's managers in maintaining its safety.

Keywords Engineering–geological investigation · Threshold · Vistula River alluvium · Włocławek dam · Geodetic/bathymetric measurements

Introduction

The design of a hydrotechnical structure, construction and then its maintenance are substantial and difficult undertaking. During the construction and the subsequent operation, we must consider many environmental factors, such as the characteristics of the river, the morphology of the bottom and even the structure of the shore around the dam. The construction and operation of the dam are also influenced by the ground on which it was built. It should be stable and tight. An example is the Karakaya dam built on the Euphrates river, where landslides can cause flooding (Ertunç 1999). The dams are often used to supply water to the surrounding villages, as is the case with Tabarak Abad Dam (Lashkaripour and Ghafoori 2002). Thanks to this project, it is

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possible to irrigate 1150 ha of agricultural land and provide drinking water for the inhabitants. Seismic waves are another factor to be considered in the design phase of a large hydrotechnical structure. An earthquake can lead to cracks in the elements, which in turn can cause damage or collapse of the structure. Evidence can be found in the case observed on the Minjang River, where the design of the dam failed to cope with the shocks and damage was caused after the earthquake (Lin et al. 2015). Scientists from China have simulated damage to the structure of dams of various shapes, heights, properties of the river bed, as well as material properties and water inflow velocity. The results showed that hard and solid river beds and dam material with low water permeability have an adverse effect on its durability and stability. (Chen et al. 2015). The biggest factors influencing large dams are large fluctuations in flow and water level. Sudden increases in water levels, floods and also very low flow rates have an adverse effect on the safety of the dam construction and the balance of the surrounding environment. The Renzonghai dam on the southeastern edge of the Qinghai-Tibetan Plateau in China has experienced large amounts of leaking water at the bottom of the dam with a high level of water in the reservoir, far exceeding the maximum allowable leakage level, which poses a serious threat to the safety of the dam (Wang et al. 2019). The Skokomish River, on the other hand, where there are two dams regulating the flow, is frequently affected by floods which have had a devastating effect on the salmon population and the surrounding infrastructure and private property (Collins et al. 2019).

However, not only the construction of such structures is important, but also their operation as it changes the character of the engineering–geological environment. River bed morphology changes are significant problems in river alluvia as they influence a number of parameters that affect the river use. The research carried out on the Polish river Wilga showed that the bottom morphology is significantly influenced by temperature, which is conducive to the development of vegetation. Measurements were carried out using an echo sounder equipped with ADCP (Acoustic Doppler Current Profiler), which, among other things, allowed to examine the flow rate. It turned out that vegetation slows down the flow and thus affects changes in the bottom morphology (Sziło and Bialik 2016). An analysis of the influence of groundwater on the rate of biogemorphological development of the river and morphodynamics was also carried out. There was a link between, among others, the occurrence of groundwater and the growth of vegetation. Vegetation, as mentioned earlier, influences changes in flow velocity and shape of the riverbed. The authors concluded that by controlling river biogeomophology, river morphodynamics can also be controlled (Bätz et al. 2016). Engineering properties of the material on the river bed is also important. Depending on its particle morphology (shape, size, angularity), particle composition, loading and mineralogical conditions, the bottom permeability can be predicted (Mehta and Patel 2018). The natural evolution of the river also changes the morphological characteristics of the bottom (Li and Gao 2019).

The engineering–geological investigations of alluvial sediments are important not only in terms of dam construction, but also in terms of river bottom changes after dam construction, as the changes may endanger the power plant structures. The problem faced by the Ayvali Dam is seepage and instability, which is due to the inadequate adaptation of the structure to local geotechnical conditions (topography, geology and ecology). It was not predicted that after the dam would be activated, the decrements of rock slide can occur. Attention has been drawn that it is necessary to provide protection against landslide in large engineering constructions like dams (Kanik and Ersoy 2019). The article (Poeppl et al. 2019) addresses the problem of bottom and river bed changes caused by dam removal. On the basis on 2-D model, it was found that the geomorphological changes are variable and complex in time and space. These changes depend on a lot of factors: dam size, presence of upstream dams, buffering effect, velocity of moving sediments, emerging feedback process and the presence of construction to river bed stabilization. Sediments geometry and capacity can be measured using electrical resistivity and sonar system. This combination was used to define Slnecné Jazerá bottom sediments. Definite geometry and capacity parameters are necessary to efficiently manage the water body and to avoid contamination by too many sediments, which can be unhealthy for humans (Marschalko et al. 2019). There are many cases of dams which were built in proximity of evaporites. These are very vulnerable geological formations which can be quickly destroyed or washed out, especially if there are also hills in the vicinity. Additionally, dissolved evaporites have a devastating effect on plant cultivation, which can be irrigated by water from the river where was dam built. (Milanović et al. 2019). The dams are an enormous engineering—economic undertaking. On many occasions in history, there have been accidents which proved impossible to predict. Nature is governed by its laws, so it is so difficult to control it.

A slightly different case is the largest hydroelectric power plant in Poland in Włocławek (power station and weir), the construction and work of which had a major impact on the erosion and incorrect shape of the river bed downstream of the dam. In order to reduce the impact of the dam operation on the erosion of the river bed and to optimize the hydrological river regime, a threshold has been built to stabilize water flow (concrete slabs down the power station and gabions down the weir). Unfortunately, this threshold itself is being continually damaged by the process of erosion (downstream of the hydroelectric power station section) and sedimentation (downstream of the weir section). This poses a risk of uncontrolled changes in water level, instability of water masses and, consequently, a threat to the stability of hydraulic structures.

Therefore, the first objective of our research was to study and evaluate the erosion process of the threshold structure. We are directly engaged in engineering and geological investigation of the riverbed near the threshold of the dam (geodetic and bathymetric measurements).

The principal aim of the study was to propose and implement a new methodology to perform a risk assessment and to indicate how to protect the threshold structure. In the first step, we point out the differences in river erosion behind the dam as one section of the study area showed prevailing erosion with potholes (down the power station) while the second section suffered from sedimentation (down the weir). In the next step, we conducted integrated geodetic and bathymetric measurements and elaborated a numerical model of the shape of the threshold and the bottom of the Vistula River downstream from the Włocławek power plant. The obtained results were analysed, the risks were estimated and two independent risk assessment procedures were proposed.

Finally, on the basis of engineering and geological studies of one river bed (4-year monitoring), we developed a method for assessing the risk and designing the subsequent protection of two different parts of the threshold (concrete threshold and gabion threshold) using two different methodologies.

Characteristic of the study area and its problem

Study area

The study area is an alluvium of the Vistula River including thresholds that make part of the Włocławek hydroelectric power plant (Figs. 1, 2, 3). It was built in 1970. The power plant in Włocławek includes a frontal dam, weir, fish pass and sailing lock (Fig. 3). The hydroelectric power plant is placed on the left river bank between the navigable lock and weir, separated by the fish pass pillar. There are three sections with two hydro complexes each. The total power of the plant is 160.2 MW. Five hundred meters below the dam, an underwater threshold of damming and flow stabilization is located (concrete structure). The Włocławek power station operation causes up to 2.0 m daily movement of vertical reference water surface in aspect of local bathymetric survey. The total water flow via hydro complexes varied from 0 to 4600 m^3/s and from 0 to 2100 m^3/s via power station depending on the Vistula river discharge and operational schedule of the power plant in Włocławek. The momentary maximum flow during floods can reach 6000 m^3/s, such as in 1979 and 2010.

Based on the original plan, eight power stations should have been built on the Vistula River, which would form a system of water management facilities to recover renewable electrical power. The secondary aim was to stabilize the water flow along the lower Vistula River. Nevertheless, due to economic and technical reasons, only one dam, i.e. Włocławek, was constructed. This caused discrepancies between the planned scenario and the current situation. The water level downstream of the power plant is lower than planned. Moreover, the water flow rate and flow character have altered. This leads to the formation of potholes on the river bottom downstream of the power plant, which need not have occurred if a higher number of cascade power plants had been built.

The environment of the largest Polish river is well described in research literature (Staužlis et al. 2003; Mościcki et al. 2014; Labak-Mechowska 2014; Magnuszewski and Moran 2015; Falkowski et al. 2017).

Włocławek dam problem

The realization of the investment contrary to the original plan (Fig. 1a) had a very adverse effect on the formation of the bottom. The current construction (Fig. 1b) has a destructive impact on the bottom due to the formation of numerous holes (Fig. 1c). The situation in the study area was partially addressed by building thresholds (Fig. 1d), but the formation of potholes continues and the thresholds are endangered. The study area was divided into two sections (Fig. 1e), where the first Vistula River alluvium section is characteristic of dominant potholes and a concrete threshold (Fig. 1f1). The engineering–geological environment of the study is the Vistula River alluvium. Erosion prevails over sedimentation in the first section. The second section of the study area is specific for its gabion threshold protection (Fig. 1f2) as the river bottom is not threatened by potholes, but by sedimentation. The differences are one motivation in the study.

The study area section 1 (Fig. 2) is characteristic of a specific water flow as it is located downstream of a water power plant, where there is a dominant water flow in the power plant channel (Fig. 2a1, a2). This section belongs to the power plant Włocławek and the water flow is influenced by the construction of the concrete slab threshold (Fig. 2b1). On the contrary, the study area section 2 (Fig. 2a2) is a characteristic of a weir channel (Fig. 2a1) with a protective gabion threshold (Fig. 2c1). Increased water volume is observed there only during floods, when extra water must be discharged over the weir, and not only through the power plant itself. A common problem of both the study area sections 1 and 2 is the fact that both the concrete threshold (Fig. 2b2) and the gabion threshold (Fig. 2c2) suffer from damage.

