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ANALYSIS OF IN-STREAM RESTORATION STRUCTURES IMPACT ON HYDRAULIC CONDITION AND SEDIMENTATION IN THE FLINTA RIVER, POLAND

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Abstract: In the paper usefulness of one dimensional model for restoration purposes was investigated. The sediment model of downstream part of the Flinta River (Western Poland) was prepared using HEC-RAS 5.0.0. The set of deflectors, which was implemented as constrained cross-sections, was analyzed. Computations were carried out for three formulas for intensity of sediment transport: Yang, Ackers-White and MPM-Toffaleti. Two geometry variants were tested: without modifications of the channel and with deflectors. Moreover, within geometry with structures, two variants of markers for mobile beds were distinguished, where at the location of structures erosion was allowed (variant A) or blocked (variant B). The obtained results showed different responses of each formula in relation to inflow hydrographs, and impact of deflectors on sediment transport processes. At the bank opposite to structures obtained erosion while, in the location of structures, there was erosion (variant A) or deposition (variant B) of sediment. Additionally, analysis of maximum values of shear stresses indicated high peak values for variant B. Basically, results were consistent with other studies with deflectors however, the size and length of the scour, which are crucial during designing these structures, were not obtained. For this reason, one dimensional model was considered as insufficient to planning restoration measures, as simplistic information about impact of structures was not enough. The main practical output of our research is showing the limits in application 1D models to analyze simple river management hydraulic structures.

Keywords: river restoration, in-stream deflectors, hydraulic models, one-dimensional models, sediment transport processes.

1. INTRODUCTION

The most severe changes in riverine ecosystems occurred during the Industrial Revolution and continued into the 19th and 20th centuries (Roni & Beechie, 2012). Intensification of urban and agricultural activities led to fragmentation of water ecosystems by migration barriers like dams, weirs, rails and roads. Industrial development and population growth resulted in an increased amount of pollutant entering the watercourses and channelization of rivers (Roni & Beechie, 2012; Gore 1985). Accumulation of these factors led to a decline of several migratory fishes in Europe and North America. This was an impulse to action. In 1885, measures related to the protection and restoration of trout streams in the Eastern USA, were undertaken (Van Cleef 1885). Currently, river restoration is a basic action used to improve the water status, because there few rivers with natural character left (Walega & Mlynski, 2017). The maintenance of a good ecological state is contained in provisions of the Water Framework Directive (WFD), a unifying management of water quantity and quality for the entire European Union. This guideline, with other EU directives, provides support to conduct restoration actions (Roni & Beechie, 2012; Dufour & Piegay, 2009; Pan et al., 2016).

River restoration needs a comprehensive approach, including engineering tasks, e.g. methods for the prediction of hydraulic, hydromorphological and ecological restoration outcomes (Bockelmann et al., 2004). Such opportunities are given by hydraulic and ecohydraulic modeling (Elkins et al. 2007; Miwa & Parker, 2012; Gibson & Pasternack, 2016; Greene et al., 2013; Guo & Zhang, 2016; Laks et al., 2017; Matisziw et al., 2015; Papanicolaou et al., 2011; Rana et al., 2017; Yi et al., 2014). Models can be used in two ways. First, those may forecast past and future conditions in the riverbed and at the floodplains, what may give overall notion about whole system. Secondly, more specific changes caused by restoration measures and techniques may be assessed before implementation. Both are important during planning restoration actions and during development of model of ecological responses, which define the aim of restoration (Hobbs & Harris, 2001; Palmer et al., 2005; McDonald et al., 2016). There are a few examples of ecohydraulic models, which present prediction of restoration outcomes. Clilverd et al., (2016) used coupled Mike SHE/Mike 11 hydrological/hydraulic models to predict changes caused by embankment removal. To achieve restoration impact, he considered two options: pre-embankment and post-embankment conditions of an analyzed channel. Bockelmann et al., (2004) developed an ecohydraulic model composed of 1D HEC-RAS/2D DIVAST models with a PHABSIM habitat model to predict distribution of two species of macroinvertebrate habitats caused by restoration measures. Also, Chou & Ming (2011) used a two-dimensional habitat model (Rriver2D) to predict the weighted usable area for target species before and after modified spur dikes.

