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Two approaches to forecasting of sedimentation in the Stare Miasto reservoir, Poland

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ABSTRACT: The main idea of the presented paper is a comparison of the two approaches to modeling reservoir sedimentation. The analysis is preformed on the basis of the actual data and simulations performed for the real lowland reservoir, Stare Miasto, located in central part of Poland. Both compared methods are one dimensional. The first is the basic approach based on the sediment routing model described by several transport formulae. The second is a newer approach called the Sediment Impact Analysis Method (SIAM). The purpose of the analyses presented is evaluation of usefulness of the methods for design of a lowland reservoir. Such elements as (1) sediment distribution along the reservoir, (2) need for geometry update in SIAM, (3) number of computations needed to obtain valuable results, are taken into account. The robustness of obtained results is verified on the basis of comparisons with field measurements. The general conclusions state that the new approach SIAM is very interesting and characterized by huge computational efficiency in comparison with the standard sediment routing model. However, the SIAM method is still not able to provide as reasonable results as the standard one. Hence, further developments in this area are necessary.

1 INTRODUCTION

The aim of the presented research is to compare the two methods for forecasting of sedimentation in a lowland reservoir. The chosen object is the Stare Miasto reservoir on the Powa river located in central part of Poland. Two 1D methods are used for modeling of the sedimentation process. The first is the standard sediment routing model. The second is the Sediment Impact Analysis Method (SIAM). The implementation of the methods and the obtained results are compared and discussed. The analysis is made taking into account the usefulness of the methods for design of lowland reservoirs.

One of the main problems related to the assessment of reservoir sedimentation is effective simulation of this process. The most popular of 1D/2D models describing sediment transport and deposition are based on the same construction as flood wave propagation models (e.g. Papanicolaou et al., 2008). The fundamental conservation laws are integrated in a relatively small control volume under several assumption. The most important are short time intervals and continuity of all parameters in the resulting partial differential equations (e.g. Wu, 2008). Such models work well for relatively short time flood phenomena of duration from one week to two months at most. The duration of reservoir sedimentation phenomena is much longer, from a few to fifty years. The time steps, which guarantee the stability of computations are too small to perform such simulations effectively. The problem of different time scales was noticed and described in the papers written by Cao et al. (2007) and Cao et al. (2011). The additional side of the problem is huge uncertainty of parameters describing the features of the sediment transport model (e.g. Bogardi et al., 1977; Salas & Shin, 1999). Hence, such models may be properly calibrated and validated only when confronted with the existing reservoirs. During the design process, the forecast of sedimentation over long period requires repetition of simulations taking into account variability of inflows as well as uncertainty of parameters.

The problems with effectiveness of sediment transport simulations lead to simplified approaches. There are numerous examples of them in the scientific literature varying from more physically based models, e.g. Rahmanian & Banihashemi (2011), to those based on black-box idea, e.g. Yitian & Gu (2003), Nourani (2009). One of the most interesting approaches seems to be the so-called Sediment Impact Analysis Method (SIAM). The method was developed by Mooney (2006). The primary idea of this approach is the sediment budget tool, balancing the sediments inflows from watershed to the river. The computations of sediment aggradation and degradation are made along one dimensional river reach. Although, there is no update of geometry related to sediment transport results, the construction of the method seems to be applicable to the problem of reservoir sedimentation.

The idea of this paper is to compare the performance of the standard sediment routing model with that of the simplified SIAM one. Several scenarios of the sediment routing model are processed and then compared with the results of SIAM. The assessment is made taking into account the sediment distribution along the reservoir, need for geometry update in SIAM and also the amount of computations needed to obtain valuable results. Finally, the results are compared with direct measurements of geometry in the chosen reservoir.

The paper consists of 5 sections. The first is the introduction. Then the materials used in our investigation are described. In the third section the methods applied are explained. The results are discussed in the fourth section. The conclusions are presented in the last section.