From the research point of view, it is important to learn about the conditions of the river bottom near the thresholds

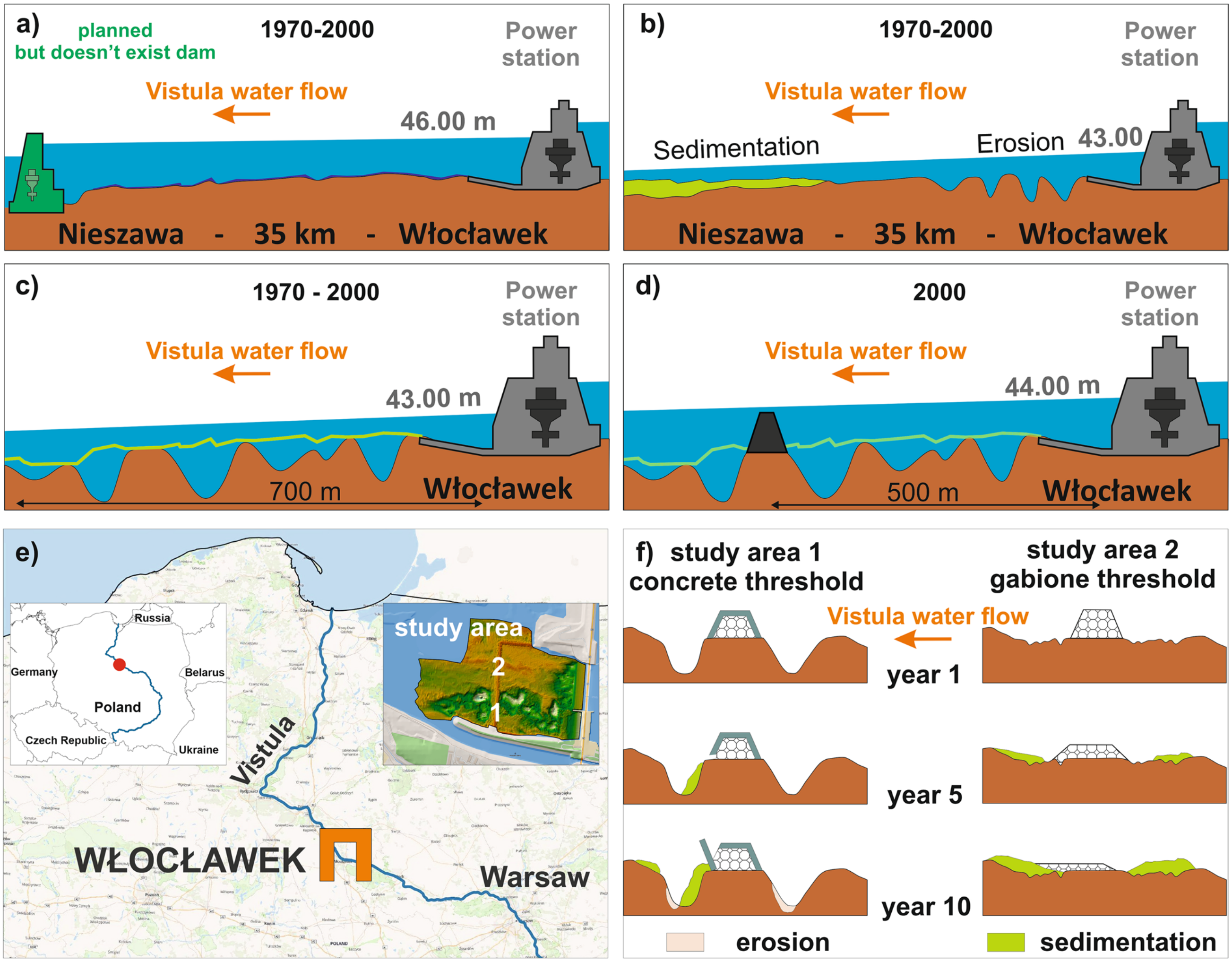

Fig. 1 Schematic visualization of the study area, **a** planned conditions of the power plant system with more dams and expected Vistula River level, **b** real situation with only one power plant (Włocławek) with marked Vistula River level, **c** real operation of Włocławek power plant led to the formation of potholes in the Vistula River alluvium, **d** the construction of a threshold changed the water regime near the power plant, but potholes keep forming, **e** map of the study area with marked sections 1 and 2, **f1** concrete threshold with potholes in section 1, **f2** a gabion threshold in section 2

as they directly influence their stability and function. It is clear that the river bottom in study area 1 behaves differently to the river bottom in study area 2. The digital model of study area 1 river bottom shows prevailing erosion with forming potholes (Fig. 3a1, a2). On the contrary, in study area 2, this process is non-existent and it is sedimentation as a geodynamic process that occurs in study area 2. For such reasons, different methodologies must be applied in evaluation as the stability of the thresholds is influenced by different processes (Fig. 3a1, a2).

The major cause of the differences in the conditions and thus different evaluation methodologies is the dominant water flow (Fig. 3b1) on the left bank downstream of the power plant. This discharge is open during everyday standard operation, i.e. the power station channel, where potholes form. In study area 2, higher volumes of water flow only during the floods (Fig. 3b2), when water is discharged over the weir too. Although water is rarely discharged over the weir, the gabion threshold also gets destroyed. Having the opportunity to apply two methodologies means that the approaches may be compared. The digital model of the river bottom points at dominant erosion processes in study area 1 and sedimentation processes in study area 2 (Fig. 3c1), which correlates with the marked power station

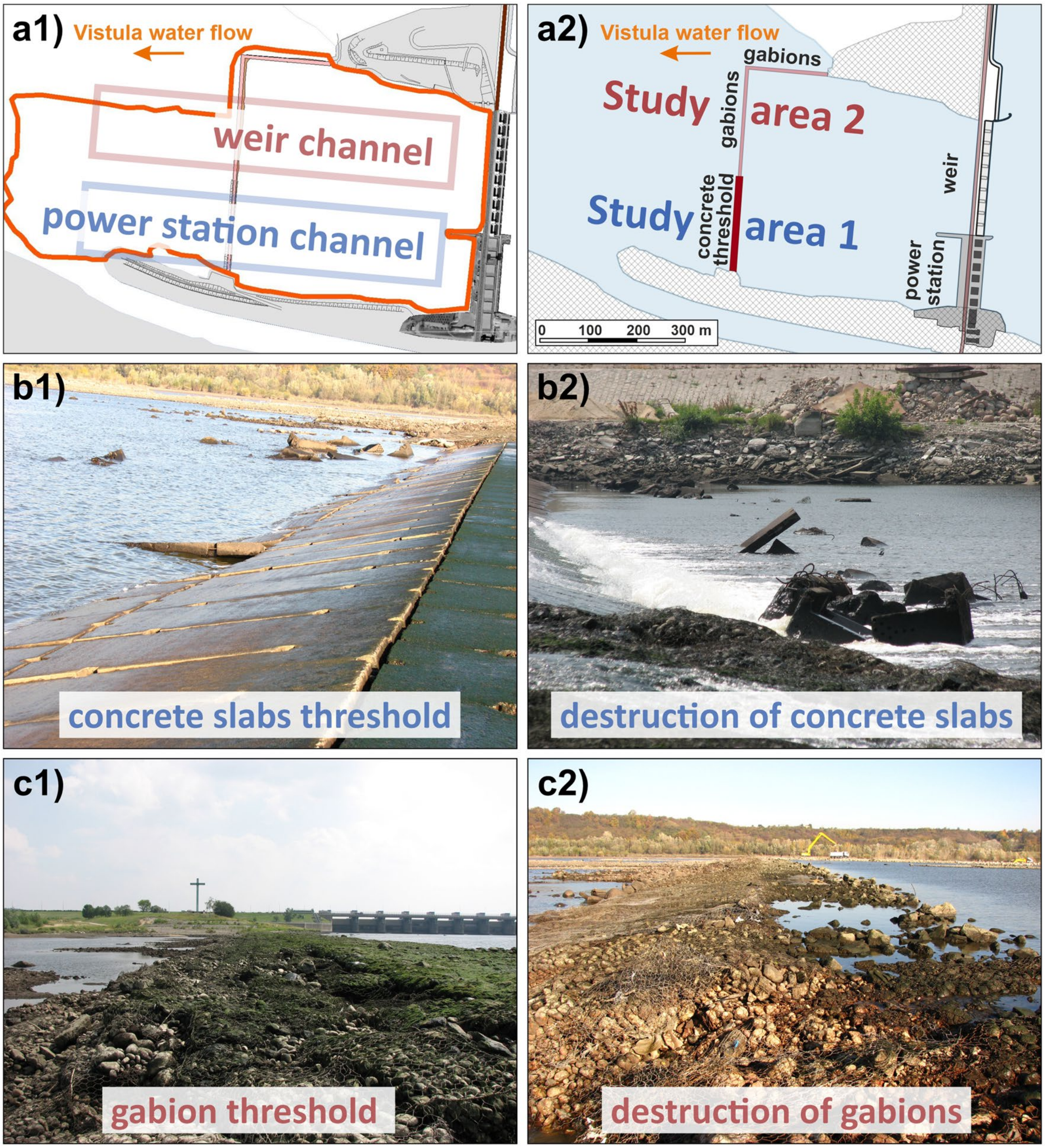

Fig. 2 Photo-documentation of the damaged thresholds in the study area sections 1 and 2, **a1** weir channel in study area 1 and power station channel in study area 2, **a2** concrete slabs threshold in study area 1 and gabion threshold in study area 2, **b1** photo-documentation of the concrete threshold, **b2** photo-documentation of its destruction, **c1** photo-documentation of the gabion threshold, **c2** photo-documentation of its destruction

area (study area 1) and the marked weir area (study area 2, Fig. 3c2).