The problems of hydraulic models may lie in definition of small hydraulic structures used for river restoration purposes, like in-stream deflectors. Those are traditional static habitat improvement structures (Roni & Beechie, 2012; Kuhnle et al., 1999; Rosgen 2001; Thompson & Stull, 2002). Deflectors are used to recreate meanders and create pools and riffles (Roni & Beechie, 2012; Gore 1985; FISRWG 2002; O'Grady 2006; Seehorn 1992; Shields et al., 2003). In general, those provide hydraulic, habitat and morphological diversity (Downs & Thornre, 2000; Żelazo & Popek, 2014). Investigations about changes caused by deflectors were performed. So far, studies were concerned mainly with flow dynamics (Biron et al., 2005; Biron et al., 2012; Haltigin et al., 2007; Carré et al., 2007; Zhou & Endreny, 2012), however the sediment transport analyses were also needed, as this remain a critical aspect of stream rehabilitation design (Bhuyian et al., 2009; Shields et al., 2003) and provide information for sediment management strategies (Beckers et al., 2015). The size of the scours caused by deflectors was analyzed in laboratory conditions (Biron et al., 2005; Zhou & Endreny, 2012; Pagliara & Kurdistani, 2016), during field measurements and finally with model simulations (Carré et al., 2007; Bazin et al., 2017; Thompson 2002). The studies revealed relation between angle of the structure and size of the scours (depth and volume) (Biron et al., 2005). Additionally, Zhou & Endreny (2012) investigated changes induced at meanders. The researchers observed erosion around deflectors and at the opposite bank, while deposition occurred downstream to the structures (Biron et al., 2005, Pagliara et al., 2016).

To sediment transport calculations 3D models were used. Those very precisely reflect conditions around the structures and its geometry (Biron et al., 2005; Haltigin et al., 2007; Carré et al., 2007; Zhou & Endreny, 2012). However, for large-scale restoration projects 3D models may be too time and cost-consuming, especially in case of long reaches. Additionally, input data for 2D and 3D models require higher accuracy and more complicated pre-processing, what may limit utilization of hydraulic modeling in practice. Restoration projects very often consider several different solutions, thus those have to be analyzed comprehensively and it is possible only with some simplifies. For this reason, the main aim of our paper was study the usefulness of 1D sediment model in river restoration, in opposite to more precise 2D and 3D models. The accuracy of output parameters indicating the impact of deflectors was analyzed. Firstly, to solve a problem with definition of small in stream hydraulic structures, we choose set of deflectors, which was introduced into the model as modifications of cross-sections. Secondly, to observe sediment transport process and scouring, additional cross-sections at the edges of the deflectors were introduced. Simulations were performed using HEC-RAS 5.0.0 software with three formulas for the intensity of sediment transport: Yang, Ackers-White and MPM-Toffaleti. We tested two calculation variants: (1) the channel without deflectors, and (2) after introducing structures. Moreover, within geometry with deflectors, two variants of markers of the mobile bed were analyzed. The main practical output of our research was showing the possibility of application 1D models to analyze of simple river management hydraulic structures (wooden low head hydraulics deflectors in our case) which might significantly change river bed morphology and have the influence on fluvial processes.

2. CASE STUDY

The case study is the Flinta River, which is located in the Wielkopolska region, Poland. This watercourse is a right tributary of the Wełna River. The Flinta River disembogues to the Wełna in the village of Rożnowo-Młyn in the municipality of Rogoźno. The total river length is approximately 27 km, and the catchment area is equal to 345.47 km^2 (Fig. 1a). Along the Flinta River, several hydraulic structures are located: 6 weirs, 9 bridges and 2 thresholds. In terms of topology and in accordance with guidelines from the Water Framework Directive, the Flinta River represents a sandy lowland stream. The structure of land use shows that in the areas adjacent to the river, grassy vegetation, coniferous and mixed forests and arable lands dominate. The cross-section with the water gauge is located at 15 km along the river in the village of Ryczywół. The watershed area to this cross-section equals 251.00 km^2.

The Flinta River is a representative example of the majority of lowland Polish rivers, which in the 19th and at the beginning of the 20th century has undergone significant modifications (Paluch 2009). The technical regulation, hydraulic structures and the ongoing maintenance treatments have resulted in several sites becoming IV class (significantly modified) of hydromorphological state (according River Habitat Survey method) (Jakubas et al., 2014; Szoszkiewicz et al., 2011; Raven et al., 1998). One of these sites is located in the downstream part of the analyzed reach, above a bridge in village of Rożnowo-Młyn, as shown in figure 1b. This reach is locally straight, deep and shows little variety. The deflectors would promote the creation of pools and riffles within the channel and would also improve the habitat state of the river.

The analysis was performed for a length of 1.8 km. The beginning of the reach was located below the weir Piłka-Młyn and the outlet in the estuary. The reach is characterized by large slope 1.09‰. Additionally, on 24th September 2016, the first perpendicular deflector was introduced into the channel.