2 MATERIALS

The Stare Miasto reservoir is located on the Powa river in the central part of Poland. The main dam is located to the south of Konin city. The reservoir is a relatively new object, built in 2006. Its length is 4.5 km and the area of inundation in normal conditions is 90.68 ha. The total capacity of the reservoir is 2.159×10^6 m^3, but the capacity used for water supply is 1.216×10^6 m^3. Highway A2 is narrowing the active flow cross-section in the central part of the reservoir. The dam splitting the object into the main and upper part is located upstream of the bridge (Fig. 1). The upper dam includes a small sluice. The area of the upper part is 27 ha. The capacity of this part is 0.294×10^6 m^3 (Woliński & Zgrabczyński, 2008). The depth of the reservoir varies from 1.2 m in the upper part to 5.7 m near the main dam.

The upper part of the reservoir plays a specific role. It is used to collect sediment and protect water quality in the main part from degradation. It is expected that the sediment transported with the inflowing water is settled in the upper part of the reservoir. After some time the upper part should develop conditions good for vegetation growth. This enables the removal of pollutants from water or their deposition with the sediments.

The Stare Miasto reservoir is multi-purpose and works in the annual cycle. The main part of the reservoir is used in ordinary way. It includes water supply capacity, the dead zone as well as the flood protection capacity and the hydraulic flood protection zone. The water stored is used mainly for irrigation and protection of biological life in the Powa river. An important purpose is the flood protection of Konin city. The reservoir is additionally used for tourism and fishery.

The basic data used for presented analyses are the geometry of the reservoir, water surface levels measured at the main dam as well as the inflows to the reservoir. The preparatory data include analysis of measurements and topographic maps in the scale 1:2000 from 2006 (Woliński & Zgrabczyński, 2008). On the basis of the historical maps, the digital terrain model for the reservoir was prepared. Then the DTM was processed using ArcGIS 9.2 with HEC-GeoRAS set of

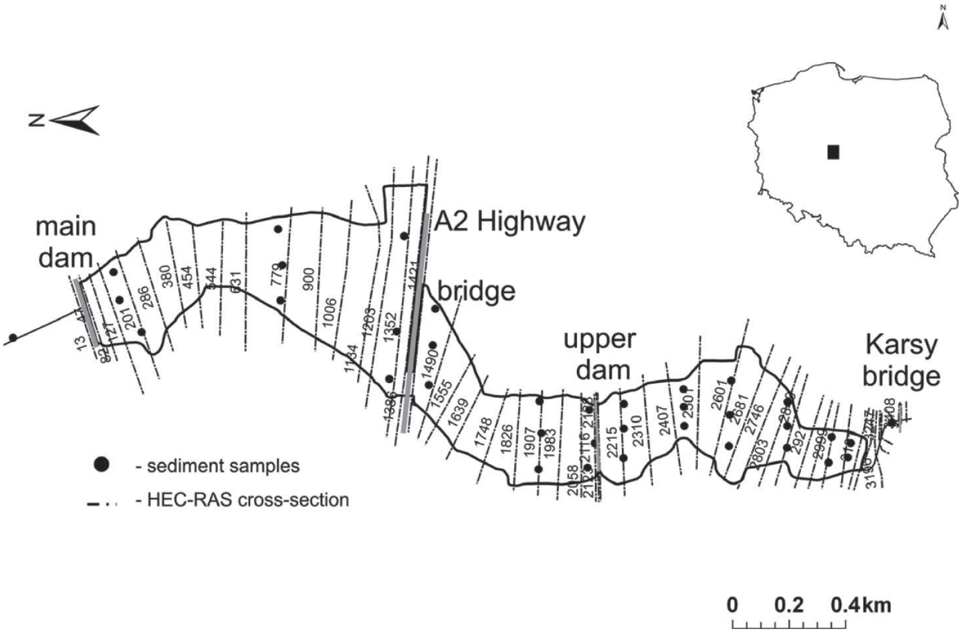

Figure 1. The Stare Miasto reservoir.