The geological structure of the study area (Fig. 4) contains Miocene clayey silts, topped by Pliocene variegated clays and Quaternary gravels and sands, where potholes occur.

What is specific about the Vistula River bottom is that each section is cared for by a different owner. The left section is operated by the Energa SA Włocławek power plant (concrete slabs threshold), but the right one is operated by the National Water Holding Polish Waters.

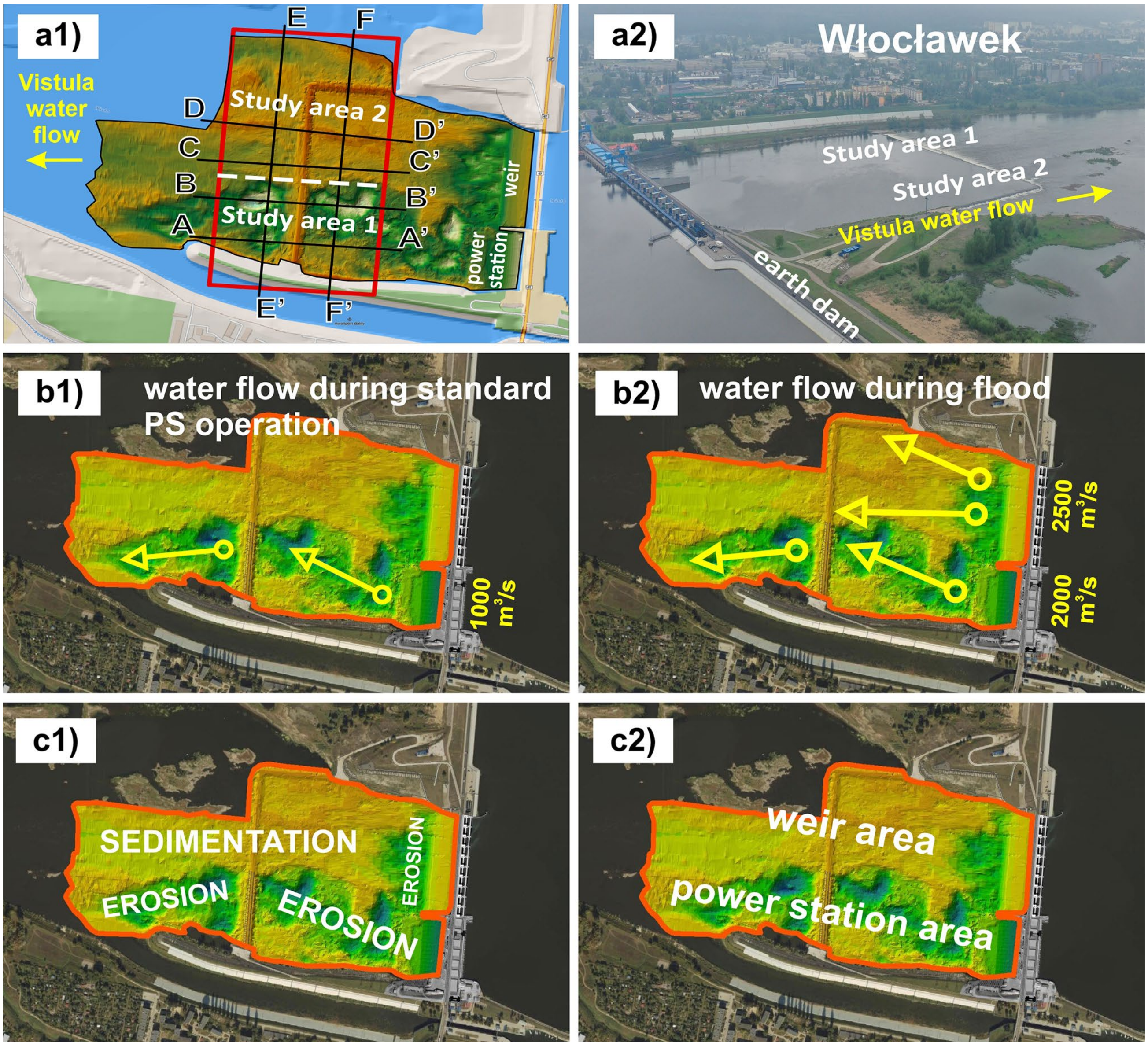

Fig. 3 The conditions on the Vistula River bottom with marked study areas 1 and 2, **a1** a digital model of the river bottom with marked study areas 1 and 2, and cross-sections A–A′, B–B′, C–C′, D–D′, E–E′ and F–F′, **a2** an aerial photo of the study area, **b1** water flow during standard power station operation, **b2** water flow during floods, **c1** dominant erosion processes in study area 1 and dominant sedimentation processes in study area 2, **c2** power plant area (study area 1) and weir area (study area 2)

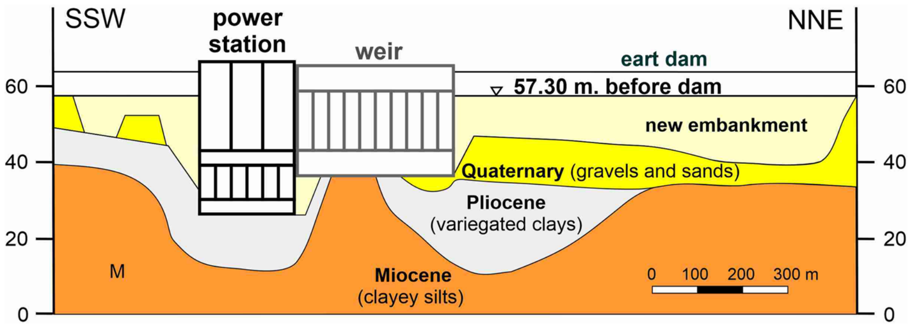

Fig. 4 Engineering–geological cross-section of the study area

Methodology

Geodetic and bathymetric measurements

In order to analyse the size and characteristics of the erosion of the river bed, specialized inventory measurements techniques were implemented. The shape of the threshold and the bottom of the Vistula River downstream from the Włocławek power plant were modelled on the basis of integrated geodetic and bathymetric measurements. Currently, research of the aquatic environment is carried out using modern, geodetic and hydroacoustic measurement techniques, supported by remote sensors and processing algorithms (Popielarczyk et al. 2015). The river bathymetry was studied by a number of authors (Merwade 2009; Pan et al. 2015; Lee et al. 2018; Chow et al. 2019), where the methodology is important in terms of identifying the river bottom morphology and other related information.

The thresholds were measured each year using two methods: bathymetric soundings and classical geodetic surveys. During the high water flow (min 2400 m^3/s), the water level at the threshold made it possible to carry out a hydroacoustic survey with the measurement boat in the whole study area. Depth measurements with the Simrad EA501P professional single-beam echosounder covered both the area of the bottom upstream and downstream threshold as well as the threshold itself. Figure 5a shows a bathymetric boat Orbita taking depth measurements directly above the pothole (about 38 m ASL) just behind the threshold (45 m ASL). The pothole with a depth of about 9 m is shown in the echogram in Fig. 5b. On the right side of the echogram, the threshold is clearly visible. This place is also visible in Fig. 5a just in front of the boat, where the water level change and its turbulent and disturbed flow can be seen. During the measurements, the water flow varied and depended on the operation cycle of the power plant and the weir. Figure 5c shows the flows through the weir and power plant as well as the total water flow of 1760 m^3/s. Depending on the total flow, measurements were made on different parts of the reservoir behind the Włocławek hydroelectric power plant (Fig. 5d). The water flow also affected the water level, which determined the stages of geodetic and bathymetric surveys (Fig. 5e). In addition, during a power plant break (total flow 0), the water level dropped so that the conventional total station surveying (using Leica TS 15) was carried out on the exposed threshold. The collected measurement data were used to develop a three-dimensional model of the threshold and the Vistula River bottom (Fig. 3a, b, c).

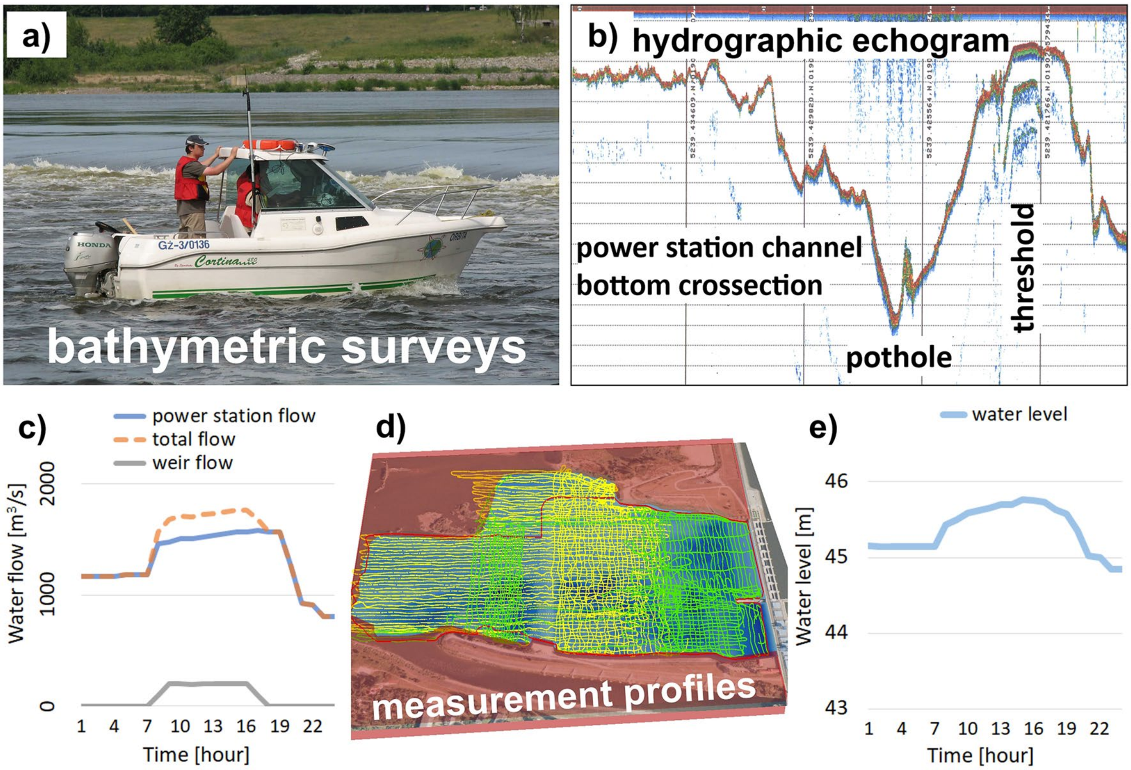

Fig. 5 Methodology of the bathymetric measurements, **a** photo-documentation of bathymetric surveys, **b** hydrographic echogram, **c** graph of water flow changes, **d** measurement profiles, **e** graph of water level changes