3. MATERIALS AND METHODS

3.1 Materials

The model of the analyzed Flinta River reach was constructed with four types of data: (1) a digital elevation model (DEM), (2) river geometry data, (3) hydrological data and (4) sediment samples. The digital elevation models were obtained from the Geodesic and Cartographic Documentation Centre (CODGiK). The resolution of the DEM was 1 m x 1 m

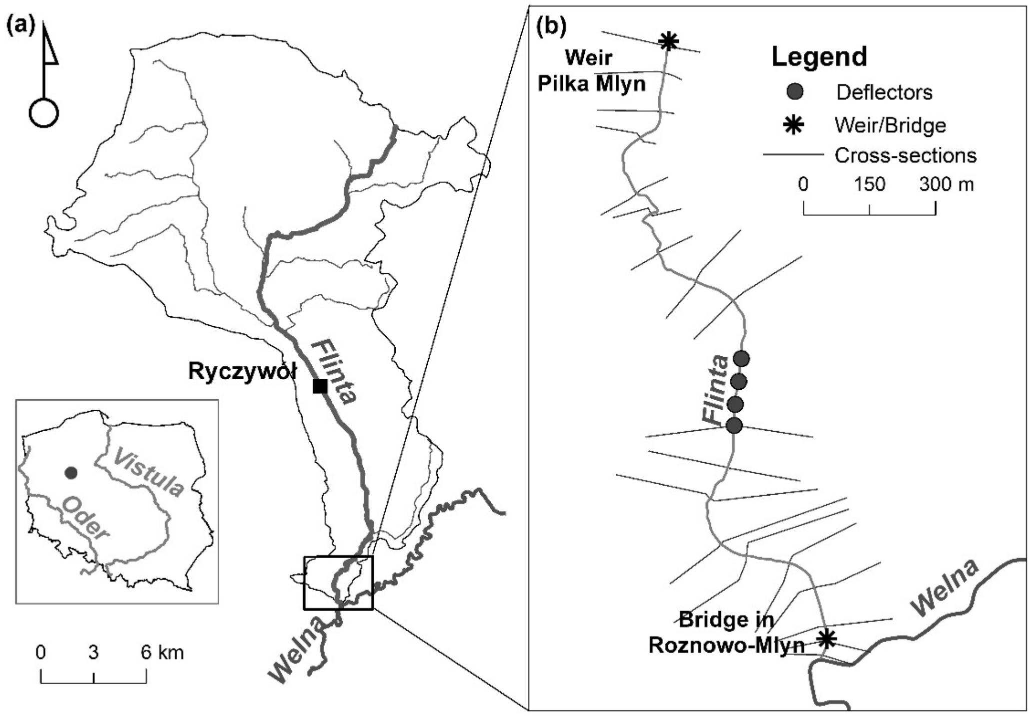

Figure 1. Location of the (a) watershed and (b) analyzed reach of the Flinta River.

with a vertical accuracy of 0.15 m. The DEM was complemented by measured ordinates of the bottom.

Hydrologic data were obtained from the Institute of Meteorology and Water Management National Research Institute (IMGW-PIB). In the analysis, observations at the Ryczywół gauge station were used. To prepare daily flow hydrographs for uncontrolled cross-section (inlet cross-section of the analyzed reach), values were calculated proportionally to the catchment areas. To the calibration, data during the period of 01st January 2016 to 16th June 2017 were used. In the final calculations, data from the period 1951-2015 were applied.

The last type of data was sediment granulation. During field measurements, three different samples of sediment were collected and processed according to sieve analysis rules: "D", "D+" and "D-". Granulation of the samples was similar and the largest fraction in each was sand (Fig. 2). To the analysis was used sieve curve, which gave the best match during calibration.

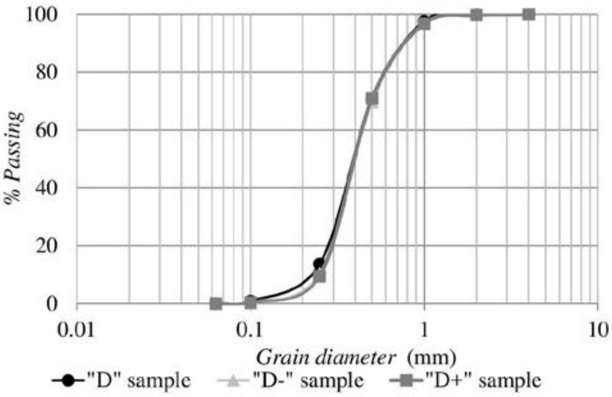

Figure 2. Sieve curve of the sediment samples collected in the Flinta River.

