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THE STUDIES ON CHECK DAM RESTORATION EFFECTIVENESS

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Abstract

A check dam is a hydraulic structure, which is constructed in order to limit river sediment transport. A sedimentation reservoir is created upstream from the body of the dam, where river sediment is constantly accumulated. These structures were constructed starting in the early 20th century in upstream parts of mountain streams in the Polish part of the Carpathian Mountains. At present, the reservoirs of most check dams are already fully filled with sediment and the impact of these structures on the ecosystems of streams is unfavorable. Moreover, the dams that have not been renovated are in poor technical condition. In the paper two cases of check dam lowering and restored is discussed and the one hypothetical case of gradual check dam lowering is presented and discussed as well. The cases of Krzczonówka and Trzebuńka, where the method of removing sediment from reservoirs was different, showed that the sudden change of „established" hydrodynamic conditions for decades is not favorable for the stream. The results of hypothetic simulation of gradual check dam lowering for the case of Isepnica Stream leads to the conclusion that lowering the construction of check dam and removing sediment from its reservoir in a way that does not have a drastic impact on the hydrodynamic balance of the stream channel is possible. However, as it was shown in the case of Isepnica Stream, it is very complicated task.

Key words: mountain stream channel, sediment, check dam, restoration

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INTRODUCTION

A check dam is a hydraulic structure, which is constructed in order to limit river sediment transport. A sedimentation reservoir is created upstream from the body of the dam, where river sediment is constantly accumulated. Check dams were constructed starting in the early 20th century in upstream parts of mountain streams in the Polish part of the Carpathian Mountains. The main purpose of the construction of these structures was to trap sediment being transported downstream. The streams carried both their own sediment produced due to downward cutting and lateral cutting in the streambed as well as sediment supplied in huge amounts by local catchments, the hillslopes of which were used for agriculture at the time. At present, the reservoirs of most check dams are already fully filled with sediment (Ratomski 1991), and the impact of these structures on the ecosystems of streams is unfavorable. Moreover, the dams that have not been renovated are in poor technical condition. Therefore, any further operation of these check dams in Carpathian stream channels in their present technical condition becomes a problem, especially since they constitute a transverse barrier to the migration of aquatic organisms if the flow is interrupted in a stream channel. Thus, damaged check dams cause a permanent interruption in the continuity of the ecological corridor of streams in the Carpathians and elsewhere.

CHECK DAM EFFECTS ON THE STREAM CHANNEL

Prior to the construction of check dams in the Polish Carpathians, their mountain streams carried both their own sediment, which originated in the process of downward cutting and lateral cutting in the streambed, as well as sediment supplied in immense amounts from local catchments, the hillslopes of which were used for agriculture. The amount of material in the studied streams exceeded their material transport capacity. As a result, most streams became transformed into braided systems in both their downstream and middle sections (Krzemień 1981, Klimek 1987). The functioning of check dams was one of the main causes, which reduced the sediment load available for fluvial transport in the Polish Carpathians in the studied period of time (Korpak *et al*. 2008). Downward erosion became the dominant process occurring in stream channels deprived of sediment. Channel beds were cut down to bedrock in many reaches, which also decreased their geomorphologic diversity (Korpak *et al*. 2008). The living conditions of river organisms worsened, and overall river biodiversity decreased as well (Bojarski *et al*. 2005). Dams interrupt the continuity of the stream corridor, limiting the supply of sediment from the upstream part of the stream, thus dividing the channel into two dissimilar sections, which function differently: deposition is the leading process upstream from the dam, while erosion is the leading process downstream from the dam. The composition of sediment in terms of grain size is clearly less differentiated downstream from the dam (Korpak *et al*. 2008).