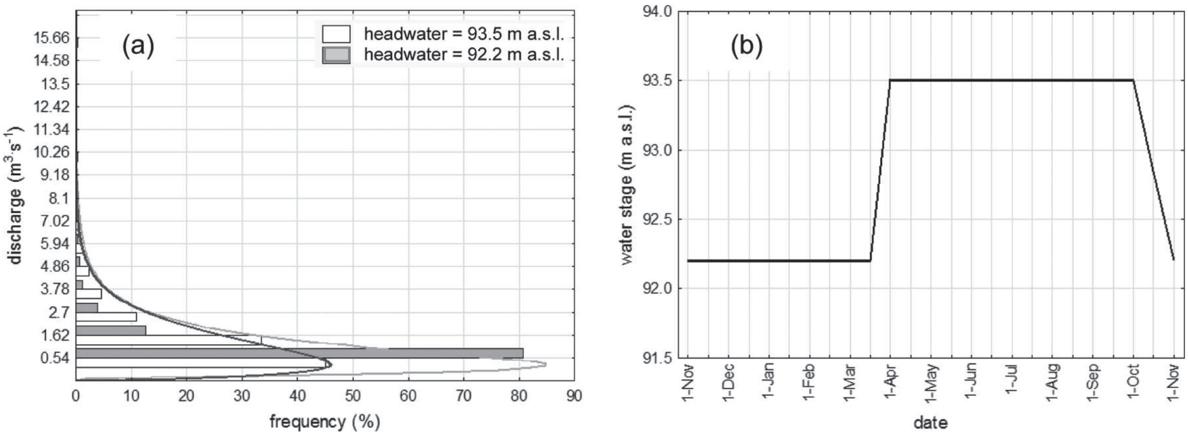

Figure 2. Hydrology and water management: (a) Relative frequency curve of discharges observed at the Posoka gauge station in the Powa river; (b) Typical changes in water levels in the Stare Miasto reservoir.

tools. It enabled definition of basic geometry for hydraulic and sediment computations. Direct measurements were also used for determination of current reservoir bathymetry. Such a survey was made in September 2013. The field survey was made using Echotrac CVM, which is an echo sounder produced by Teledyne Technologies Company.

The average annual unit outflow from the watershed in the dam cross-section is estimated as 3.52 $dm^3/(km^2\ s)$. The closest gauge station is Posoka controlled by the Institute of Meteorology and Water Management (IMGW). The data collected at this gauge station for the period 1975–2009 are available. The inflow varies from 0.012 to 42.6 m^3/s. Two discharge frequency curves were prepared on the basis of these data. The first represents variability of discharge in the months with minimum headwater in the dam. The second is prepared for the seasons with normal water level in the reservoir. The basic frequencies are shown as bar graphs in Figure 2.a. The water surface level varies from the minimum elevation of 92.70 m a.s.l. to 94.00 m a.s.l. Normal water level is 93.50 m a.s.l. (Woliński & Zgrabczyński, 2008). The lower levels are kept during the first part of the year (Fig. 2.b). From April to October the reservoir is used with normal water level.

The data set is completed with analysis of 36 bed sediment samples. They were collected at the sites marked in Figure 1 (center). The sieve analysis is used to determine the mass ratio in classes of diameters compatible with Polish regulations. The bed samples are used to make the standard gradation curves. The particles coarser than 2 mm were not observed in the samples. In general the sediments analyzed were classified as fine or very fine sands. These data were previously used and described, e.g. Dysarz & Wicher-Dysarz (2013a), Dysarz et al. (2013b).

3 METHODS

Two methods were used for estimation of sedimentation in the Stare Miasto reservoir. These were 1D methods namely the standard sediment routing and the Sediment Impact Analysis Method (SIAM). The first is based on the well known Exner's equation (e.g. Exner, 1920, 1925; Parker, 2004; Brunner, 2010). The second is a modern computation technique invented by Mooney (2006). Both of them are implemented in HEC-RAS package for hydraulic computations. The newest version of this software was used for computational tests, namely HEC-RAS 5.0 Beta (Brunner, 2010). The methods are described briefly below.