3.2 Methods

The main elements of the applied methodology were as follows: (1) methods implemented for the preparation and calibration of the hydraulic model and (2) methods applied for the organization of simulation scenarios and comparison of results. The basic element of the presented approach was the simulation model, namely, HEC-RAS 5.0.0 (Brunner 2016).

3.2.1 Calibration of hydraulic model

In the first step, geometry was prepared. The spatial data were connected using GIS tools (ArcGIS 10.3, overlay HEC-GeoRAS) and features of the HEC-RAS 5.0.0. software. Parameters of the bridge located in village of Rożnowo-Młyn were also introduced into the model. The bridge width was equal to 12.56 m and elevations of low and high chords were 58.60 and 59.30 m a.s.l. The total length of the model reach was about 1800 m. The number of cross sections was 18 with a 100 m average distance between each of them. The average cross section width was about 200 m. This prepared geometry was used to calibrate roughness coefficients along the analyzed reach (Gibson et al., 2017). Water surface elevations were measured at the same time as the cross section used for the calibration, on February 2016. The water level was compared in 12 cross sections. It was assumed that the difference between observed and calculated water surface elevations had to be lower than 10 cm (Borowicz et al., 2009). The obtained values of roughness coefficients were taken for further computations of sedimentation.

The most important element of HEC-RAS 5.0.0 in our analyses was sediment routing. Taking into account the purposes of the present study, the quasi-unsteady flow model was a sufficient basis for the simulation of long-term river bed changes. This algorithm is based on the assumption that the time scales of the two processes, flow and sediment transport, are different (Cao et al., 2011; Cao et al., 2007). Hence, the description of flow may be simplified to fit the scale of sediment routing to long-term computations. The sediment transport simulation is based on the numerical solution of the well-known Exner's equation (Brunner 2016; Wu 2007). The equation describes the mass balance of sediment, taking into account changes in riverbed elevation and sediment net inflow. Exner's equation must be completed with the empirical formula for the calculation of sediment transport intensity. HEC-RAS includes eight sediment transport functions. Each of them is applicable for specific grain sizes (Brunner 2016). For this reason, during the calibration the following formulas for sand material with share of gravel fraction were considered: Ackers-White, MPM-Toffaleti, Yang and Wilcock-Crowe.

The calibration was performed on the basis of cross-sections measured on September 2016 and June 2017. The geometry based on measurements from September 2016 was the initial one for the calibration. The sediment module of HEC-RAS doesn't work with the structures module, and for this reason, the bridge in village of Rożnowo-Młyn was reconstructed using proper modification of river cross-sections. In the same way, a wicker deflector was also introduced. Calculations were performed for the daily flow hydrograph for the period 24th September to 16th June 2017. During the calibration, three collected sediment samples were considered. Differences between observed and simulated elevations were calculated using longitude profiles.

On the basis of mean square error, three formulas for intensity of sediment transport were chosen for further analysis.

3.2.2 Final analysis

In the final calculations, the impact of a set of deflectors on sediment transport processes was analyzed. In the analysis, two geometries were tested: (1) without structures and (2) with deflectors. The second geometry was created on the basis of the first by modifying particular areas of the channel bed. The modifications were introduced according to the same concept, which was tested during calibration of the sediment model. The interpolated cross-sections located at shorter intervals were used to properly reconstruct the topography near the deflectors – each deflector was represented by three cross sections, as shown in figure 3. The deflectors were introduced from 714.45 to 860.92 m along the channel. Four structures were inserted alternately over a distance of 50 m. Two deflectors were located on the left bank and the other two on the right. Triangular deflectors were chosen with an orientation of 90°. It has been suggested that triangular deflectors would most effectively direct flow to the center of the channel (Hey 1996) and it was observed that for perpendicular deflectors, scours were the greatest (Biron et al., 2004). The length and the width of a single deflector was 2 m.

For the scenario that used deflectors, markers of the mobile bed area were defined for two ways. In the first variant, referred to as variant A, erosion was allowed within the whole cross section, whereby deflectors were a part of the erodible area. For the second scenario, referred to as variant B, erosion within the deflectors was blocked, as shown in figure 3. In case of deposition, the process was allowed outside of the movable bed limits.

The main sources of uncertainty in this study included inflows and sediment transport formulas. Five inflow scenarios and three formulas selected during calibration were applied. Two types of beds were compared, namely with and without deflectors. Additionally, for geometry with deflectors, two marker locations were considered. The total number of simulations was thus equal to 5×3×3=45. The result of each simulation was a bed profile and cross-section that reflected the applied scenario and assumptions. Taking into account the 10-year hydrographs, the results may be averaged with respect to the initial bed and the formula used. The results can be compared by analyzing the initial bed impact, the significance of the sediment transport formula and marker locations for the mobile bed.