The ideal ecological corridor associated with the river and stream valley should include the riverbed (watercourse, aquatic and terrestrial organisms and vegetation), a flooding area, both slopes of the valley, and a forested area at least on one side of the watercourse. However, nowadays, because of the environment anthropogenic transformation, such a situation is rather very rare. In mountain streams, where the channels are modified by steps and check dams constructions, the continuity of water and sediment flow is disrupted. Migration of fish and other aquatic organisms is also difficult or impossible. Consequently, the habitats typical for a given region are degraded. In the Polish Carpathians most check dams are either not equipped with fish passes or passes are not operational, which makes it impossible for the fish of the Salmonidae family to migrate to their spawning grounds in the upstream reaches of streams. Thus, stream restoration is required to counteract these shortcomings, especially since the European Framework Directive on Water (EFD – 23 October 2000) strongly emphasizes that at least two thirds of all watercourses should be restored to good ecological status.

THE AIM, MATERIAL AND METHODS

The aim of the article is to present two different methods of check dams lowering and a brief analysis of the impact of these works on the hydrodynamic balance of the channel above and below the reconstructed objects. The proposed third method of check dam lowering, as a hypothetical one and perhaps a recommended one, has been additionally analyzed.

The studies concern Krzczonówka and Trzebuńka Streams. In both cases, the way of sediment releasing the from the check dams' reservoirs was different. The paper presents results of simulation of hypothetic check dam gradual lowering on the Isepnica Stream as well.

The Krzczonówka Stream, a tributary of the Raba River, drains a 92.2 km^2 catchment in the southern region of Poland (Fig.1,2). The check dam located at kilometer 2+250 of the stream course was lowered, redesigned, and rebuilt as a cascade due to the Ab Ovo Association project in 2014.

Trzebuńka Stream, is left side tributary of Raba River. Its catchment area is 33 km^2, length: 9.0 m. On the km 0+370 of the stream course the existing check dam was lowered of 4.0 m and reconstructed in 2015 (AB OVO Tarliska Górnej Raby, 2011), (Fig.1,2).

The Isepnica Stream, the tributary of Sola River, is situated in the Silesia Province, in the southern, mountainous part of Poland. Three sediment check dams are located in this reach, at km 2+570, km 2+320, and km 1+389. The sediment check-dams were constructed in the 1950s in order to protect the adjacent villages against hillslope erosion. Now their reservoirs are completely full of sediments and some of them are in very bad technical conditions (Fig.1).

The studies are based on cross-sectional geometry and sediments analysis measured downstream the Krzczonówka stream before and after the check dam lowering ; upstream the check dam of Trzebunka Stream after the dam lowering and throughout the Isepnica Stream course upstream and downstream one of three check dams.

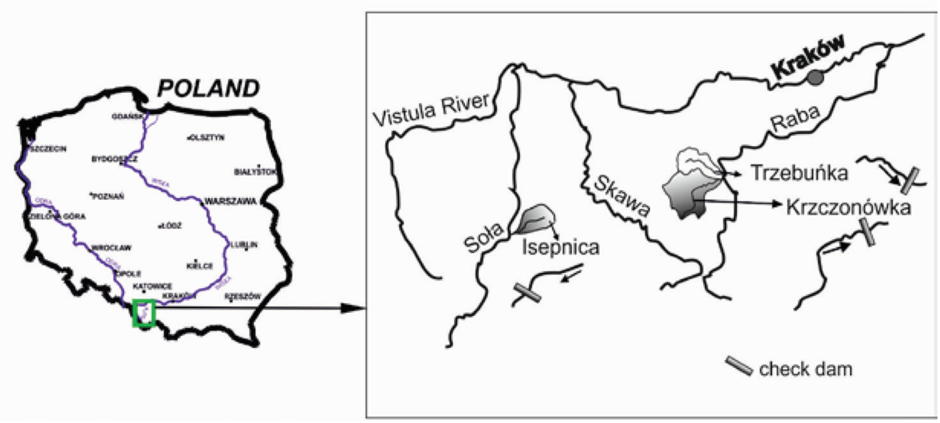

Figure 1. The study areas location: Krzczonówka Catchment, Trzebuńka Catchment, Isepnica Catchment.