The HEC-RAS is the well known 1D hydraulic software including flow modules as well as sediment transport and water quality algorithms. The newest version 5.0 Beta is used in this research. The first step in configuration of any HEC-RAS computations is preparation of the modeled system geometry. The cross-sections and their layout is prepared by means of HEC-GeoRAS (Fig. 1). The river stations are at the same distance from the reservoir outlet to the particular cross-section. In general there are 38 cross-sections inside the reservoir with river stations varying from 47 to 3100. The sediment transport module consist of two elements: (1) quasi-unsteady flow model, (2) sediment transport algorithm. In the quasi-unsteady flow module the boundary conditions and water temperatures are set. Two types of simulations were made, namely one year and eight year computations. In the one year simulation the inlet boundary condition is a single annual hydrograph of flows. In the outlet, the stage hydrograph representing water heads in the reservoir is imposed. Thirty five simulations were performed, each one represented one hydrological year. Also ten eight-year simulations were carried out. In these simulations, individual hydrological years were randomly chosen to compose the inlet boundary conditions. The downstream boundary was composed by simple repetition of previous stage hydrographs. The sediment transport algorithm was configured by definition of soil samples, their assignment to cross-sections, definition of admissible erosion depths and sediment boundary conditions. The last element was set as equilibrium load in all simulations.

The second approach used in this study is SIAM. This is one dimensional sediment budget tool, which differs significantly from the typical sediment routing model. The method was developed as part of the Mississippi Delta Headwaters project as a joint effort of the Engineering Research and Development Center (ERDC) and Colorado State University (Little & Jonas, 2010). The first implementation of SIAM was made by Mooney (2006). SIAM is also available in the versions of HEC-RAS 4.1 and next (Little & Jonas, 2010; Brunner, 2010). In this study two SIAM models were configured. Both of them were used to calculate aggradation and degradation inside the reservoir. Hence, the sediment reaches were defined between river stations from 47 to 3100. There were two configurations of sediment reaches used for simulations. In the first there were 38 sediment reaches. Each of them was defined between two subsequent cross-sections. The second SIAM configuration was simplified and included only 14 sediment reaches representing consistent areas of the reservoir, e.g. inlet zone, upstream of a structure, downstream of a structure, etc. The averaged soil samples were assigned to each reach in both configurations. The important element of SIAM implementation is discharge frequency curve (Fig. 2.a). The curves were made for the two states of the reservoir (1) headwater of 92.2 m a.s.l., (2) or 93.5 m a.s.l.. These water levels and their duration was consistent with the rules of water management in the Stare Miasto reservoir (Woliński & Zgrabczyński, 2008).

Both algorithms, sediment routing as well as SIAM, were used with the same sediment transport functions, (1) Engelund-Hansen, (2) Meyer-Peter & Müller (MPM). The first of them was designed for sand transport, which corresponds to the actual conditions in the reservoir studied. The second one was a more general formula used mainly for bed load transport. It was used for comparisons (e.g. Yang, 1996). Other transport functions available in HEC-RAS were notused, because they are not suitable for fine sediments, e.g. Ackers-White, or they have occurred unstable, e.g. Yang. The results of sediment mass transported calculated by sediment routing module were also used as the sources of sediment for the most upstream reach for SIAM computations.

The results obtained are presented as distribution of invert changes along the reservoir profile. The term "invert" is used in a way consistent with the manuals of the HEC-RAS (e.g. Brunner, 2010). It simply means the minimum bottom elevation. The values of invert changes are obtained directly from sediment routing procedure. The standard SIAM results include aggradation or degradation of sediments in a year for particular reaches. These values are recalculated into invert changes assuming that deposits/removals are uniformly distributed along the cross-section bed. This assumption permits definition of the area of deposition/erosion. Than the invert change may be calculated on the basis of bulk density. The contraction related to fine sediments was also taken into account.

4 RESULTS

The results are presented in Figures 3–6 and some raw values are shown in Table 1. The presentation of results in all figures is split into two parts. In the left figure, the results for the inlet part of the reservoir are presented. The rest of results are presented in the right figure. This division had to be made because the values shown in the two parts differ significantly.