4. RESULTS

4.1 Calibration of hydraulic model

An important step in the preparation of the hydraulic model was calibration of the roughness coefficients. The calibration was performed based on measurements of cross sections and water surface elevations performed on February 2016. On the basis of hydrological data for gauge station Ryczywół, it was estimated that during measurements, the flow was equal to 0.36 $m^3{\cdot}s^{-1}$. This value of inflow was contained in the range of low water levels for the Flinta River. During calibration, it was estimated that roughness coefficients for the channel were between 0.029 to 0.070 $s{\cdot}m^{-1/3}$. At the floodplains, the values were between 0.035 to 0.075 $s{\cdot}m^{-1/3}$.

Calibration of sediment model was performed with four different formulas for intensity of sediment transport processes: Ackers-White, MPM-Toffaleti, Yang and Wilcock-Crowe. The elevations measured on 24th September are referred to as “initial state” and bottom elevations measured on 16th June 2017 as “reference state”. On the basis of differences between the “reference state” and simulated bottom elevations, the mean square errors were calculated and are shown

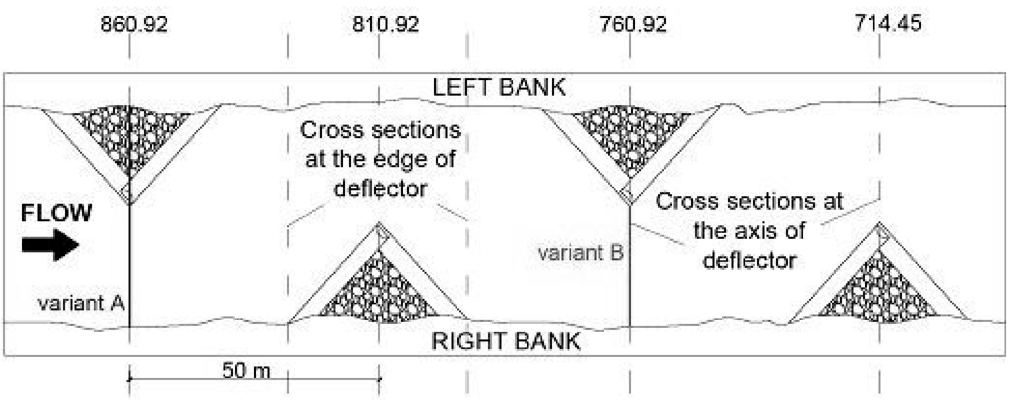

Figure 3. Scheme of location of deflectors along the studied reach of the Flinta River

in table 1. The lowest values of the mean square error oscillated between 0.14 (MPM-Toffalti formula) and 0.18 (Wilcock-Crowe formula). After analysis of the mean square error and bottom profile for the Wilcock-Crowe formula, it was decided to exclude this formula from further analysis. Three out of four of the lowest mean squared error (MSE) values were gained for sample "D". For this reason, only this sample was considered for the scenarios where deflectors were present.

Table 1. Mean square error calculated for analysed formulae for intensity of sediment transport and collected sediment samples.

Formula	Mean square error (m a.s.l.)			
	Sample "D-"	Sample "D"	Sample "D+"	The lowest value
Ackers_White	0.16	0.15	0.15	0.15
MPM-Toffaleti	0.14	0.14	0.14	0.14
Yang	0.15	0.15	0.15	0.15
Wilcock-Crowe	0.18	0.18	0.37	0.18

4.2 Impact of set of deflectors

In the final analysis, the impact of the deflectors on sediment transport processes was considered. Analysis was performed for three different formulas for intensity of sediment transport, five random inflow hydrographs, two variants of geometry and two locations of mobile bed markers within geometry with deflectors. The obtained result showed different responses of each formula in relation to inflow hydrographs. The biggest differences between scenarios were obtained for the Yang formula (Fig. 4) and the lowest for MPM-Toffaleti formula (Fig. 5). For the Yang formula, the mean difference between extreme scenarios at the location of deflectors was 0.18 m and 0.16 m (for deflector variants A and B, respectively) and 0.17 m (for geometry without deflectors). For the MPM-Toffaleti formula, the mean difference between extreme results was 0.07 m and 0.06 m (for deflector variants A and B, respectively) and 0.06 m (for geometry without deflectors).