Figure 2. Check dams lowering: Krzczonówka and Trzebuńka Streams (Photos: M.Łapuszek., Ab Ovo Association).

The field measurements of the streams channels were surveyed for the studied reaches using a GPS Topcon Hiper II. A total of 31 bankfull cross sections were surveyed to document the stream channel topography for Krzczonówka and Isepnica cases. Surveys were completed in Krzczonówka once before the check dam lowering and three times after dam lowering: in 2014, 2015 and 2016. For Isepnica case the topography of the channel was measured in 2004. The field observation downstream the lowered check dam was carried out for Trzebuńka stream. Based on the above-mentioned monitoring measurements, trends of stream bed processes were worked out.

The numerical analysis of the impact of the check dam lowering process and the removal of sediment previously accumulated upstream on geomorphologic conditions in the stream was carried out. A one-dimensional model (Łapuszek *et.al.,* 2007) was used. The model used for the computation have two components: a component to simulate the flow and a component to characterize the changes in river morphology due to erosion or deposition of sediment. The models is relied on:
de Saint Venant equations for water (Paquier 2003):

$$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=q \tag{1}$$

$$\frac{\partial Q}{\partial t}+\frac{\partial}{\partial x}\left(\beta\frac{Q^2}{A}\right)+gA\frac{\partial z}{\partial x}=-g\frac{Q^2}{K^2 A R^{4/3}}+kq\frac{Q}{A} \tag{2}$$

equation for conservation of sediment mass (Paquier 2003):

$$(1-p)\frac{\partial A_s}{\partial t}+\frac{\partial Q_s}{\partial x}=q_s \tag{3}$$

and sediment transport capacity relation (Meyer-Peter and Müller, 1948):

$$C_s=\frac{8L_a\sqrt{g}}{(\rho_s-\rho)\sqrt{\rho}}\left(\rho JR-0.047D_{50}(\rho_s-\rho)\right)^{3/2} \tag{4}$$

where: A – cross-sectional flow area (m^2), A_s – bed-material area (m^2), β – the coefficient of quantity of movement, C_s – sediment transport capacity (m^3/s), D_{50} – median diameter of sediment (m), g – acceleration due to gravity (m/s^2), J – friction slope, K – Manning-Strickler coefficient (m$^{1/3}$/s), k – ratio between the velocity of the main flow and the axis velocity of the lateral flow, q – lateral water flow per unit of length (m^2/s), Q – water discharge (m^3/s), Q_s – sediment discharge (m^3/s), q_s – lateral sediment flow per unit of length (m^2/s), R – hydraulic radius (m), ρ – density of water (kg/m^3), ρ_s – density of sediment (kg/m^3), x – stream wise coordinate (m), Δx – distance between cross-sections (m), z – water surface elevation (m).

In the model, sediments are represent by a mean diameter (D_{50}). This parameter do not clearly fully describe the processes that occur in many channels such as armouring. Therefore, the model represents sediments by a mean diameter D_{50} and a complementary parameter, the standard deviation σ. The standard deviation is assessed as the square root of the ratio between D_{84} and D_{16} (Paquier 2003). The most significant changes of riverbed geometry occurs during high flows. The flood events should be modelled in a detailed way to assess the main morphological changes. Hence, unsteady flow modelling should be possible. The unsteadiness may be linked with the characteristics of the flow linked with the evolution of the riverbed during the flood itself. Coupling of sediment transport modelling and flow modelling are thus necessary. And in this point the difficulties of calibration of a sediment transport model, that generally depends on the measurements performed before and after the flood event only, appears. The main questions remain at the scale of the whole reach of a river for which the river flow can be described by a 1-D model. It implies that, in most cases, a 1-D sediment transport model is the more relevant; it takes into account a smaller set of parameters, which also means a simpler way for model calibration (Paquier, 2003). In the current research erosion and deposition processes location through the river channel as a result of the sequence of flows is examined. Data requirements for the model are modest, involving only a few parameters. Thus, the models are relatively easy to calibrate and to implement. Thus, 1D model is sufficient.