The first graphs (Fig. 3) present average invert changes obtained from the sediment routing simulations for one year time horizon. The results are expressed in centimeters, while the river stations are presented in meters. The sediment transport algorithms based on the

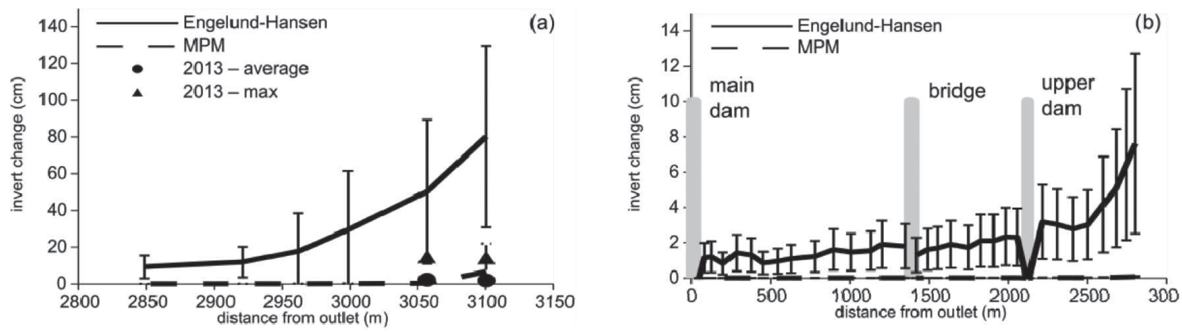

Figure 3. Average invert changes simulated by sediment routing algorithm with Engelund-Hansen and MPM formulae: (a) inlet part—river stations 2849–3100; (b) river stations 47–2849.

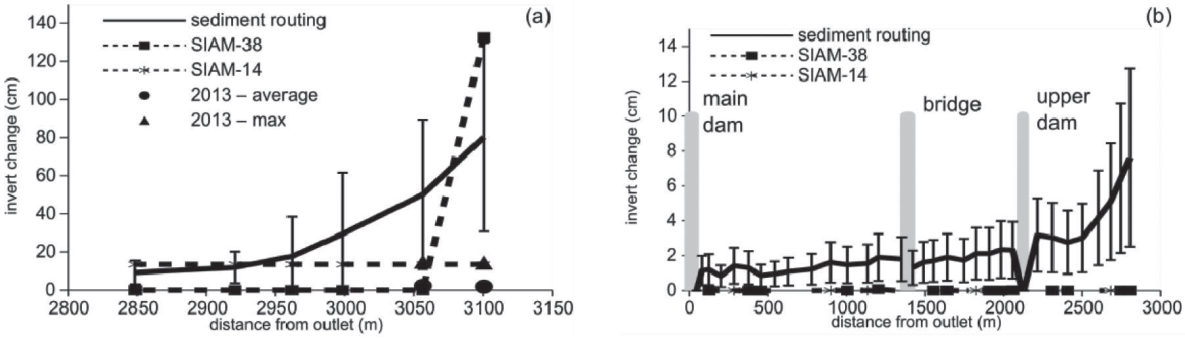

Figure 4. Comparison of invert changes for sediment routing and SIAM with Engelund-Hansen formula: (a) inlet part—river stations 2849–3100; (b) river stations 47–2849.

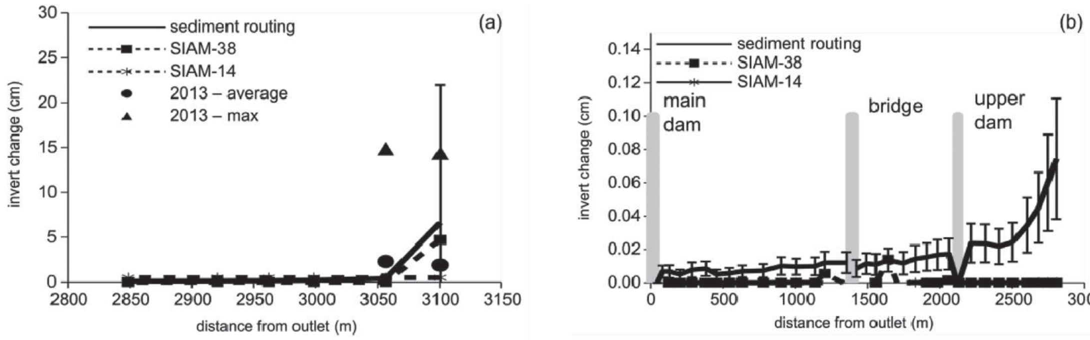

Figure 5. Comparison of invert changes for sediment routing and SIAM with MPM formula: (a) inlet part—river stations 2849–3100; (b) river stations 47–2849.