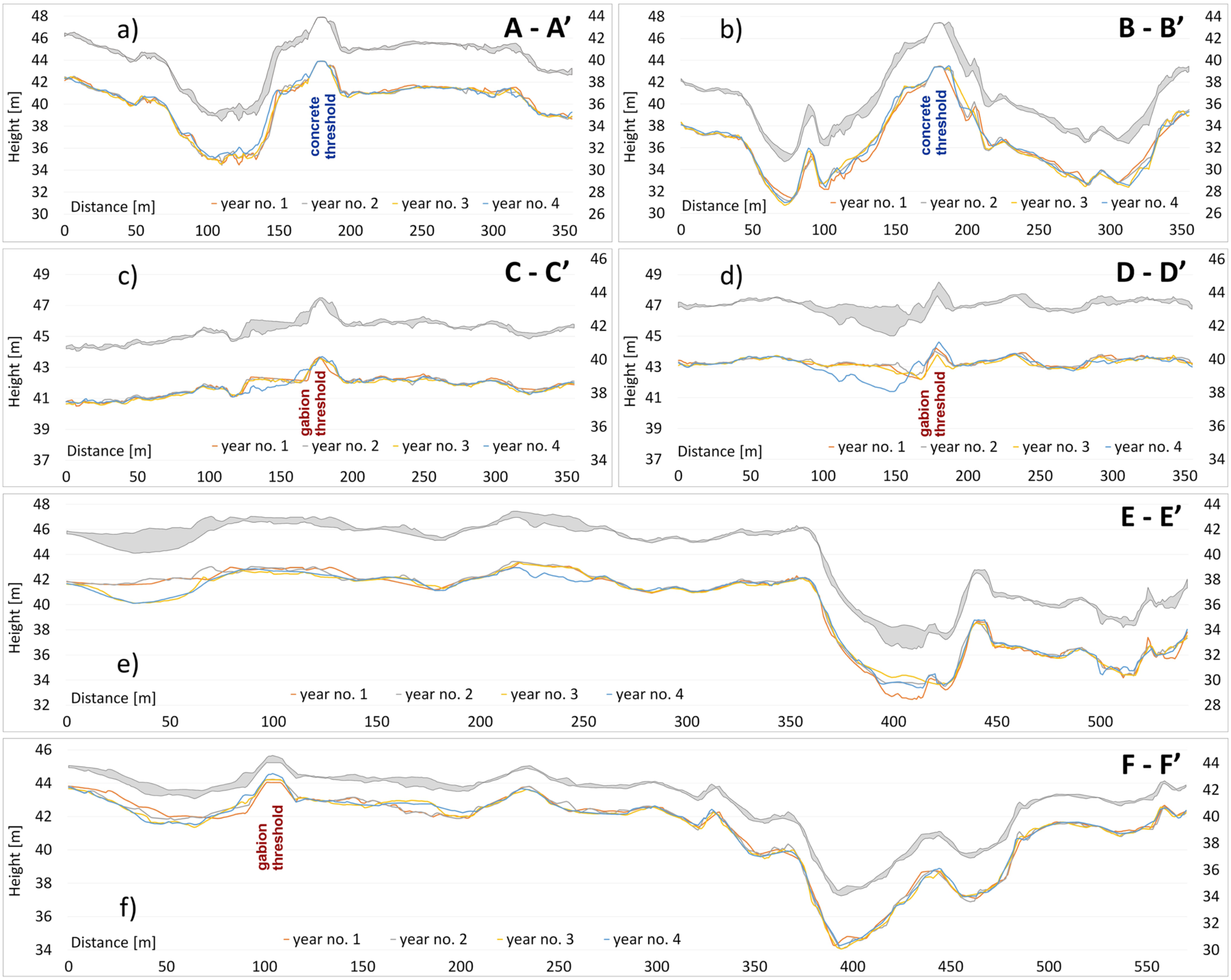

Fig. 6 Cross-sections of river bottom changes during a 4-year bathymetric monitoring in the study area (cross-sections marked in the map in Figs. 3a1 and 7g **a** cross-section A–A′ with a concrete threshold (study area 1), **b** cross-section B–B′ with a concrete threshold (study area 1), **c** cross-section C–C′ with a gabion threshold (study area 2), **d** cross-section D-D´ with a gabion threshold (study area 2), **e** cross-section E–E′ in the study areas 1 and 2, **f** cross-section F–F′ in study areas 1 and 2

Evaluation of riverbed changes

Slope analysis

The research evaluated the slope based on the Vistula River bottom digital model obtained from the geodetic and bathymetric measurements described above. When evaluating the cross-sections A–A′ to F–F′ (Fig. 6) using pie-charts (Fig. 7a to f), the trends are as follows.

The vertical cross-sections of the river bottom surface reveal a different trend in cross-sections A–A′ and B–B′ in study area 1, when compared with cross-sections C–C′ and D–D′ in study area 2. At the same time, there is a clear “mixed’ trend in the cross-sections E–E′ and F–F′. The cross-sections A–A′ and B–B′ (Figs. 6a, b, 7a, b) have a different trend as opposed to cross-sections C–C′ and D–D′ (Figs. 6c, d, 7c, d) as the cross-sections A–A′ and B–B′ have steeper slopes in the potholes. This is caused by the continuous water discharge in the power plant channel with dominant erosion processes.

The first two cross-sections A–A′ and B–B′ (Fig. 7a, b) are characteristic of steeper slopes in the potholes. The percentage of slopes (> 5°, 5°–10° and 10°–15°) is from 57 to 75%, while in steeper slopes (15°–20°, 20°–25°, 25°–30°, 30°–35° and 35°–40°), it is from 25 to 43%. In cross-sections C–C′ and D–D′ (Fig. 7c, d), the percentages are different. The angles (> 5°, 5°–10° a 10°–15°) dominate with 97–99%.

If we evaluate the cross-sections E–E′ and F–F′ (Figs. 6e, f, 7e, f), it is clear that their northern part crosses study area 2, while the southern part crosses study area 1. This means that their values are a mix of the two study area trends. This

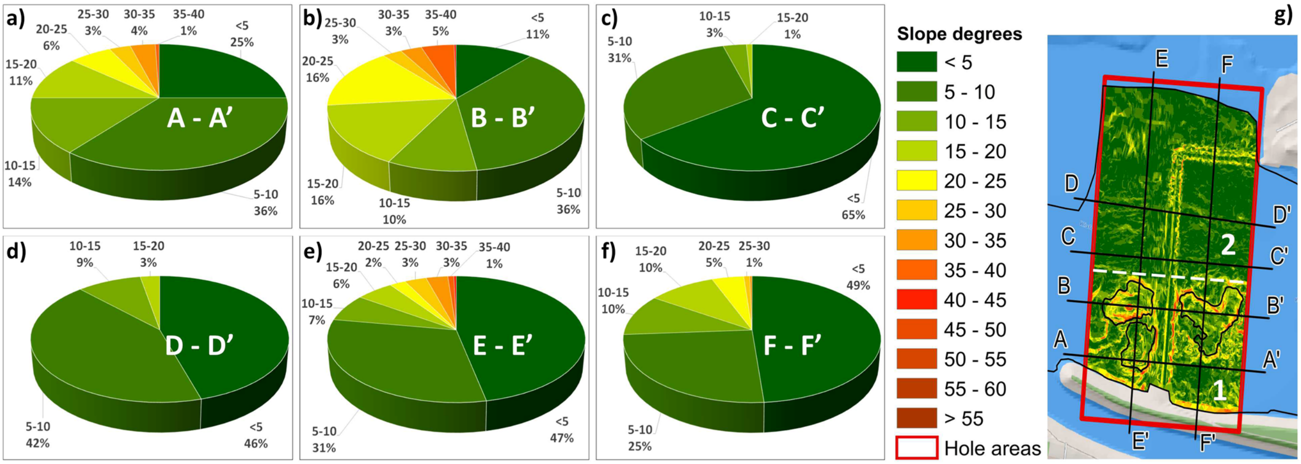

Fig. 7 Frequency of the different slopes in the Vistula River bottom in selected vertical cross-sections: **a** A–A′, **b** B–B′, **c** C–C′, **d** D–D′, **e** E–E′, **f** F–F′, **g** map of the Vistula River bottom slopes with marked location in selected vertical cross-sections

shows in the quantification structure of the graph, where the lowest slopes (> 5°, 5°–10° and 10°–15°) represent 84–85%.