Monitoring the studied area was carried out by the team of the Institute of Water Engineering and Water Management. The initial and boundary conditions for the study cases are as follows:

- the initial condition for equations of water: for time $t=0$: $Q_1=Q(t)=const$, $z = f(x,t)$, $q_r=f(x)$
- the initial condition for equation of sediments is the initial geometry of cross-section in time t=0, with the assumption of steady flow throughout the whole reach in time t=0.

The boundary conditions:

- left boundary condition: the sediment discharge corresponds to the hydrograph of water flow for x=0, $q_r=f(Q,t)$, left terminal interval is prolonged by the value $\Delta x_{1,}$ behind the experimental river reach. for x=0: $z = z(t)$, $Q = Q(t)$ – flow hydrograph, $q_r = q_r(Q,t)$ – sediment transport quantity incoming to the experimental reach, $\Delta z(Q,t)$ – increment established in the right terminal cross-section,
- right boundary condition: the uniform flow, with interval prolongation behind the experimental river reach, for x=L: $z = z(Q, t)$ – from the right boundary condition, as: $z_L=(Q,t)$, $q_r=f(x,t)$ – established increment, $z(Q, q_r, t)$ – established increment in the left terminal cross-section.

RESULTS OF COMPUTATION AND ANALYSIS

THE CASE OF KRZCZONÓWKA STREAM

Preliminary work on the lowering of an existing check dam on the Krzczonówka Stream was begun in 2013. Finally, in 2014, the check dam was lowered, redesigned, and rebuilt as a cascade. Downstream from the modified dam, man-made nine riffles were constructed in the stream channel, in order to reduce the excessive, downward slope of the stream bed. During re-opening the body of the dam, the flood event of recorded discharge 164 m^3s^{-1} (according to Institute of Meteorology and Water Management) has appeared. The sediment was supplied from the upstream section of the channel, which lies upstream of the check dam. Field measurements in the channel of Krzczonówka Stream after a flood event showed that most part of stream channel reaches became covered with a thick layer of sediment. Deposition is currently the primary process shaping the stream channel downstream the dam (Lenar-Matyas *et al*. 2015). In Fig.3 there are pointed out erosion and deposition processes measured after flood event. Looking throughout the longitudinal profile of the studied stream channel (Fig.3), it can be noticed that the stream bed elevation has increased along almost the entire reach. The thickness of deposited sediment ranged from 0.20 up to 0.8 m throughout the reach. The local erosion is observed in 1.45 and 1.85 km of the reach only. It means, that the whole mass of sediment covered the stream channel below the lowered check dam. The material, set in motion, was transported down the stream, which caused certain changes, including the fact that the streambed level was raised at the Krzczonów gauging station. It was noticed in the values of lowest annual water stages established for 2015, 2016 and 2017 that the values of lowest annual water stages are about 50 cm higher than those recorded in previous years. This indicates that the bottom has increased in this section by about 50 cm (due to Institut of Meteorology and Water Management).

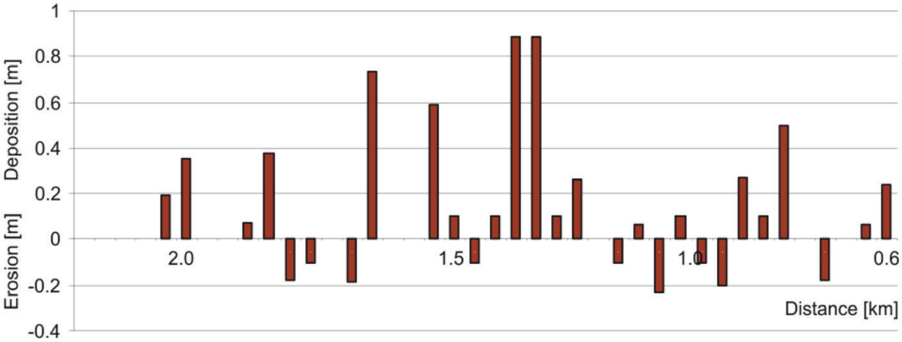

Figure 3. Bottom level changes at the studied Krzczonówka stream course after the flood event in 2014.