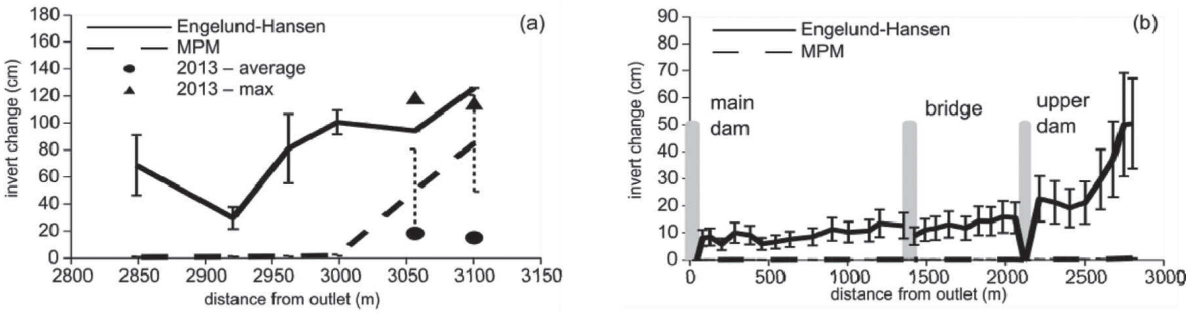

Figure 6. Comparison of invert changes between measurements and long period simulation of sediment routing: (a) inlet part—river stations 2849–3100; (b) river stations 47–2849.

Table 1. Values of invert changes for selected cross-sections.

	Sediment routing				SIAM-38		SIAM-14	
	Engelund-Hansen		MPM		Engelund-Hansen	MPM	Engelund-Hansen	MPM
RS (m)	Invert change (cm)	Standard deviation	Invert change	Standard deviation	Invert change			
3100.57	80.24	49.46	6.64	15.31	132.53	4.70	13.39	0.47
3056.61	50.19	39.21	0.39	0.44	0.01	0.00	13.39	0.47
2848.61	9.21	6.19	0.09	0.05	0.00	0.00	13.39	0.47
2501.23	3.01	1.97	0.02	0.01	0.00	0.00	0.00	0.00
2122.78	Upper dam							
1983.07	2.34	1.64	0.02	0.01	0.00	0.00	0.00	0.00
1747.59	1.72	1.25	0.01	0.01	0.00	–0.01	0.00	0.00
1400.51	Bridge							
1351.90	1.80	1.26	0.01	0.01	–0.03	0.00	–0.01	0.00
899.65	1.61	1.16	0.01	0.01	0.00	0.00	0.01	0.00
454.36	0.85	0.64	0.00	0.00	0.00	0.00	0.00	0.00
25.29	Main dam							

Engelund-Hansen and MPM formulae are compared. The results of the first formula is denoted as continuous line. The results of the second is represented by dashed line. In both cases the standard deviations from averages are marked as vertical error bars. The results of measurements are denoted as large black dots and triangles. Such results are provided only for two river stations in the inlet, namely 3100 and 3056. The spatially distributed results of measurements are presented as average and maximum invert changes in each cross-section. The structures such as upper dam, the bridge and the main dam, are marked by vertical gray lines.

The sediment routing with the Engelund-Hansen formula gives greater results than the same algorithm with the MPM formula. The results of measurements are closer to the latter. This observation is in contrast to expectations as the Engelund-Hansen formulae was derived for finer sediments and expected to provide better results. The only explanation is good theoretical and experimental basis of MPM and complex nature of sediment transport in lowland rivers and reservoir. Fine sediments transported as suspended load in a mountain river become bed load in lowland streams.

The results presented in Figure 4 are comparison of sediment routing and two SIAM models for cases with Engelund-Hansen formulae. The invert changes obtained from sediment routing are displayed as a continuous line with error bars as shown in Figure 3. The SIAM results are dashed lines with points marked as rectangles (SIAM-38) and stars (SIAM-14). The graph prepared for the inlet part (left) includes also results of measurements. The right graph presents also structures. In both cases the graphical elements are the same as those used in Figure 3.