When evaluating the spatial distribution of the slopes in the map (Fig. 7g), there are the following trends. The first most important trend is the fact that the steepest slopes (red and yellow colour) have a different character in study areas 1 and 2. This is explained by the fact the steep slopes are found only in study area 1, which corresponds to the heterogeneous distribution of the erosion manifestations with maximum manifestations in the three dominant potholes. The erosion processes in river alluvia are responsible for the formation of potholes as reported in Spotila et al. (2015), Dhali and Sahana (2017), Rannie (2017) and Ji et al. (2018, 2019). However, study area 2 is characterized by distributed sedimentation processes. The sedimentation processes in the river alluvia cause sediment accumulations and formation of morphological elevations on the river bottoms as reported in Schleiss et al. (2016), Iwuoha et al. (2016) and Blum (2019).

The percentage of steeper slopes in the erosion potholes in study area 1 is clearly higher than the spatial distribution of the slopes in study area 2, where nearly all of the study area is green (Fig. 7g). This corresponds to the slope degrees 0°–10°, particularly below 5° due to the spatial sedimentation downstream of the weir channel. On the contrary, in study area 1 the percentage of slope degrees 10°–40° is clearly higher due to the erosion in the power plant channel.

Studying the distribution of steeper slopes (yellow and red colour; Fig. 7g) in the study area, study area 1 is characterized by heterogeneous distribution of all slopes. This means that erosion occurred all over study area 1. There is only one sector unaffected by erosion in the bottom right corner of the study area.

When evaluating the relationship of water flow and slope distribution, there are two trends. One trend points at the linear erosion structure of the potholes with steeper slopes along the concrete threshold on both sides. This structure has a north–south direction and is perpendicular to the groundwater flow. The second trend is clear in the distribution of steeper slopes in areas with marked potholes, and in the direction of river flow (east–west), while the trend shows in longer pothole sections, e.g. in the round pothole in the northern part of the study area 1 downstream threshold, or the longer pothole section in the north of the study area 1 upstream threshold. However, it does not show in the southern part of the pothole as its border is more irregular.

Evaluation of study area 2 shows the lowest slopes. Steeper (yellow colour) slopes occur only near the gabion threshold. However, these are not mostly potholes but the geometric border of the gabion threshold, which is steeper on the west and east.

Erosion/sedimentation analysis

When evaluating the 4-year monitoring (Figs. 8, 9) in terms of the overall quantity of eroded materials and formation of new sediments, we found the following trends. We identified a variable trend of erosion and sedimentation in both study area 1 (Fig. 8a1, a2) and study area 2 (Fig. 8b1, b2). Erosion prevailed in study area 1, while sedimentation dominated in study area 2. Although this trend was not very clear on the basis of the 4-year monitoring (study area 1—Fig. 8a3 to a6 and study area 2—Fig. 8b3 to b6), this is corroborated by the results obtained since the dam was construction. Based on this comparison, we see the dominance of erosion in study area 1 (Fig. 9a1, a2) with the value of 168,111 m^3 of gravel alluvium, which corresponds to 53.8 Olympic-size pools. Although study area 2 experienced both erosion and sedimentation during the 4-year monitoring, the monitoring

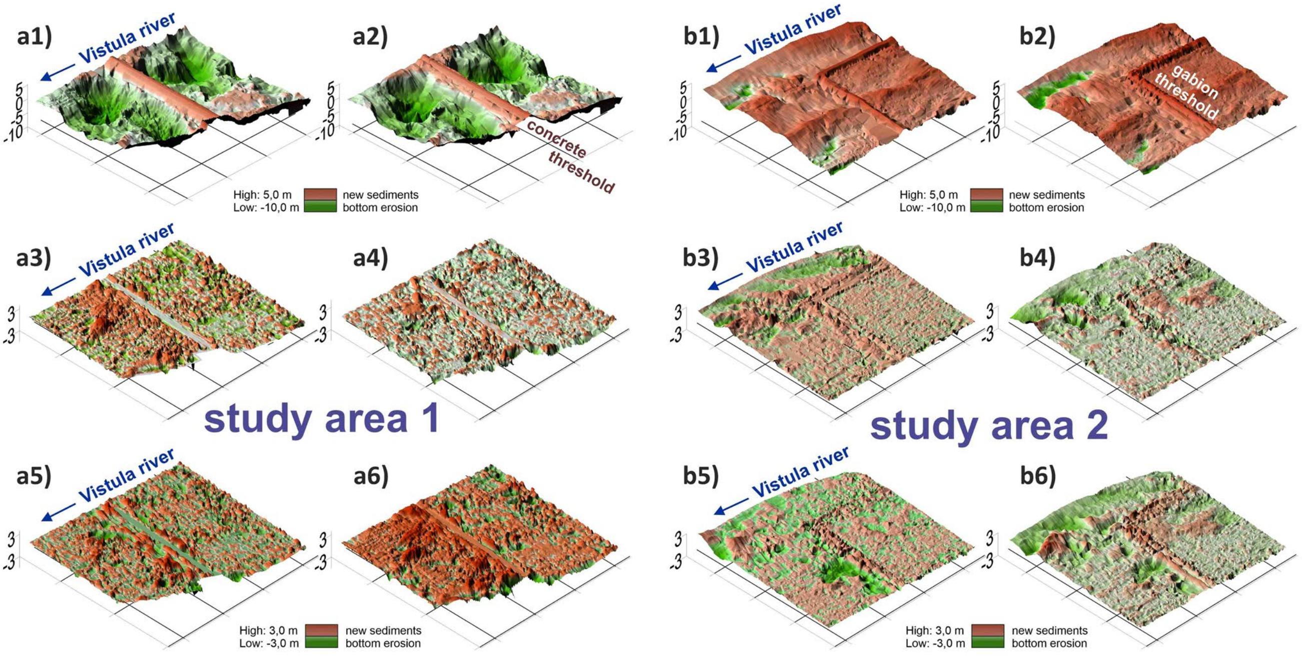

Fig. 8 Map of study areas with marked erosion and sedimentation, **a** study area 1, **b** study area 2—**a1**, **b1** digital model in the first year of monitoring, **a2**, **b2** digital model in the last year of monitoring, **a3**, **b3** marked changes in erosion and sedimentation between the first and second year of monitoring, **a4**, **b4** marked changes in erosion and sedimentation between the second and third year of monitoring, **a5**, **b5** marked changes in erosion and sedimentation between the third and fourth year of monitoring, **a6**, **b6** marked changes in erosion and sedimentation between the first and fourth year of monitoring

since the dam construction shows an absolute dominance of sedimentation with the value of 140,757 m^3 of sediments (Fig. 9b1, b2), which corresponds to 45 Olympic-size pools.

This implies that the overall volumes of erosion and sedimentation in both of the examined study areas are similar and differ only by the volume of 8.8 Olympic-size pools. The majority of the eroded material from the southern area (study area 1) was transported north (study area 2). As mentioned earlier, the value of 53.8 Olympic-size pools in study area 1 clearly correlates with the value of 45 Olympic-size pools in study area 2.

As for the quantification of surface areas, they clearly correspond to the cubic volumes (Fig. 9a3, b3). When comparing the influence of erosion and sedimentation in both study areas, we can see that erosion dominates over sedimentation, which is logical (Fig. 9a3, b3).

Potholes analysis

The research also focused on selected potholes in study area 1 and selected sedimentation mountains in study area 2. These shapes represent typical problems in study areas 1 and 2 (Fig. 10a, b). The 4-year monitoring of pothole cubic volumes showed that the changes were not significant, but most prominent since the origin of the dam. The top cubic volume was observed in pothole 1B in the north downstream threshold in study area 1. Its maximum cubic volume was observed in the first year of monitoring, i.e. 42,216 m^3. The minimum cubic volume was observed in the fourth year of monitoring, i.e. 35,904 m^3. The cubic volume of pothole 1C was similar to pothole 1B. The difference lies in the fact that the first pothole 1B was filled mostly with sediments during the 4 years, while in pothole 1C, erosion prevailed. The smallest pothole was pothole 1A with maximum cubic volume of 10,984 m^3; it is located in the south downstream threshold. This is explained by the fact that the main erosion channel with higher flow rates and stronger water flows occurs more northwards.

As for the cubic volumes, study area 2 has a different character, where all the defined features have much lower cubic volumes than in study area 1. This is caused by the fact that in study area 2 erosion is not caused by increased water flows as it is located downstream of a weir. In study area 2, the biggest cubic volume was in feature 2C, where its maximum cubic volume was 7462 m^3 (in the first year of monitoring). The other two features 2A and 2B have much smaller cubic volumes, i.e. in the interval from 2240 m^3 (in the third year of monitoring) to 2666 m^3 (in the second year of monitoring). There, higher water flows are found only on the flood periods.