The question is when the stream channel will reach their hydrodynamic balance and the sediment will be transported throughout the stream course downstream unblocking the channel for the flood flows. In order to study the above question, the continuing field observation and computations were carried out. Computaion was carried out on the base on as the initial geometry of cross-section measured after flood in 2014 and for daily water level readings using the stream gauge in the Krzczonówka channel (period: June 2014 – September 2016: discharges shaping the channel only taken into account). Calculation results summarizing the lowest value of riverbed elevation, both those measured in September 2016 and values based on model calculations, are plotted on a graph (Fig.4), including the magnitude of erosion and accumulation of material at cross sections in the Krzczonówka Stream channel, both values measured in the field and values calculated based on the studied model. The simulation was carried out for the discharges of the period: June 2014 – September 2016. The field measurements of cross-sections' geometry taken in September 2016 show no significant effects on change in channel geometry. The subsequent discharges in 2015 and 2016 were lower than 23 m^3s^{-1} (according to Institute of Meteorology and Water Management). The changes of geometry are visible, but not high, comparing to 2014. The process of deposition is still observed mostly throughout the studied reach (Fig.4). Results of numerical simulation were examined if data from modeling correspond to the real data obtained in field measurements (Węglarczyk 2010) and if data is statisticaly similar (Moriasi *et al.* 2007). Nash-Sutcliffe efficiency (NSE) equal 0.407 means that it is acceptable level of performance (Fig.4). Pearson's correlation coefficient and coefficient of determination for obtained results ofcomputation are acceptaptable as well (Fig.5B),

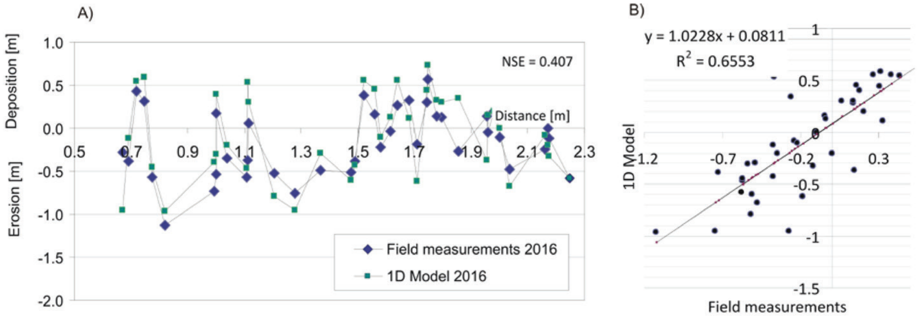

Figure 4. A) Bottom level changes at the studied Krzczonówka stream course in the years: June 2014 – September 2016 – measured and simulated by 1D model, B) correlation coefficient showing how 1D model fits field observations.

THE CASE OF TRZEBUŃKA STREAM

In 2015 the check dam lowering and reconstructing on Trzebuńka Stream caused the continuity of the stream restoration (AB OVO Tarliska Górnej Raby, 2011). The dam's overspill was lowered by 4.0 meters, and the structure below was changed into rapids of boulders embedded in a concrete structure (so-called „grouted rock"). The whole structure constituting 12 small reservoirs for water is currently a kind of fish pass way, (AB OVO Tarliska Górnej Raby, 2011). The main difference of the structure reconstruction was the way of sediment removing from the upstream reservoirs: in the case of Krzczonówka the whole mass of sediments was carried out from the reservoirs taken by flood wave; whereas in the case of Trzebunka the sediment was removed mechanically and did not feed the channel downstream the dam.