To analyze the impact of deflectors on sediment transport processes, analysis based on cross sections was needed. On the basis of comparison between geometries with and without structures, the analysis showed that deflectors have an impact on sediment transport processes. For three of four locations, there was erosion of the bank opposite to the deflector. Only within the deflector in location 810.92, erosion of this part of the bank did not occur. Erosion occurred for both variants of markers of the mobile bed. For geometry without structures, these processes were not observed.

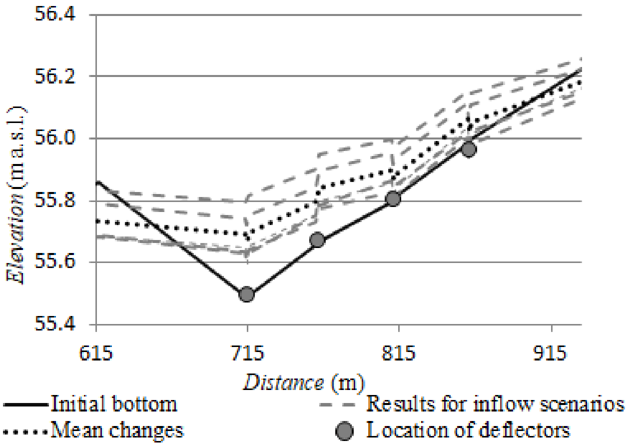

Figure 4. Changes of bottom elevations at the location of deflectors obtained with Yang formula for geometry with structures (variant A of markers).

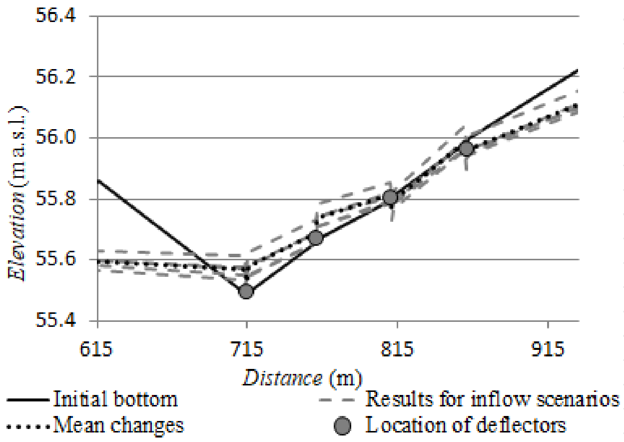

Figure 5. Changes of bottom elevations at the location of deflectors obtained with MPM-Toffaleti formula for geometry with structures (variant A of markers).

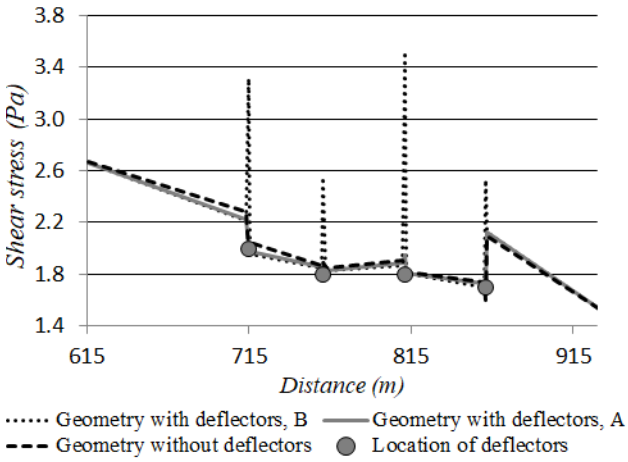

Figure 6. Maximum values of shear stresses, which occurred for analyzed geometry variants with Ackers-White formula.

The results obtained for two variants of markers of the mobile bed differed significantly at the location of the deflectors. In variant A, in which erosion was allowed at the location of deflectors, erosion occurred at the location of the structures. In variant B, locations of deflectors were excluded from the mobile area and at the deflector locations, deposition of sediment was observed. These differences were observed for all cross sections with deflectors. Analysis of maximum values of shear stresses (averaged for whole cross-sections) indicated high peak values for variant B (Fig. 6), what may be caused by rigid constriction of the cross-sections. As a result, stronger erosion of the bank opposite to deflectors was observed for variant B. The area around the deflectors was described by three cross sections. However, changes caused by deflectors occurred only at the cross sections at the axis of the structures, as shown in figure 7.

Such use of deflectors and changes of shear stresses confirm findings done by Mikuś et al., 2016 (also compare in Hajdukiewicz et al., 2016 and Kałuża et al., 2018), where simple river management works done on the Czarny Dunajec River improved hydro-dynamics of the river in a very significant way.