It is well seen that invert changes in the first cross-section of the reservoir resulting from SIAM-38 are greater than those obtained from sediment routing. In the subsequent cross-sections the amount of sediment deposited is smaller and invert changes are also not so great. The results of SIAM-14 show a more uniform distribution of sediments in the inlet part of the reservoir.

Similar results are presented in Figure 5, drawn for the Meyer-Peter & Müller (MPM) equation sediment transport formulae used. The vertical scales of the graphs are different, because the invert changes obtained in these cases are smaller. When this formula is used, the SIAM-38 results are more similar to those provided by the sediment routing algorithm.

Because the values presented in Figures 3–5 significantly differ in scale, some of them may be not visible well. Hence, the results for selected cross-sections are presented in Table 1. The first column consists of river stations numbers of the selected cross-. The table is composed in such a way that a comparison of sediment routing and SIAM models is clearly visible. The invert changes are expressed in centimeters. The results presented in Table 1 confirm those shown in the graphs.

The average invert changes obtained from long period simulations of sediment routing in the reservoir are shown in Figure 6. The denotations and their meaning are the same as those in Figure 3. The obtained invert changes are compared with those resulting from field measurements made in 2013. Once again the sediment routing with MPM formulae gives results closer to measurements, though, the difference between Engelund-Hansen and MPM is not so great. However, the relative compatibility between measurements and long term computations should suggest that all sediment routing simulations are reliable.

In general all SIAM results suggest huge accumulation in the inlet cross-section of the reservoir. The distribution of sediments is better, when sediment reaches are longer. Such effects are caused by the lack of any sediment redistribution or update of hydraulic conditions. The sediment redistribution is better, if the standard sediment routing algorithm is used.

5 CONCLUSIONS

In the paper a comparison of two 1D methods for assessment of reservoir sedimentation is presented. The first is the standard sediment routing model used in multi-scenario scheme. The second is the adapted SIAM algorithm. The main ideas of the methods tested are presented in section 1 and 3 of the paper. The configuration of the methods is briefly described in section 3. In both algorithms two sediment transport functions are used. These are (1) Engelund-Hansen and (2) Meyer-Peter & Müller (MPM). The choice of such functions is explained in section 3. The methods are tested on the basis of data collected and measurements from the Stare Miasto reservoir. The object as well as the data used are presented in section 2. The main element of comparisons are invert changes. The results are presented and briefly discussed in section 4. In the same section small validation of results on the basis of field measurements and long term simulations is shown.

The results presented indicate significant differences between two methods used. The differences are also visible between the transport functions applied independently of the algorithm tested. In general, the sediment routing with the Engelund-Hansen function shows greater deposition than the results obtained with the MPM formula (Fig. 3). This tendency is seen along the whole reservoir. The long period simulations show the MPM results as closer to field measurements (Figs. 3 and 6). In general, the SIAM approach shows greater irregularity in sediment deposition. The main accumulation is indicated in the inlet part of the reservoir (Figs. 4 and 5). When the Engelund-Hansen formula is applied the invert change resulting from the SIAM algorithm with 38 sediment reaches are much greater than those calculated by the sediment routing. The increase in the sediment reaches lengths and decrease in their number causes more regular distribution of sediments at least in the inlet part of the reservoir. However, the results of SIAM-14 still differ much from the sediment routing results (Figs. 4 and 5).

There are some pros and cons of the two methods applied. The sediment routing computations require complex configuration. It is time consuming, but provides more reasonable results. The results are closer to field measurements. The differences may be explained by application of 1D simplification of flow and sediment transport phenomena. On the other hand, the SIAM algorithm is simpler for configuration. The computations are faster and the results do not need to be repeated several times. However, the simplifications introduced to construct the method cause some non-physical effects. Significant irregularity in the sediment accumulation is caused by the arrangement of calculations in SIAM. The direct reason is the lack of any sediment redistribution between the sediment reaches. Such a role is played by the update of geometry and hydraulics in the sediment routing algorithm.

Although, the idea of SIAM seems to be promising, this method still needs some improvement. On the other hand, application of the sediment routing requires too much time consuming computations to be effectively used in ordinary problems such as reservoir design and prediction of capacity changes due to sedimentation. Further research in this area is necessary.

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