Due to the fact that below the check dam the stream channel is rocky with a small amount of stones and gravel, there is no change noticed after the dam lowering. There is no sediment supply from the upstream, because it has been removed outside the valley. Whereas, above the dam, a progressive process of backward erosion is observed. Comparing the condition of the channel from 2015 with the state of 2016, the accumulation of sediment directly above the reconstructed dam is observed. This process may be related to the newly formed channel as a result of engineering works. And the process of backward erosion on a section located about 100 m from the dam and upstream is observed (Fig.5).

The former check dam, as a typical hydraulic structure, which permanently blocked the stream channel and the valley, interrupted the continuity of the fluvial system and changed the longitudinal profile of the channel.

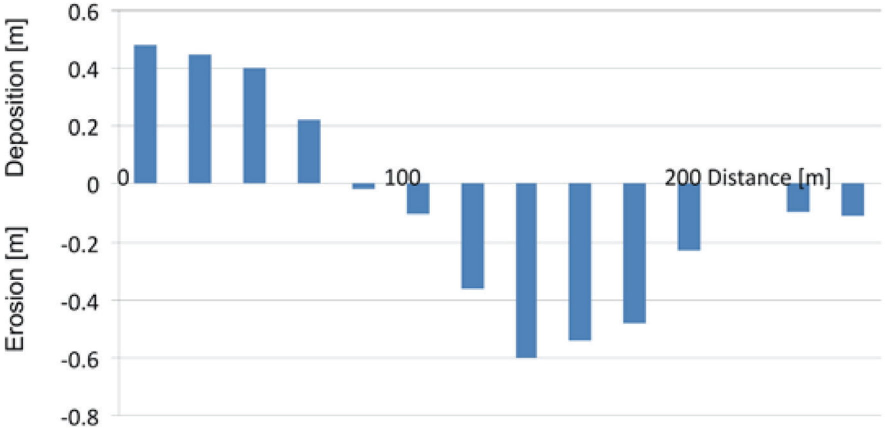

Figure 5. Bottom level changes at the studied Trzebuńka stream course upstream the check dam in the years: September 2015 – September 2016.

Currently, the reach upstream and downstream the reconstructed structure creates a new fluvial system. The question is: how long will the new equilibrium be achieved over time (Stanley et al., 2002)? At present, sediment can be supplied from upstream the check dam coming directly from the process of bank erosion. Hence, it can be expected that the Trzebuńka's channel downstream the check dam will rebuild its sediment base and over time the habitats of fauna will be recreated. In turn, on the course located upstream the check dam there is a hazard of the intense uncontrolled bank erosion becoming active.

THE CASE OF ISEPNICA STREAM

The question is: how to develop existing check dams whose technical condition is bad and their reservoirs are filled with sediments? And how to restore the maintain of hydromorphological continuity in the stream channel?

The hypothetic simulation of gradual check dam lowering has been done for the case of Isepnica Stream, because as it was shown above, the removing all the sediments accumulated in the reservoir makes the drastic changes of hydrodynamic balance upstream and downstream the construction. The proposed methodology of lowering the overspill of the construction by stages is studied. The first step is to cut out the upper part of the overspill by 2.0 metres (Fig.6). The field measurements show that the upper layer in the reservoir is a 2m-deep layer of 0.4 – 0.2 m diameter boulders. Because the reach just behind the check dam is almost horizontal and the upper layer has a high resistance to flow, removal the sediments from the upper part of the sediment-layers must be done manually. The next part of work is gradual lowering by 1.0 metre each half of the overspill and let the flood waters remove the sediments. To achieve the state of the project demand, the gradual lowering has to continue up to the required level. Then, it is time to re-construct the body of the dam due to the project. In the current paper the overspill gradual lowering simulation is presented for the check dam located at 2+570 km of Isepnica Stream reach. The first simulations presented in the paper are made for the following case: the hydrograph with Q_{max}=41 m^3/s, 31 natural cross-sections, lowering the overspill by 2.0 m and taking away the sediments mechanically, lowering half of the crest by 1.0 m, lowering second half of the crest by 1.0 m, computing for the state after previous lowering the overspill (no other lowering).