Except for banks, there was no significant erosion within the cross sections. Only in a few cases for the MPM-Toffaleti and Ackers-White formulas, bottom erosion was observed. However, the changes between initial and simulated elevations were equal to only a few centimeters. This indicates that no significant scour was created around the deflectors. Such results were obtained for both variants of the markers of the mobile bed. Moreover, bottom deposition of the sediment was observed (e.g. for all cases calculated with the Yang formula). The small differences between erosion and deposition within cross-sections are indicated by the total sediment mass movement. Since bankfull discharge is important in such case studies because it is a shaping channel kind of discharge responsible for the river channel morphology (Radecki-Pawlik 2002; Radecki-Pawlik & Skalski, 2008; Radecki-Pawlik 2015), we calculated sediment load here and compared with inflow sediment load at the deflector's place. With the bankfull discharge equal 2.65 m^3/s, amount of sediment leaving the sediment control volume exceeded slightly the inflow sediment at the location of deflectors (Fig. 7) thus bankfull might be treated here as a channel shaping flow. The lowest values of the bottom elevations (reflecting scour-deposition and sediment transport relations), in each analyzed case, were always obtained with the MPM-Toffaleti formula, whereas the highest elevations were obtained with the Yang formula.

5. DISCUSSION

In this study impact of set of deflectors on sediment transport processes was analyzed. Two variants of geometry were tested: with and without structures. Moreover, for the geometry with deflectors, two locations of markers of the mobile bed were considered. At the cross sections for the reflected axis of the deflectors, as a function of location of the mobile bed markers, results indicated erosion of the banks (variant A) or deposition of sediment (variant B) at the location of the structures. In the literature, it is well known that deflectors induce local erosion and cause local scouring. It was observed during field measurements, simulations and laboratory experiments (Biron et al., 2005; Biron et al., 2012; Carré et al., 2007; Zhou & Endreny, 2012; Pagliara & Kurdistani, 2016; Thompson 2002; Biron et al., 2004; Radspinner et al., 2010). But in analyzed cases, scouring was not obtained. In variant A, erosion occurred at the bank with deflectors, instead of at the bottom around structures. It was expected that variant B would block erosion of the structure and induce higher changes of the bottom elevations. In fact, erosion within the structures was stopped, but it resulted in more intensive deposition of the sediment instead erosion of the bottom. The results gained for the geometry with deflectors indicated erosion of the bank opposite to the deflectors. This effect was also observed by other researchers. Moreover, deflectors oriented at 90° and 135° were shown to have the greatest potential for bank erosion (Biron et al., 2004).

The results obtained with the two variants are an effect of the constraints related to the one dimensional models. In variant A, the energy caused by the constraints was used to cause erosion of the protruding element of the bank. After blocking structure by using proper markers, modifications of the bank were not treated as constraints, but rather as a normal bank (variant B) hence, erosion of the bottom was also not obtained. Markers would allow only partial erosion within the structure, when it would be possible to locally strengthen of the banks. It was observed in the field that structures, like deflectors, would be washed away. Riprap, as well as framework elements, could be taken (Thompson 2002). Partial erosion may reflect this effect.

Three different formulas of intensity of sediment transport were considered. Taking our analysis and other studies into account, the most