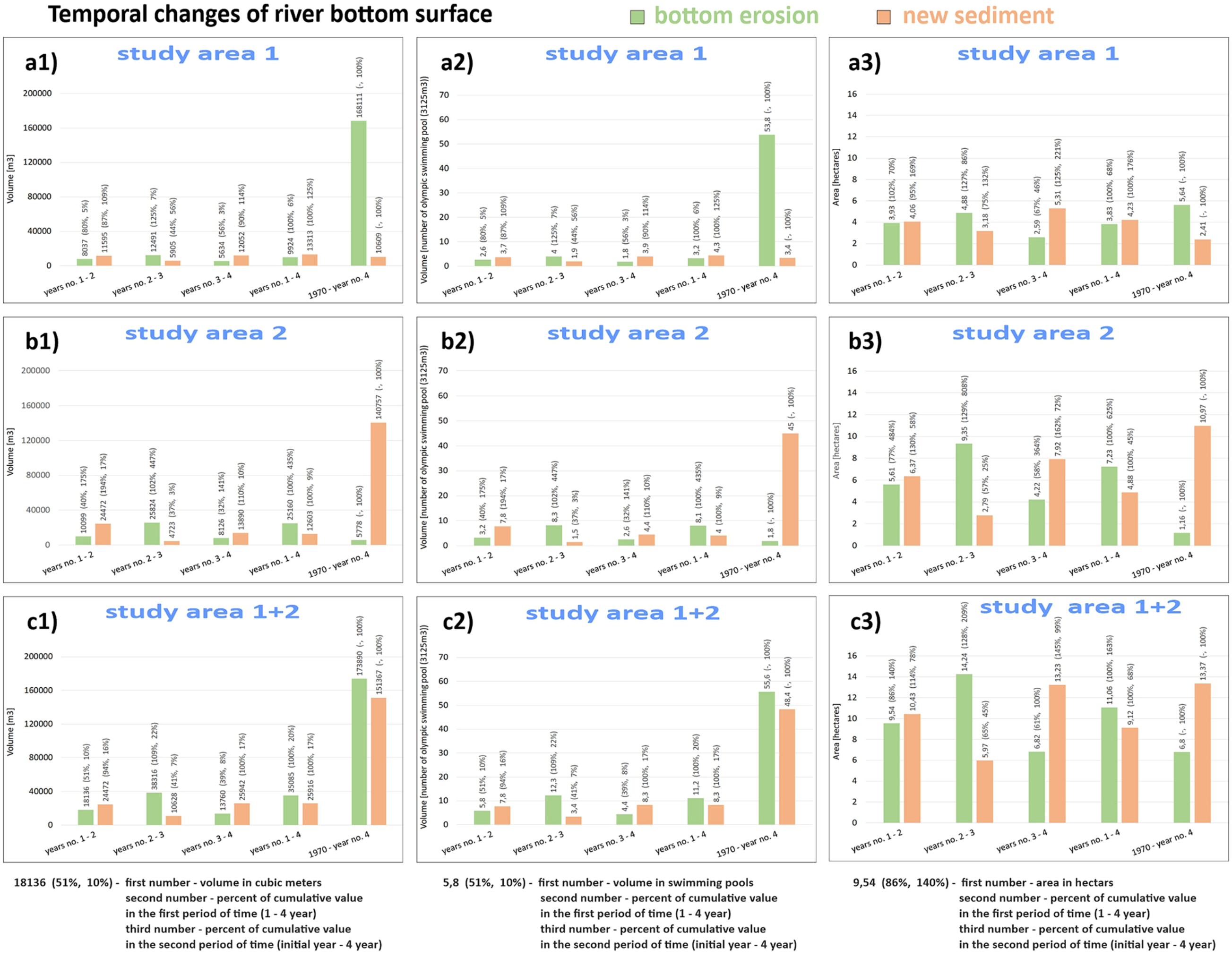

Fig. 9 Temporal changes of river bottom surface (bottom erosion and new sediment), **a1** study area 1—volume (m^3), **a2** study area 1—volume (number of Olympic-size pools), **a3** study area 1—area (m^2), **b1** study area 2—volume (m^3), **b2** study area 2—volume (number of Olympic-size pools), **b3** study area 2—area (m^2), **c1** study area 1 + 2—volume (m^3), **c2** study area 1 + 2—volume (number of Olympic-size pools), **c3** study area 1 + 2—area (m^2)

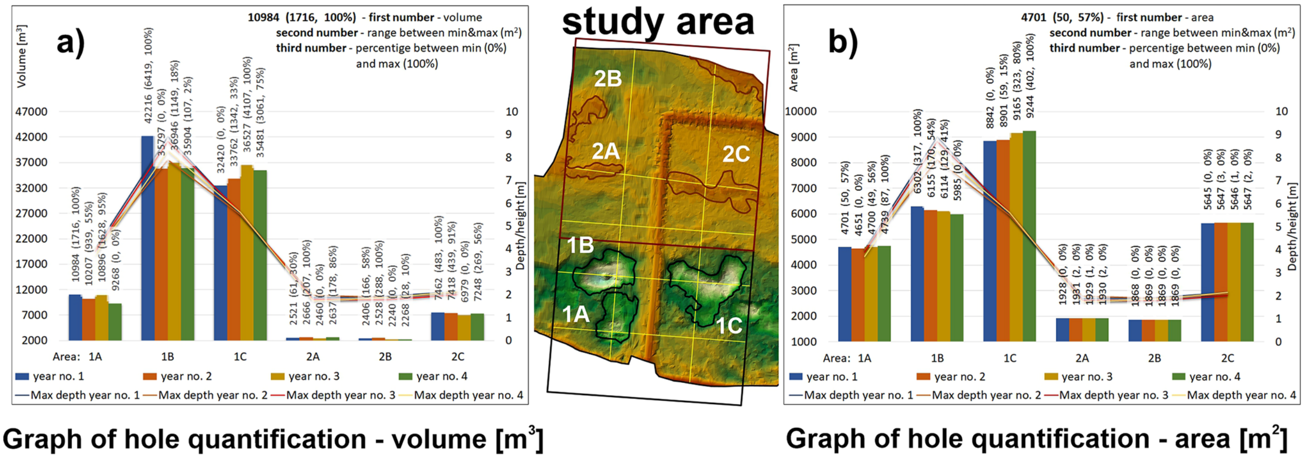

Fig. 10 Quantification of selected potholes in study areas 1 and 2, **a** graph of pothole quantification—volume (m^3), **b** map of study area 1 with localization potholes (1A, 1B and 1C) and study area 2 (potholes 2A, 2B and 2C), **c** graph of pothole quantification—area (m^2)

Upon the evaluation of the surface area of the features, it roughly corresponds to their cubic volumes (Fig. 10c). In other words, the biggest potholes take up the largest surface areas.

Threshold stability hazard map

Study area 1 evaluation

River bed hazard map for the stability of the concrete threshold

To evaluate the hazards in study area 1, we selected an approach (Fig. 11) that aims to describe the conditions of the alluvium bottom related to the threshold. The threshold in study area 1 is most endangered by erosion manifested in the form of potholes. Potholes which are too close too deep may lead to the destruction of the threshold. To address this situation, we selected two criteria to evaluate the hazards in the Vistula River alluvium near the threshold.

The first criterion is the depth of the pothole parts. Based on empirical experience in the Włocławek dam, we chose three depths. The most hazardous depth is one over 3 m. The second, conditionally hazardous, depth is 1 to 3 m, and the third, the least hazardous depth is less than 1 m (Fig. 11a). According to Fig. 12a1 and a2, the most hazardous depth corresponds to 18% of pothole volumes (7932 m^3) and 30% of surface area (5878 m^2) of study area 1. The conditionally hazardous depth is associated with 44% of pothole volume (19,657 m^3) and 45% of surface area (8813 m^2). The least hazardous depth corresponds to 40% of pothole volume (17,544 m^3) and 25% of surface area (4955 m^2).

The second criterion is the distance of the pothole from the threshold. The most hazardous distance is below 20 m from the threshold, the second (conditionally) hazardous distance is 20–50 m from the threshold, while the least hazardous distance of the pothole is over 50 m (Fig. 11b). As for the quantification of the second criterion (Fig. 12b1, b2), it showed that only 1% of pothole volume (492 m^3) and 2% of surface area (470 m^2) in study area 1 fall in the most hazardous category. The conditionally hazardous distance corresponds to 17% of pothole volume (7783 m^3) and 24% of surface area (4783 m^2). The least hazardous distance is related to 82% of pothole volume (36,858 m^3) and 73% of surface area (14,393 m^2).

For the final risk evaluation map, we used a risk matrix stated in Fig. 11c, where the most hazardous group are all pothole parts closer than 20 m in all depths as well as potholes 20–50 m from the threshold with the depth over 3 m. The second, conditionally hazardous group, are pothole parts that are located 20–50 m and fall in the low (0–1) and medium (1–3) depth categories. The third, least hazardous group, are all pothole parts located over 50 m from the threshold, in all their depths. Upon the evaluation of the final risk map (Fig. 12c1, c2), the quantification corresponds to the quantification based on the second criterion discussed above. This is explained by the

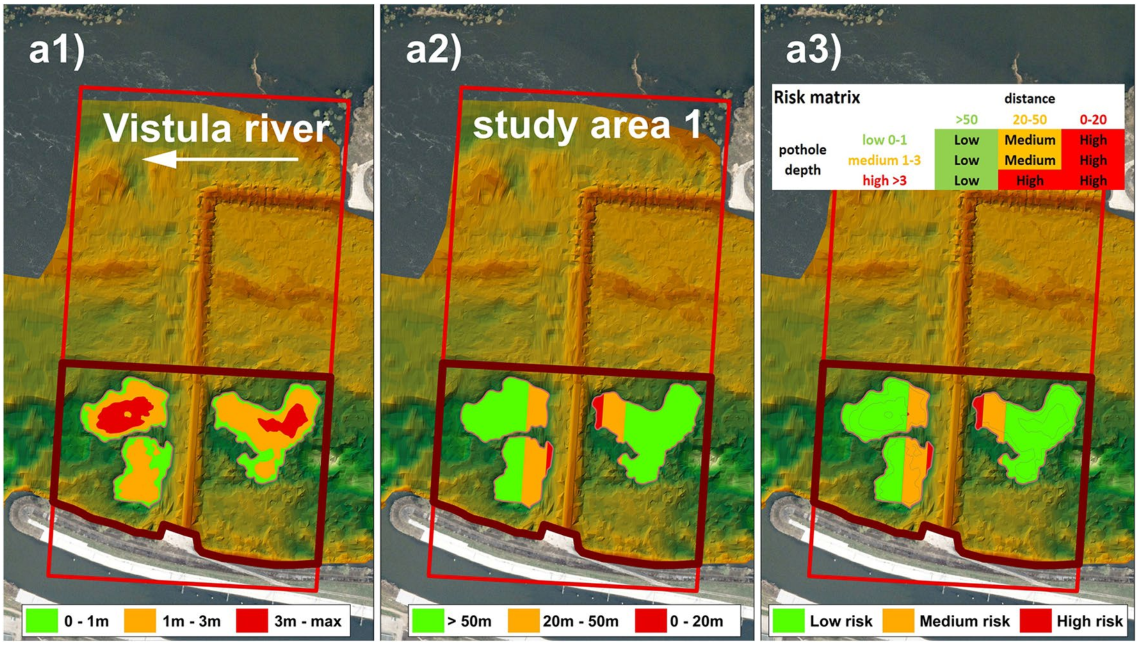

Fig. 11 Map of hazards in study area 1, **a** criterion 1—pothole depth, **b** criterion 2—pothole distance from the threshold, **c** based on the combination of criteria 1 and 2 and risk matrix