The first simulation has been made for the flood wave ($Q_{10\%}$) and for lowering half of the overspill by 1.0 m. The results show strong movement of the sediments, with high deposits and erosion in the particular cross-sections (Fig.6). In the cross-section just behind the check dam process of erosion (about 0.35 m) has appeared. A great amount of sediment has been moved forward from the back of the reservoir. Downstream the dam the erosion is observed as well. Next, the second part of the overspill has been lowered by 1.0 m and the simulation has been carried out for the same flood wave. The sediments have moved significantly, especially throughout the reservoir. And the great amount of sediment mass moved downstream the check dam, there is observed deposition at the distance of 200 m. Afterwards, the simulation has been made for the state obtained after the last case. The results show, that in the reservoir there are no significant changes of the terrain. Downstream the check dam the process of erosion and deposition is rather slight (Fig.6). That state makes it possible to begin the next step of gradual lowering of the overspill by 1.0 m like it was made before.

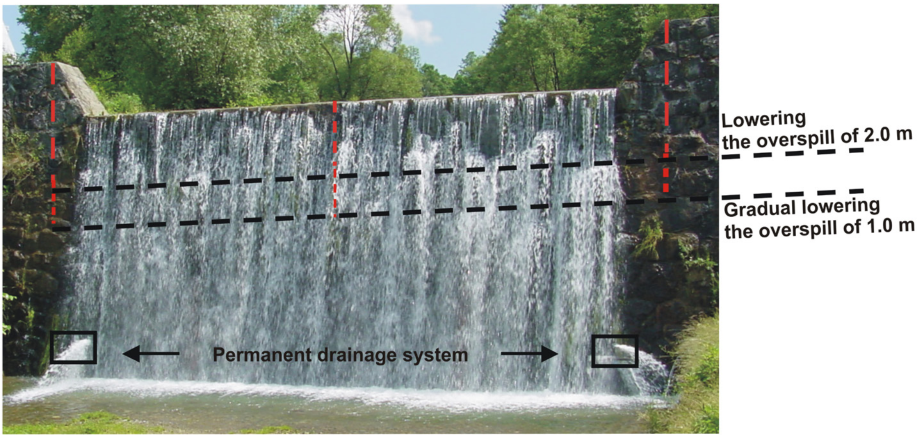

Figure 6. The scheme of check dam lowering methodology.

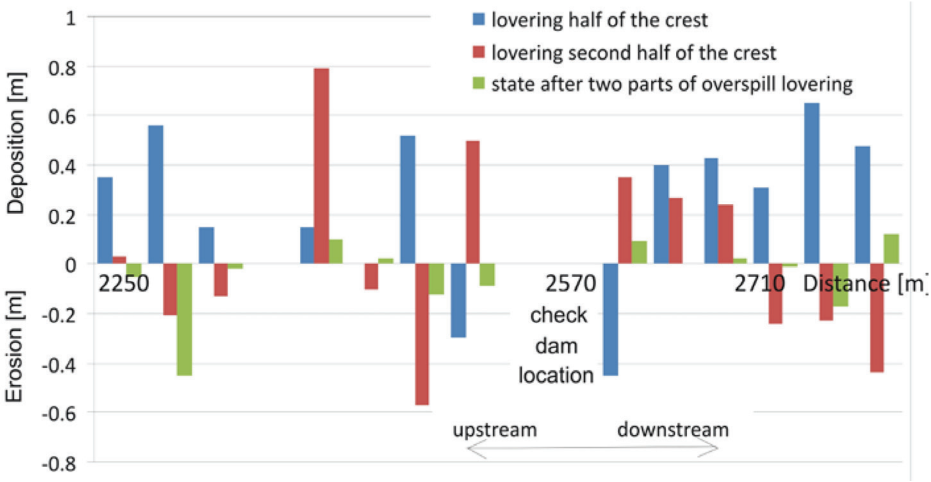

Figure 7. Bottom level changes at the studied Isepnica stream course upstream and downstream the check dam.