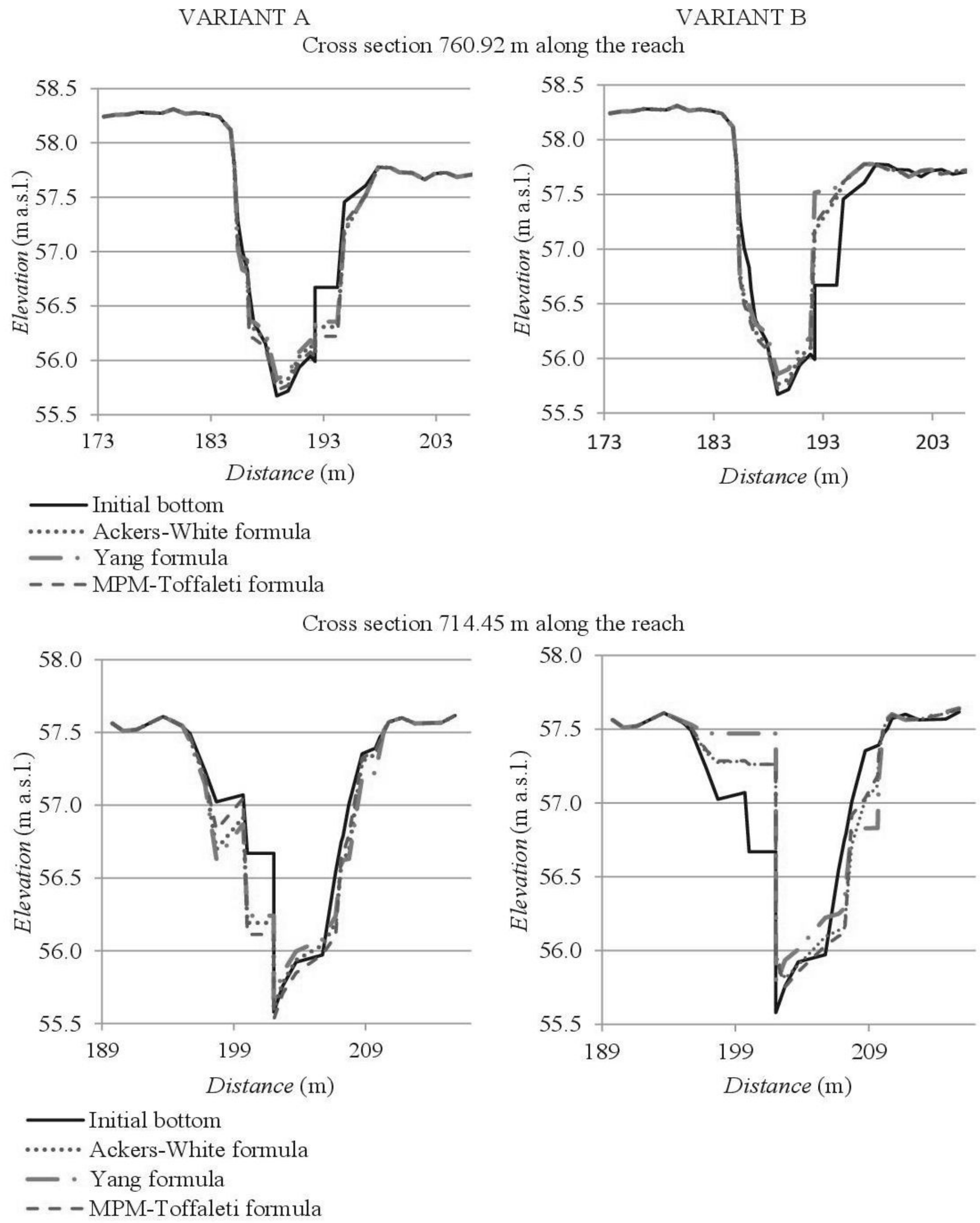

Figure 7. Mean changes of bottom elevations at the location of deflectors for geometry with deflectors, variants A and B.

proper was the MPM-Toffaleti formula. This formula gave the best match during the calibration of the sediment model. Moreover, the results obtained for different inflow scenarios showed the least sensitivity to hydrological data. The intensity of erosion of the banks, as well as the bottom, was the greatest for this formula.

On the basis of obtained results, it was possible to assess usefulness of one dimensional sediment models for river restoration purposes. Results showed that strong erosion occurred at the bank opposite to the structures, which is consistent with other studies with deflectors. However, the information about local souring was not obtained. Although one dimensional model has advantages such as simple boundary designation and easier model calibration, they cannot predict the complex flow field around structures (Bockelmann et al., 2004; Gibson & Pasternack, 2016; Nagata et al., 2005; Niezgoda & Johnson, 2006). Nevertheless, the choice of the dimensionality form of the model depends on the specific river engineering application, in addition to constraints related to time and cost (Carré et al., 2007). Thus, even if one dimensional model remains insufficient to plan restoration structures, those still may be used in large scale-simulations like flooding and debris flow. Such information is still useful during defining model of ecological response.

6. CONCLUSIONS

The effects of river restoration on hydraulic and hydrological processes are complex and are often difficult to determine if there is insufficient monitoring conducted before and after restoration (Kondolf 1995; Hammersmark et al., 2010, Mikuś et al., 2016). Moreover, when planning restoration measures, induced changes within the channel should be known, and this information can be provided by modeling (Bockelmann et al., 2004; Hammersmark et al., 2010, Hajdukiewicz et al., 2016).

In this study, we analyzed the impact of a set of deflectors on sediment transport using one dimensional modeling and three different formulas for intensity of sediment transport. It was observed that introduced structures had an impact on erosion and deposition processes. The results indicated erosion at the bank opposite to deflectors, which is consistent with other studies. However, information about the depth and length of the scour were not received, although two different locations of markers of the mobile bed were used. For this reason, even if the results showed the proper location of the erosion at the one bank, one dimensional models are insufficient to predict exact changes driven by river restoration measures. However, those should not be rejected definitely, because still may provide other valuable information useful in river restoration problems, e.g. significant changes in river bed when simple low head hydraulic deflectors are implemented to river management works.

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