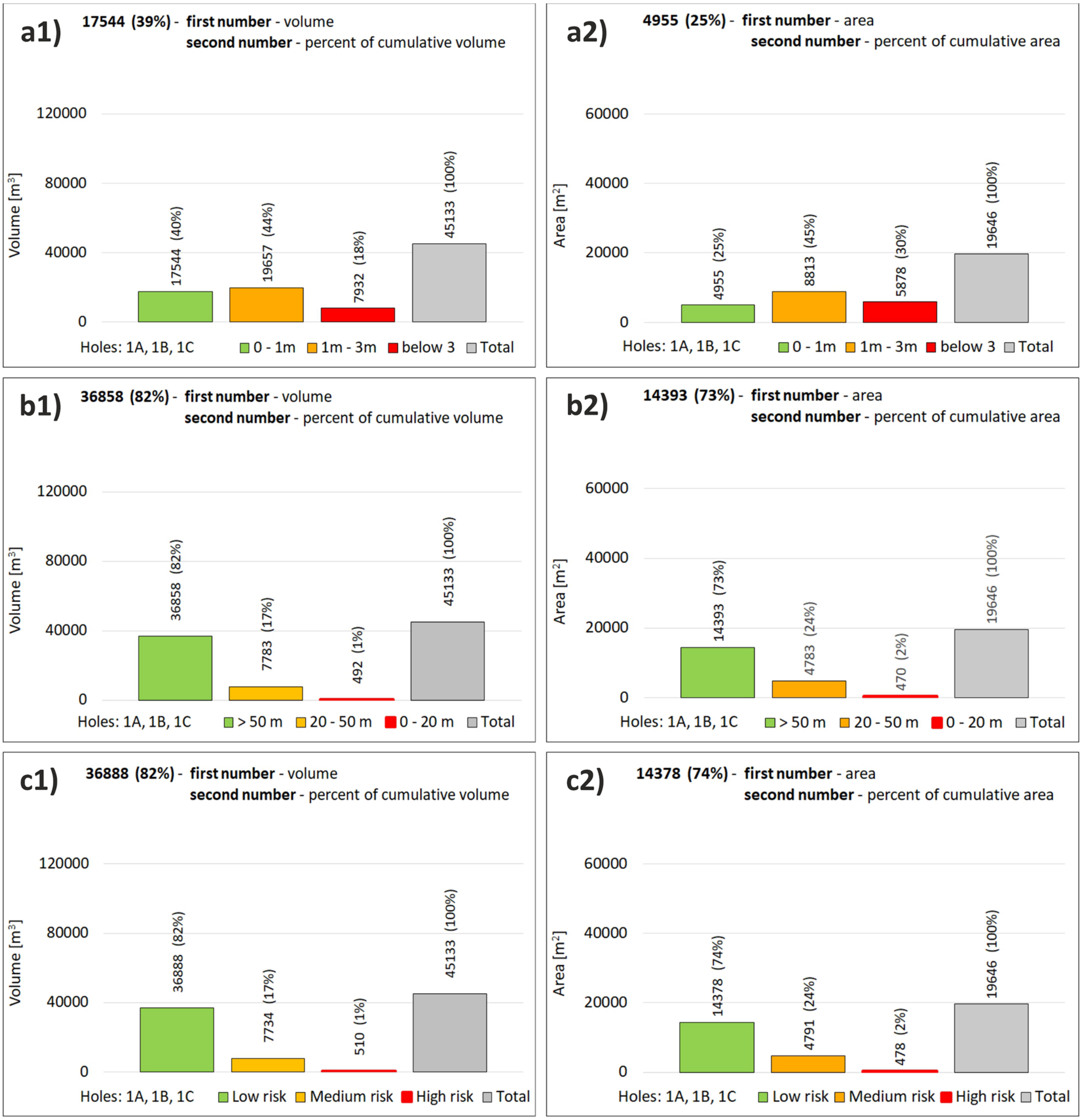

Fig. 12 Quantification of study area 1 based on risk map (pothole 1A, 1B and 1C), **a1** based on criterion 1—depth of pothole parts—volume (m^3), **a2** based on criterion 1—depth of pothole parts—surface area (m^2), **b1** based on criterion 2—pothole distance from the threshold—volume (m^3), **b2** based on criterion 2—pothole distance from the threshold—surface area (m^2), **c1** based on the combination of criteria 1 and 2 and risk matrix—volume (m^3), **c2** based on the combination of criteria 1 and 2 and risk matrix—surface area (m^2)

fact that deeper potholes are further than 20 m from the threshold, and only a smaller part of pothole 1B causes the difference. However, using the methodology in a different area, results may be much different. The methodology is universal and applicable in other river alluvia and dam/threshold protection.

Study area 2 evaluation

River flow hazard map for the stability of the gabion threshold

For this study area, we used a different approach as a different mechanism of influence on the threshold is at work there. The sustainability of the threshold is one of the motivations for the study. In study area 2, more pronounced potholes do not form as the area is protected from the direct water flow by the power plant structures.

The empirical evidence shows that the gabion threshold gets damaged only during increased water flows during floods. Based on empirical evidence, we determined critical water flow rates (Fig. 13a). The most hazardous related to the gabion threshold is the flow rate over 3000 m^3/s. Medium risk flow rate is between 2000 and 3000 m^3/s. Low risk is associated with flow rate below 2000 m^3/s as this is the maximum level when water is discharged only through the power plant structure. Over this limit, water must be discharged over the weir too, which means that water flows through study area 2 and the gabion threshold gets damaged.

To evaluate the influence on the gabion threshold by the river bottom, we prepared a digital bottom model (DBM). In this article, the bathymetric DBMs of the Vistula River were processed using the ESRI ArcGIS 10.6 and hydrologic modelling tools from the ArcGIS Spatial Analyst extension. These tools were used to generate the flow direction, flow accumulation and stream characteristics. The bottom was first processed to fill sinks in surface raster to remove small imperfections in the data. The

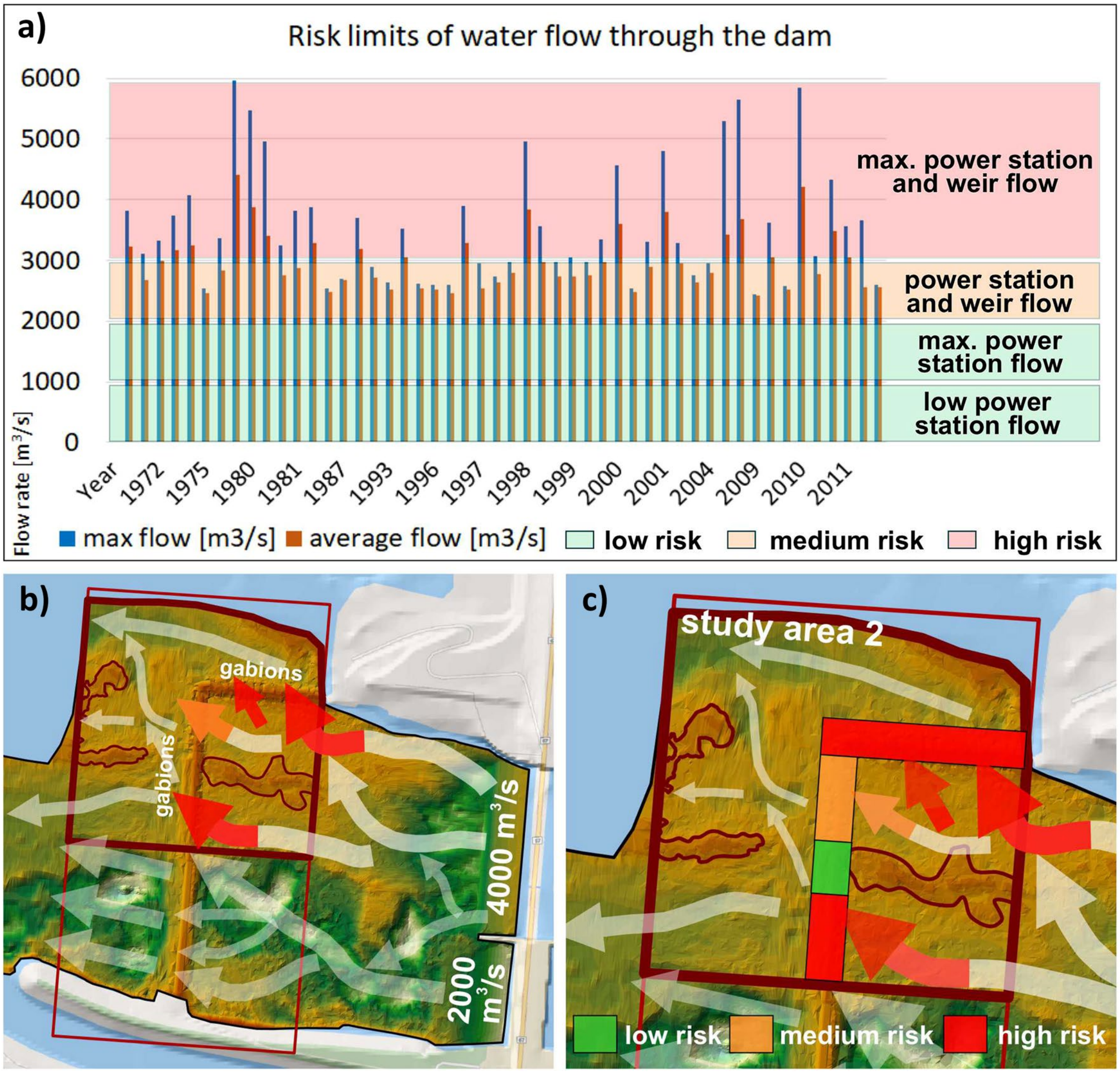

Fig. 13 Risk assessment in study area 2, **a** graph of risk limits of water flow through the dam, **b** potential direction of water flow by digital bottom models (DBMs), **c** risk map of the gabion threshold