The results of first simulation show that the 10-year return period – flood wave removes the sediments with the maximum thickness layer equal 1.0 m throughout the reservoir. However, it is too rare a flood of $Q_{1\%}$, and it is no time to wait for rare floods each time we lower the overspill: that is why in the current study the effect of smaller floods was tested. It is important to mention, that the above simulation is hypothetic without any possibility to verify the results on the field measurements. Model used the same Manning-Strickler parameter as in the case of Krzczonówka which has been verified (Fig.4).

DISCUSSION

Many check dams of different size have been lowered or demolished all over the world (Gleick *et al*. 2009). However, still there are no answers to the many questions regarding the reaction of the river channel to such an intervention. The problems that are discussed include the rate of transfer of sediment deposited in the given reservoir (Shuman 1995) and the effects of the lowering of the erosional base for the channel reach upstream of the dam (Doyle *et al*. 2003). Therefore, the activities concerning the migration barriers removal, as one of the few cases of a few meters reduction and rebuilding of the check dams, can be considered as a kind of field experiment. In the international papers, the local cases of liquidated or reduced and rebuilt check dams of various sizes are described only (Artiges *et al*. 2006, Malavoi *et al*. 2005). The cases of Krzczonówka and Trzebuńka streams, where the method of removing sediment from reservoirs was different, showed that the sudden change of „established" hydrodynamic conditions for decades is not favorable for the stream. The degree of diversity of river channels that form in the long term, after the lowering of check dams, is the resultant of performed works and rainfall events, which follow project completion (Stanley *et al*. 2002). This is especially true of gravel bed streams channels, in which the processes shaping the channel are initiated rarely, only during large flood events. The research performed so far proves that the lowering of a dam may be followed by different reactions of the stream channel upstream from the dam, depending on local conditions (Doyle *et al*. 2003). Downward erosion is most frequently reaction of the river to the process of lowering of the erosional base – if the process lasts for a short period of time (the case of Trzebuńka). The progress of the above described processes, which may occur due to the lowering of a check dam, may now be monitored. This is currently done based on observations and measurements performed in the field. The examples described above show that it is sensible to modify both existing and improperly working dams, although it should not be done on a mass scale, because every facility requires an individual, thoughtful approach to design along with careful analysis. It is possible to lower the construction of check dam and remove sediment from its reservoir in a way that does not have a drastic impact on the hydrodynamic balance of the stream channel. However, as it was shown in the case of Isepnica Stream, it is very complicated task.

CONCLUSIONS

The main purpose of check dams construction in the Polish part of the Carpathian Mountains was to trap sediment being transported downstream. At present, the reservoirs of most check dams are already fully filled with sediment, and the impact of these structures on the ecosystems of streams is unfavorable (no sediment movement, channel reaches separating, mostly no pass ways for fish). Moreover, mostly the constructions are in poor technical condition. There are some ideas of restoring or developing the structures to maintain them for hydromorphological continuity in the stream channel. The cases of Krzczonówka and Trzebuńka Streams are the examples of lowering of the check dams and creating a cascades consisting of "steps" of appropriate height, making migration of aquatic organisms possible. However, these cases, where the method of removing sediment from reservoirs was different, showed that the sudden change of „established" hydrodynamic conditions for decades is not favorable for the stream. The results of hypothetic simulation of gradual check dam lowering for the case of Isepnica Stream leads to the conclusion that lowering the construction of check dam and removing sediment from its reservoir in a way that does not have a drastic impact on the hydrodynamic balance of the stream channel is possible. However, as it was shown in the case of Isepnica Stream, it is very complicated task. The idea requires further detailed studies.

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