eight-direction flow method (D8) models flow direction from each cell to its steepest downslope neighbour was applied to determine the direction of the flow from every cell in the raster. In the end, the flow accumulation was calculated as the accumulated weight of all cells flowing into each downslope cell in the output raster. Based on these characteristics, the potential direction of water flow was calculated and presented in Fig. 13b, c.

The proposed methodology enabled us to characterize the more or less dominant flows that subsequently destroy the gabion threshold. The results of the model were compared with the real destruction of the gabion threshold, and it proved to correlate well with the model. This way a feedback was ensured and the risk evaluation of the gabion threshold produced (Fig. 13b, c). The study analyses the flows through the power plant (maximum is 2000) and through the weir. The flows through the power plant are systematic, even continuous, and through the weir sporadic, depending on the river flow. Critical flows over the weir during floods reach 4000 (a total of 6000 over the whole dam).

Sections of larger destructions of the gabion threshold fall in the high-risk category. We found that it concerned 64% of the threshold, i.e. 272.5 m (Fig. 14a). If we evaluate the cubic volume of the category, it adds up to 60% (8584 m^3) of the cubic volume (Fig. 14b). As for the surface area, it corresponds to 70% (8781 m^2) of the overall threshold area (Fig. 14c).

In the category of medium risk, smaller damage of the gabion threshold occurred. Only 26% (112 m) of the gabion threshold length was affected. Evaluating the cubic volume, the risk category adds up to 27% (3961 m^3) of material from the overall cubic volume and 20% (2469 m^2) of the overall threshold area.

As for the length of the gabion threshold affected by the low-risk category, it is only 10% (40.5 m) of the threshold. The cubic volume is 13% (1928 m^3) of the overall cubic volume and 10% (1225 m^2) of the overall threshold area.

Discussion and conclusions

The main aim of our work was to show a method of performing a risk assessment and to indicate how to protect the threshold structure stabilizing water flow downstream of the dam. The study area was an alluvium of the Vistula River, including the thresholds that are part of the hydroelectric power plant in Włocławek (the dam built in 1970 includes a frontal dam, weir, fish pass and a sailing lock). Eight power stations should have been built to form a system of water management facilities, but for economic and technical reasons, only one dam was constructed. This resulted in erosion and sedimentation, which led to potholes in the river bottom and the destruction of the concrete/gabion threshold behind the power plant.

In the first step, we point at the differences in river erosion behind the dam as one section of the study area showed prevailing erosion from potholes (down the power station) where the second section suffered from sedimentation (down the weir). In the next step, we conducted integrated geodetic and bathymetric measurements and elaborated a numerical model of the shape of the threshold and the bottom of the Vistula River downstream from the Włocławek power plant. Finally, we proposed and implemented a new methodology to perform a risk assessment and to indicate how to protect the threshold structure.

The engineering–geological investigation of the Vistula River alluvium on the Włocławek dam brought interesting

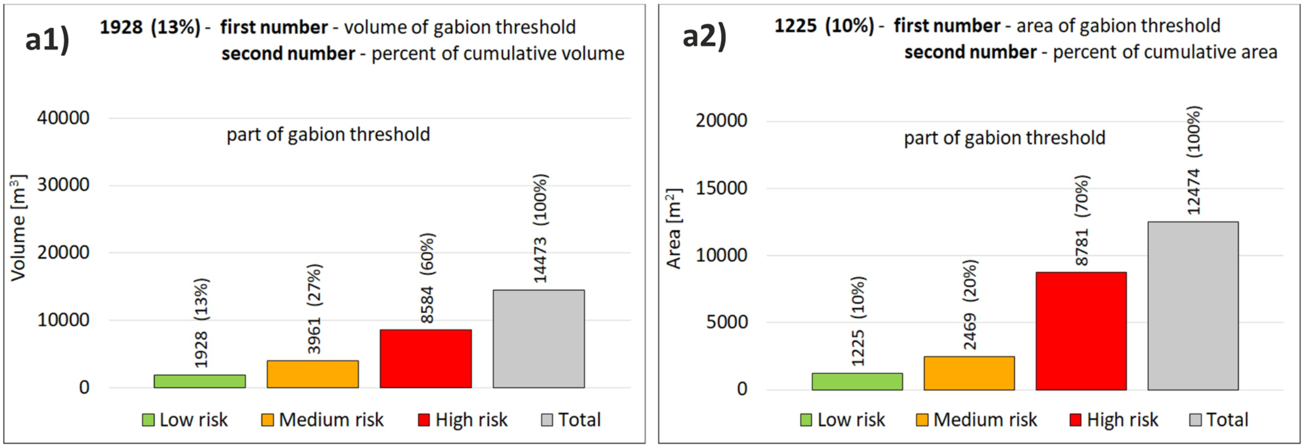

Fig. 14 Quantification of risk categories in study area 2 according to the risk map of the gabion threshold, **a** length of gabion threshold part (m), **b** volume of gabion threshold part (m^3), **c** surface area of gabion threshold part (m^2)

results. The first is the fact that the river downstream of the dam may have different influence on the river bottom. The left part in the direction of water flow is characterized by dominant geodynamic process of river bottom erosion conditioned by everyday average flow rates of downstream from the Włocławek power plant structure. On the contrary, the right part of the study area is characterized by dominant sedimentation over erosion, where the weir is located and water is discharged only during floods. Potholes thus form only near the dam, but do not occur near the threshold. The sedimentation in the right part is related to the pothole erosion near the weir as well as the potholes in the left part of the river. All these impacts lead to the destruction of the threshold. To be able to protect the locality, it is important to evaluate the two study areas separately. This also gives an opportunity to compare the two approaches.

The evaluation of study area 1 was based on geodetic and bathymetric measurements of pothole formation near the concrete threshold. The key for the concrete threshold stability was regular monitoring (4 years) and redevelopment through backfilling. We produced three hazard maps of study area 1. The first was based on the pothole depth, and the second on the pothole distance from the concrete threshold. The final map combined criterion 1 and 2 with the risk matrix (Fig. 11). We found that the high-risk category concerned 1% of the area (cubic volume of 510 m^3) due to the potholes 1A and 1C near the gabion threshold (less than 20 m). The medium risk category concerned 17% (cubic volume of 7734 m^3), where some of the potholes are within 50 m from the gabion threshold. Both categories are planned to be backfilled based on the concrete threshold redevelopment.

As for the surroundings of the gabion threshold, the 4-year bathymetric measurements of the river bottom showed that sedimentation prevailed over potholes. The gabion threshold was endangered during floods, when increased water flows were discharged over the weir too. Therefore, the gabion threshold was repaired only after floods. To evaluate the risks, we first empirically determined the critical flow rates causing the destruction of the gabion threshold. The high-risk water flow was determined to be over 3000 m^3/s, which corresponds to the floods periods. The medium risk water flow was determined to be between 2000 and 3000 m^3/s. This flood conditions mean that water is discharged over the weir too in the study area 2. With flow rates below 2000 m^3/s (low-risk water flow), water is discharged only through the power plant structure, and thus, the gabion threshold is damaged the least. For the geometric categorization of the risk zones of the gabion threshold, we used the digital bottom models methodology. We found that the most hazardous category is related to 64% of the gabion threshold length (272.5 m); the medium risk category is related to 26% (112 m), and 10% are in the low-risk category (40.5 m). Based on the data, it is possible to plan gabion threshold repairs on a selective basis.

On the basis of engineering and geological studies of the river bed and the stabilization threshold (4-year monitoring using geodetic and bathymetric measurements), and on the basis of a thorough analysis of two different parts of the same river (cross-section/area slope and erosion/sedimentation analysis), we have developed a method for risk assessment and design for subsequent protection of two different parts of the threshold (concrete and gabion threshold) using two different methodologies. Based on our research results, measures were taken to prevent further leaching and displacement of concrete slabs in area 1 and repair flares of gabion bags in area no.2. The work supports the structure's managers in maintaining its safety. Thresholds will be measured (geodetic and bathymetric surveys) after completion of their upgrades and repairs.

The scientific contribution of the study lies in the conclusion that one alluvium of the Vistula River may need two approaches for observation and redevelopment. This means that a genetically identical area (Vistula River bottom alluvium) with the identical geological structure may be influenced in a heterogeneous manner due to different water flows and thus lead to various influences on the engineering structures, such as thresholds. Subsequently, customized evaluation methodologies and redevelopment methods must be applied.

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